An Investigation into the Qualities of New and Field Aged Cycloaliphatic Epoxide Insulation in the Republic of South Africa

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously, in its entirety, been submitted at any university for a degree.

Signature   Date

Synopsis

The application of cycloaliphatic epoxide (CE) insulation in the Republic of South Africa is investigated within this thesis. There was a request from industry to evaluate the product and indicate its suitability for application within the various geographic and climatic zones typical of the RSA.

An extensive survey was conducted into the historic origins of the material, and the experiences of international utilities applying the insulation medium in respect of polluted conditions. The properties of the Automatic Pressure Gelation (APG) CE insulator manufacturing process are discussed with reference to the manufacture of glass and porcelain insulation, and typical areas for concern are discussed with reference to insulators found to deviate from specification.

Typical insulators were obtained from the manufacturers and utilities associated with the product, and were subjected to electrical, material and visual examination tests. The electrical tests included AC wet and dry, lightning impulse, clean fog, salt fog, mould release resiliency and the IEC 1109 voltage test. The material tests included the identification of the epoxide systems in use in the RSA, ultraviolet radiation aging simulation, water hydrolysis and salt deposit density tests.

The main findings are:

- CE insulation is sensitive to marine pollution and continuous-wetting pollution types.
- The use of CE insulation is promoted in respect of inland and medium industrial pollution types.
- Class B pin-type CE insulation is prone to partial discharge related failures.
- Surface roughening on the insulator surfaces leads to reduced AC wet flashover voltages and increased pollution catch.

Additionally:

- A comprehensive aging hypothesis was developed detailing three independent aging stages/modes applying to CE insulation.
- A hypothesis was developed for a new evaluation method for documenting changes on insulator surfaces due to the action of aging mechanisms: The Surface Area Index.

Samevatting

Die aanwending van sikloalifatiese epoksied (SE) isolasie in die Republiek Van Suid Afrika word in hierdie skripsie ondersoek. Hierdie ondersoek is geloods op versoek van die elektrisiteitsbedryf om die toepaslike aanwending van die produk onder die verskeie heersende streeksweersomstandighede binne die RSA te evalueer.

Breedvoerige navorsing is gedoen om die geskiedkundige oorsprong van die materiaal vas te stel, sowel as om die prestasie daarvan as insulasiemiddel te boekstaaf. Daar is veral gelet op die prestasie van die materiaal onder besoedelende omstandighede en ondervinding wat opgedoen is deur internasionale ondernemings. Die eienskappe van die automatiese drukjelvormings-vervaardigingsproses (APG) word behandel met verwysing na die maak van glas en porselein insulators. Tipiese probleemareas word bespreek van insulators wat afwyk van spesifikasie af.

Verteenwoordigende isolators is vanaf vervaardigers en ondernemings verkry wat met die produk bemoei is. Hulle is blootgestel aan elektriese, materiaal en visuele toetse. Die elektriese toetse het die volgende behels: nat en droog wisselstroom, skoon waterdamp, sout waterdamp en die IEC 1109 spanningstoets. Die effek van die verlies van die anti-kleefmiddel (gebruik tydens die gietproses) as gevolg van veroudering is ook in detail behandel. Die materiaaltoetse het ingesluit: die uitkenning van die epoksied stelsels in gebruik in die RSA, gesimuleerde veroudering deur ultravioletligbestraling, water hidroliese en soutlaag digtheids toetse.

Die hoof bevindings is:

- SE isolasie word beïnvloed deur seelug besoedeling sowel as volgehoue benatting. Die gebruik van SE isolasie word voorgestel vir binnelandse gebruik sowel as in gebiede met mediumvlak nywerheidsbesoedeling.
- Klas B pen-tipe SE isolasie is geneig tot deelontladings wat dan tot faling lei.
- Oppervlakvergroffing lei tot 'n verminderde wisselstroom orvonksspanning onder nat toestande sowel as verhoogde vangs van besoedeling.

Bykomend hiertoe is:

- 'n breedvoerige SE verouderingshipotese ontwikkel wat drie onafhanklike stadia en modusse van die verouderingsproses uitgewys het.
- 'n hipotese ontwikkel vir 'n nuwe evaluasiemetode om die verandering in die isolatoroppervlak as gevolg van veroudering te dokumenteer: Oppervlakte-Area Indeks (SAI).

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Glossary of Terms

Class A Insulator	A post insulator where the flashover path through the insulator dielectric is at least one-third the flashover path through the air surrounding the insulator dielectric.
Class B Insulator	A post insulator where the flashover path through the insulator dielectric is less than one-third the flashover path through the air surrounding the insulator dielectric.
Desorption	To remove an absorbed or adsorbed quantity from an object.
Field-aged Insulator	A reference insulator that has been subjected to typical duties in the utility electrical networks and exposure to naturally occurring aging factors.
Gelation	The process that allows liquid epoxide resins to become mechanically robust through the cross-linking of the polymer molecules – typically accelerated by the application of heat to the reaction site.
Hydrophilic	Having an affinity for water, readily accepting water or dissolving in water.
Hydrophobic	Repelling, tending not to combine with, or incapable of dissolving in water.
Hypothesis	A tentative explanation that accounts for a set of facts and can be validated by further investigation.
Insulator	A material or device that insulates by not permitting the conduction of sound, heat or electricity. Electrical insulators are characterized by their additional duty of mechanically preventing electrical conductors from contacting earthed structures.
Microscopy	The use of microscopes for the purposes of research.

Modified Insulator   An insulator that has been modified by mould release removal.

Morphology   The form and structure of an entity, or one of its parts.

Oxidation   A reaction in which the atoms in an element lose electrons and the valence of the element is correspondingly increased.

Reference Insulator   An insulator that has not been modified, and is representative of an insulator delivered by the manufacturer to the customer.

Sorption   The process in which one substance takes up or holds another (by either absorption or adsorption).

Topology   The topographic (profile) study of a surface or surface area.

Ultraviolet Radiation   Of or relating to the range of invisible radiation wavelengths from about 4 nanometers, on the border of the x-ray region, to about 380 nanometers.

CHAPTER 1

INTRODUCTION

1.1 General Background

Until the 1980's, porcelain and glass insulators enjoyed widespread application within high voltage electrical networks. The last 25 years (since 1976) have been characterized by the influx of new materials into the high voltage insulator market. Cycloaliphatic Epoxide (CE) resin insulators have been used extensively in reticulation networks throughout the western world (Appendix A).

It is generally accepted that approximately 7.5 million CE insulators have seen service in the world to date.[1] The combined production of CE insulators in the Republic of South Africa (RSA) is in the vicinity of 3.8 million individual units, as indicated in Figure 1.1.

Worldwide Distribution of CE Insulator Manufacture

Asia 0%
Europe 30%
RSA 51%
America 19%
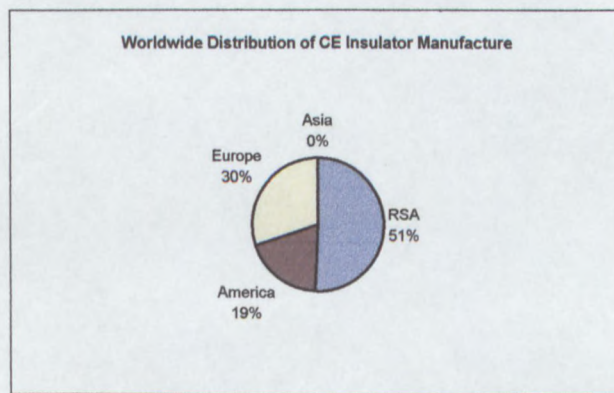
Figure 1.1: Worldwide Distribution of CE Insulation Manufacture (Approximated)

Most of the CE insulators used by RSA utilities are of the outdoor type, and are therefore exposed to pollution and the elements while performing their electrical duties. There has been concern as to the ability of CE insulation to withstand the aging effects of the elements (solar radiation, condensation) in conjunction with pollution (natural and man-made).

It is generally accepted that the environment has a detrimental effect on the performance of outdoor electrical insulators. The type of climate that the insulation is deployed in can affect its ability to perform its insulating functions under various pollution environments.

As an example, the RSA is prone to particularly high levels of solar ultraviolet (UV) radiation that is known to modify the surfaces of non-ceramic insulators (NCI's).[2] Large doses of UV radiation have been known to cause serious detrimental effects to the abilities of NCI's to prevent the accretion of pollution to their surfaces. This is

because UV radiation causes NCI surfaces to roughen or lose their ability to repel water.

Typical pollution can be the following:

- Natural   marine

- Industrial pollution: acid rain
  smoke particles
  conductive salts and deposits

- Agricultural pollution: dust from land utilization
  residues from crop spraying

- Combined: a combination of industrial and agricultural pollution

The main thrust of this thesis is to investigate the effects of the South African environment on CE insulation.

1.2 Research on CE Insulation to Date

CE applied as outdoor insulation has not received a similar amount of recent research interest as glass, porcelain, EPDM or silicon rubber insulation. International research has focused on the following aspects surrounding CE insulation:

- The effect of moisture on epoxies

- Improvement of aging resistivity

- The influence of partial discharges on epoxide castings during the early aging process

- Decomposition products of epoxide castings during the early aging process

- Reports of experiences of CE insulators under European and desert conditions

1.3 The Aims of this Thesis

It was decided to investigate the history of CE insulation, the materials and methods employed to create the final insulator product. It was hypothesized that the following aspects of the product could affect its performance as electrical insulation:

- The inherent chemical, mechanical and electrical properties of epoxides

- The qualities of the manufacturing process employed to create CE insulators

- The conditions and length of time that the CE material is exposed to aging stimuli

By investigating the inherent qualities of CE's and the manufacturing methods used to create CE insulators, one can predict the mechanisms that could induce aging and the resultant reduction in electrical performance. By observing the environments that CE insulators are exposed to, one can accumulate a set of acceptable simulation (laboratory) aging techniques that are useful to evaluate the properties of CE products. The CE exposed to the simulated aging stimuli can be cross-referenced to field aged CE by comparing their respective properties using accepted laboratory test techniques.

There are accepted laboratory tests that can be applied to electrical insulators to determine their ability to withstand applied electrical stresses. Similarly, laboratory test techniques are available for the evaluation of polymeric materials (CE's) – to determine their ability to withstand applied environmental (chemical, physical) stresses. These tests were evaluated and combined into a cohesive set of analysis techniques (Chapter 4) – in the hope that they would provide insight into the respective reactions that the CE insulators would have to them. This would allow for the evaluation of the effects of the applied aging techniques on the CE materials and insulators.

Thus, the aims of this work are:

- To compare the differences in electrical performance between naturally aged and new CE insulators

- To evaluate the use and performance of CE insulators in inland and marine pollution environments

- To use laboratory aging techniques to assess the properties of CE materials when exposed to isolated aging mechanisms.

- To propose a hypothesis for the aging processes inherent in CE insulators under RSA service conditions

- To comment on the suitability of CE insulators for use within the electrical networks of power utilities in the RSA

- To indicate future areas of investigation into the performance and feasibility of the application of CE insulators in the RSA.

1.4 Structure of this thesis

Chapter 1: A general introduction into the development and application of CE insulation.

Chapter 2: An investigation into the history of CE resins, and the constitution of a generic CE resin system.

Chapter 3:   The processing of CE resins into CE insulation using the Automatic Pressure Gelation (APG) casting method.

Chapter 4:   The experimental philosophy and experimental methods used to evaluate new and field-aged CE insulation.

Chapter 5:   Results

Chapter 6:   Discussion of Results

Chapter 7:   Hypothesis for the aging cycle in outdoor high voltage CE insulation employed in the RSA.

Chapter 8:   Conclusions and Recommendations

Appendix A: Recent Experience with CE Insulation

Appendix B: Insulator Dimensions

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CHAPTER 2

RE-INFORCED PLASTICS: EPOXIDE RESINS

In Chapter 1 (Introduction), it was shown that polymers have been in use in the electrical engineering market for quite some time.

The aim of this chapter is to provide the reader with a vantage point, from which the development of epoxides can be observed as a whole – to form a balanced view of how this unique form of outdoor insulation came into existence.

2.1 A selective history of epoxide resins

The first commercial attempt at producing epoxide resins occurred in 1927 in the USA.[1] The discovery of materials first designated as being epoxide resins, derived specifically from epichlorohydrin and Bisphenol A, is shared by Dr. Pierre Castan (Switzerland) and Dr. S.O. Greenlee (USA).

Castan (de Trey Bros – Zurich) was the first person to realize the value of epoxide resins and their applications in the plastics industry. In 1935, he patented a system of epoxies where there was no evolution of volatile matter during the curing process, with low shrinkage and sound mechanical qualities. These epoxies were cured using poly(carboxylic acid anhydride)s, and were first applied in the field of dentistry.[1]

Ciba, in conjunction with de Trey, worked on two patents (DP 749912 and EP 518057) that ultimately resulted in a wide scale entry of epoxies into the market place. In July 1945, the first patent application was granted in the field of epoxide adhesives.[2] In the spring of 1946, the first epoxide resin adhesive was presented at the Swiss Industries Fair in Basel. The work carried out on epoxies in Switzerland was complimented by a similar effort in the USA. Initially work was begun by Devoe-Raynolds, and was followed by Shell.

Ciba's CY 184 resin system has seen widespread use in electrical insulation systems over the last 30 years. The most recent development in CE's was made by Ciba Specialty Chemical Inc. with the introduction of 'New Outdoor Epoxy Systems with Hydrophobic Properties".[3]

2.2 Epoxides

Epoxies are thermosetting resins and the uncured components can be either liquids or brittle solids. When magnified the molecules of the resin appear as short pieces of string. When the resin is cured, the short pieces of string join end-to-end and at the sides to form larger cross-linked structures.

A cured epoxide resin is known to be thermoset – it is not capable of returning to its original liquid condition, even on heating. Softening on heating might however take place. The greater the density of cross-linking within an epoxide, the more superior the electrical and mechanical qualities of that system over a similar less cross-linked system.[1]

Generic properties of an epoxide resin system include good mechanical, dielectric, chemical and heat resistance, and adhesive qualities.

2.3 Structure of epoxide resins

The term, epoxide, describes a 3-membered ring containing one oxygen and two carbon atoms.
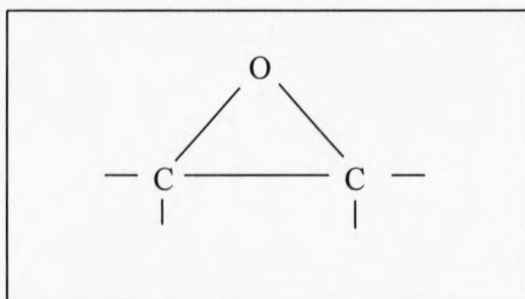
Figure 2.1 - Basic epoxide structure

Generally, an epoxide resin molecule contains more than one epoxide group. The 3-membered epoxide ring is highly reactive due to the acute angles in the structure straining the inter-atomic chemical bonds. By reacting all the reactive components within the epoxide resin, the system becomes cured, stable and thermoset.

Epoxide resins containing a high epoxide content and an advanced degree of cross-linking density tend to exhibit superior qualities to a similar resin system in a reduced state of cross-linking or cure.[1]

2.4 Polymerization of epoxide resin systems

Epoxies can be cured by catalysis or polyaddition. During catalysis, the molecules of the epoxide are induced to react with one another by the introduction of a catalyst and are then said to be homopolymerised. Curing by polyaddition is characterized by the addition of hardeners to the resin system. These hardeners form an integral part of the

cured system. Typical hardeners include Lewis acids and bases, primary and secondary amines, polyamides, polysulfides, mercaptans, organic bases, anhydrides and phenolic resins.

When curing CE's, only certain anhydrides are utilized. Anhydride hardeners require elevated temperature cures and yield superior chemical and heat deflection properties.[2] In some cases anhydride cured systems lend themselves to long pot-lives and low exotherms, thus gaining favor with end-users.

CE's are prepared from cycloolefins and peracetic acid, and are characterized by good dielectric and mechanical properties. They, however, tend to be more brittle than standard epoxide systems. CE systems, additionally, offer superior resistance to weathering, electrical arcing and tracking.[2]

2.5 Generic properties of epoxide systems

Epoxide resins possess many properties:

1. Low viscosity: Assists in the complete filling of moulds and helps to eliminate the formation of voids in the final product – is dependant on the amount of filler included in the system.

2. Cure easily: Epoxide resins cure rapidly, especially at elevated temperatures and can be annealed after withdrawal from the mould.

3. Low shrinkage: An important advantage is the reduced shrinkage during cure, allowing for manufacturers tolerances in the dimensions of the cast object to be complied with.

4. High adhesive strengths: Epoxide resins, due to the presence of polar hydroxyl and ether groups, exhibit excellent adhesive properties.[1,2]

5. Mechanical integrity: Due to the low shrinkage during cure there are reduced stresses that could weaken the casting, especially when there are foreign objects embedded in the cast object that exhibit different coefficients of thermal expansion or contraction.

6. Good electrical insulation

7. Good chemical resistance: A large proportion of epoxide resins possess good resistance to caustics and acids.

8. Versatility: The basic properties of the end product can be modified by the addition of additives and fillers, blending of resin types and by selecting the curing agents.

2.6 Traditional applications of Epoxide Resins [1]

Due to their versatility, epoxide resins are used in many industrial applications. Typical applications include the following:

1. Adhesives for aircraft structures, paintbrush bristles and concrete sealing compounds.

2. Body solders and caulking compounds for the repair of plastic and metal structures.

3. Casting compounds for prototype molds, stamping dies, patterns and tooling.

4. Encapsulation compounds and impregnating resins and varnishes for electric and electronic equipment.

5. Electrical insulators in utility networks.

2.7 Electrical Properties of Polymers

The subject of the electrical properties of polymers covers a wide range of molecular phenomena. By comparison with metals, where the electrical response is predominantly one of electronic conduction, polymers exhibit a more complex response to the application of an electrical potential.

No known polymeric insulator is totally free of electronic conduction, because of the introduction of impurities into the polymer system. These impurities provide charge carriers in the form of electrons or ions and at high fields the presence of electrodes within the polymer system may donate new charge carriers into the system.[4] This phenomenon can cause the conduction of current to increase in a non-linear fashion with applied voltage, in a manner not in accordance with Ohms law.

At very high field strengths these and other processes often involving conduction over the surface of the polymer (possibly due to a conducting pollution layer), may result in the failure of the material as an insulator.

2.8 Electrical applications of polymers

As synthetic polymers became available (1940's), the availability of polymeric insulators was continually improved. The driving force behind the move towards polymeric insulating materials was not the fact they are inherently good insulators, but that the material is easily manipulated and molded to the required design.[4]

The choice of material for a particular application depends on the compromise between the electrical, mechanical, environmental and financial requirements. The basic insulating properties of most polymers are sufficient for most insulating purposes. Most development effort is concentrated on improving the polymer for aspects of its role as an insulator – increased mechanical performance and physical

stability, resistance to acids, stability under the application of solar (ultraviolet) radiation, resistance to tracking etc.

Commercial success of polymers for use in specialized electrical applications is dependant on the careful isolation of inherent strengths in the material to be applied. The versatility of polymers allows the grooming of the material to various roles or applications.

In order to accommodate the use of polymers for high voltage applications, priority must be given to the need for the material to withstand the electrical stress in the presence of mechanical and environmental stresses.

2.9 Fillers and reinforcements

The ASTM D883 specification defines a filler as "…a relatively inert material added to a plastic to modify its strength, permanence, working properties or other qualities, or to lower costs"; and can be classified into three main categories:

1. Extender: An extender is a low cost material utilized to reduce material costs by occupying volume normally occupied by the more expensive resin system.

2. Semi-reinforcement: A semi-reinforcement is a moderately priced filler utilized to displace volume within the resin system, and to provide some improvement in the resin system properties.

3. Reinforcement: A reinforcement is relatively costly filler utilized to impart improved characteristics to the resin / filler system.

An additive is a substance that is added to organic polymers to improve their resilience to the effects of light, heat and bacteria. Additionally, additives can be utilized to modify an epoxide resin's density, thermal expansion, processing properties, lubricity, color etc.

Specifically, two types of filler have seen widespread use in CE insulation: Alumina Trihydrate (ATH) and Silica.

a) Alumina Trihydrate (ATH)

ATH is a functional filler, employed to impart flame retardance and electrical arc resistance to resin systems and is sourced from Bauxite ore, a claylike mineral, the chief source of aluminum. Bauxite reserves are located in the USA, South America, Jamaica, Europe and West Africa. [5,6,7]

ATH is produced from the raw Bauxite ore by using the Bayer Process. The Bayer Process involves the crushing of the Bauxite ore, and the digesting of the aluminum hydroxide by hot caustic soda, under pressure.

$$2\ Al(OH)_3 + 2\ NaOH \longrightarrow 2\ NaAlO_2 + 4\ H_2O$$

aluminum   sodium   sodium   water
hydroxide   hydroxide   aluminate
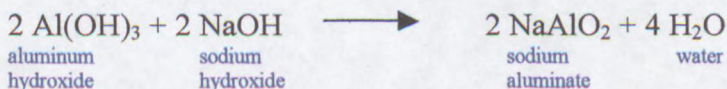
Various impurities contained within the ore are removed by the action of gravity, and the sodium aluminate is filtered. The sodium aluminate solution is constantly agitated and is seeded with ATH crystals, resulting in a crystalline alumina hydroxide. These crystals are washed, separated, dried, and if need be – ground to the required size.

An alternative and superior process is also available, and is known as the sinter process.[6] The Bauxite ore is crushed and placed into solution with water to form a slurry. The slurry is blended with limestone and sodium carbonate and then calcined at 1000 ^{0}C to produce a sinter containing dicalcium silicate and sodium aluminate.

The sodium aluminate is separated from the insoluble dicalcium silicate and is processed according to the Bayer method, yielding superior ATH products.

Key properties

ATH (hydrated alumina or aluminum hydroxide) is chemically notated as $Al(OH)_3$, is insoluble in water and has a density of 2.42 g/cm^3. It is moderately abrasive (Mohs scale 2.3 –3.5) and has a refractive index of 1.58 – thus allowing many resins of a similar refractive index to retain their translucency when filled.

ATH is unreactive at room temperature, however, slow decomposition occurs at temperatures of 205 – 220 ^{0}C. At temperatures above 220 ^{0}C ATH begins to decompose endothermically (it requires energy to decompose).

The decomposition reaction is:

$$2\ Al(OH)_3 \xrightarrow{\text{heat energy}} Al_2O_3 + 3\ H_2O$$
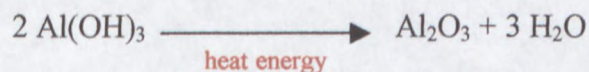
It is this endothermic decomposition inherent to ATH that imparts its characteristic for flame retardation and smoke suppression. The chemically combined water that is released during the decomposition assists in this suppression.

b) Silica (Quartz, fused and diatomaceous)

Silica is often used as an extender, semi-reinforcing filler or as a reinforcing filler. The application or use of silica in epoxide resin systems is primarily determined by the properties required of it – and these properties are in turn derived from the variations in the silica particle size, coating, loading, resin system, surface area and shape.

Crystalline silica is derived from two chief geological sources: the quartzite sands or sandstones; and the tripolitic forms. Both types are occasionally referred to as silica flour – this is specifically the case in the RSA.

The quartzite sandstone operations are large in scale and require sophisticated ore transportation networks – being either rail or road. The sandstone is crushed in primary crushers and is processed and filtered to remove unwanted materials (biological etc.). The crushed and cleaned product is thoroughly dried before being ground to the required particle size. The silica is then sorted into the required grades by screening or air-floating.

The tripolitic silica from Southern Illinois is mined by the room and pillar method, while the tripolitic silica from West Central Arkansas is strip mined.[8] The mined ore is then ground into the required particle size and air-floated to the required grade.

Applications

Silica flour is used in epoxide resin systems where hardness, strength, chemical resistance, good flow in the mould, electrical insulation, thermal conductivity, mechanical wear resistance and thermal conductivity are pre-requisites.

Silica flour is very hard (7 on the Mohs scale) and this can be considered a drawback when machining of the product is required. Care must be exercised when the application of the end product is used in moving parts, with close tolerances.

Silane treatment of silica (synthetic silica)

Synthetic silica's are white powders having the formula: $SiO - X.H_2O$, where X is the mols of water associated with the silica compound.

The surface of synthetic silica contains physically absorbed water and silanol groups.[9] The silica surface can be modified by encapsulating it in silanes – converting the hydrophilic surface to a hydrophobic surface; resulting in superior properties relative to untreated silica flour. The silane treatment of the silica flour has a further advantage of improving the bonding between the resin system and the silica flour filler.[7, 9, 10, 11, 12, 13]

Conclusion

Epoxide resins have been in existence since 1927 and have been continuously improved through research and development. Epoxide resins possess certain generic qualities that lend themselves to the requirements of insulation for high voltage equipment: good mechanical, dielectric, chemical and adhesive qualities. These generic qualities can be tweaked and improved by the addition of fillers and additives.

Furthermore, CE insulators for outdoor use must perform their duties under adverse environmental conditions such as UV, precipitation and pollution.

Epoxide resins were not developed for their present role in high voltage insulation, but this is rather an application because of the ease with which CE insulators can be manufactured, relative to glass and porcelain insulation.

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CHAPTER 3

THE AUTOMATIC PRESSURE GELATION PROCESS

Chapter 2 (Epoxide Resins) served as introduction to the qualities of epoxide resins and their inherent qualities for use as electrical insulation.

A typical epoxide resin system used in the manufacture of high voltage insulators consists of various components that need to be mixed in recommended ratios and cured according to specification in order to provide an end-product of the required electrical and mechanical properties.

Chapter 3 discusses the Automatic Pressure Gelation (APG) process with reference to the manufacture of porcelain and glass insulation, and how it (the APG process) assists manufacturers in economically providing the customer with the best possible CE insulator product.

Additionally, the specification of resin systems is discussed and how the cured final product may deviate from the specification due to variables introduced into the APG process: be it by negligence, design constraints or intent.

3.1 The manufacture of glass and porcelain insulation [1]

Porcelain insulators

Porcelain insulators are predominantly manufactured by the wet process method; and contain on average approximately 55% clay, silica filler material (approximately 25%) and a quantity of potash feldspar flux. The processing of these materials forms part of a multi-stage process.

Stage 1: the clay is prepared by mixing the correct proportions of raw materials with water to form a slurry. The slurry is stored in large storage tanks and is continuously agitated. Before use, the slurry is screened for large particles and is magnetically filtered to remove any magnetic and conducting matter.

After filtering, the slurry is compressed in a press to reduce the water content to approximately 15% and is loaded into a 'pug mill' where the mass is mechanically shredded under vacuum – allowing for degassing of the clay, thus greatly eliminating the chances of voids in the insulator mass. The clay is processed into cylinders ('green clay') of the dimensions required during the forming process.

Stage 2: The forming process: Suspension, pin and multi-cone type insulators are formed by compression of the 'green clay' in 'plaster of Paris' moulds. The 'plaster of Paris' moulds assist in the 'green clay' drying process by readily absorbing moisture from the compressed clay. Post insulators are manufactured on lathes. The formed clay is gradually air-dried – final machining and finishing of the shapes takes place

after this phase (the shapes can deform slightly due to this drying process). Glazing is then applied, and coarse sand is applied to the ends of insulators designed to accept metal end-fittings. The raw insulators are then fired in kilns at temperatures of 1200 ^{0}C. During firing, considerable dimensional changes occur – due to shrinkage of the clay during the sintering/densification process – and this dictates the use of staged temperature intervals during the heating and cooling processes.

Stage 3: The insulators are completely assembled, and electrically and mechanically tested for conformance and defects.

Glass Insulators

Glass insulators are manufactured from various raw materials, consisting of cullet (fragmented glass), soda ash, feldspar and other additives to assist with the release of gas during the fining process. The raw materials are crushed to produce a fine powder, screened and separately stored in silos. The glass furnaces are fed with the correct proportion of raw materials, supplied by conveyor from the silos. The raw materials are fed into the furnace from above, and settle into the already molten mix contained within – and undergo the melting and fining phases of production. The amount of material entering and leaving the furnace is held in equilibrium – and molten glass at a temperature of 1400 ^{0}C is drawn from the bottom of the furnace in the form of a standard quantity at a standard temperature.

The molten glass is placed within a cast-iron mould and is pressed into shape, is heat tempered and is exposed to thermal shock by immersion in water. Molded glass containing flaws is removed from the production process during the thermal shock test.

Successfully tempered glass is then assembled into insulators, is mechanically tested and packaged for distribution.

3.2 The manufacture of CE insulators

Prior to the development of the APG process in 1969, conventional methods such as gravity casting were used. Presently, the APG process is a widely used method for producing electrical insulating products from epoxy resin systems, in the high voltage engineering industry.

The Generic APG Process (Ciba-Geigy developed)

CE insulators are manufactured from resins, fillers, hardeners and accelerators. The raw materials are constituents of a specific system (Table 3.1). Each system contains its own inherent requirements in order for the end-product to achieve the stated specifications.

The qualities of the end-product of any system are dependent on:

15

- mixing ratios
- mixing efficiency
- curing temperature (Figure 3.2)
- curing time
- cleanliness

Deviation from the suggested mixing ratios of +-5% has been shown to produce modifications to the electrical and mechanical properties of the generic resin systems, and that the specification of the resin system becomes invalid for the indicated applications.[2]

The following are examples of basic raw materials for two separate systems, and their suggested proportions (p.b.w. – parts by weight) required to begin the APG process:

	Resin System C[3] Casting Resin System	Resin System B[2] Casting Resin Systems
Casting resin	CY 184 100 p.b.w.	CY 160/MV 100 p.b.w.
Curing Agent	HT 907 (hardener) 90 p.b.w.	Rütadur H 90 p.b.w.
Accelerator	DY 071 3 p.b.w.	Rütadur Acc. BDMA 0.2 - 0.5 p.b.w.
Filler	Silica Flour 300 p.b.w.	Silica Flour 285 p.b.w.
Mould Release Agent	QZ13	QZ13
Additives	Unknown	Unknown

Table 3.1 – Comparison of resin systems

The resin, curing agent and filler mixtures are prepared in vacuum mixers immediately prior to use. Intensive agitation of the mixture should take place to promote absolute wetting of the filler by the resin. Intensive wetting of the filler is imperative as it allows for the following:

- Better flow properties and reduced shrinkage of the resin system in the mould
- Lower internal stresses resulting in improved mechanical properties of the cast object
- Improved partial discharge behavior in high voltage applications due to the fact that agitation and correct wetting will improve bonding between the resin and the filler – reducing the probability of internal voids in the resin system.

The quantities of resin prepared using the batch mixture system, typically sufficient quantities for a full day's production, dictate the use of continuous agitation of the storage silo in order to prevent sedimentation of the resin/filler mixture - and the resultant inaccuracies in filler distribution that would occur during subsequent injection of the mix into the mould.

The manufacturers recommend that the thin film degassing procedure should be employed for mixing of the resin systems at lower temperatures (room temperature). These thin film degassers may produce an additional 10-15 ^{0}C increase in the mix

temperature because of friction between the components of the degasser and the resin mix (Figure 3.1). Mixing time can vary between 0.5 and 3 hours, depending on mixing temperature, quantity, mixing equipment and the end-application of the cast object.

Installations utilizing the batch mixture system require little expenditure, but are bound to using resins with long pot-life characteristics. The resin system is prepared at room temperature and the pot-life is typically in the region of 24 – 48 hours.
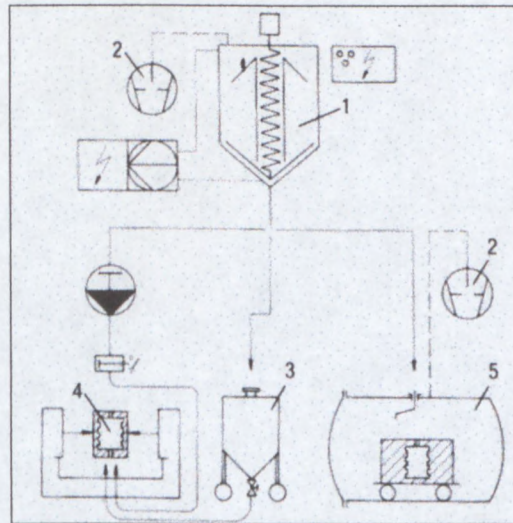
1. Thin-layer degassing mixer
2. Vacuum pump
3. Pressure Pot
4. Clamping unit / Mould

Figure 3.1 – The 'batch mixture' system [2]
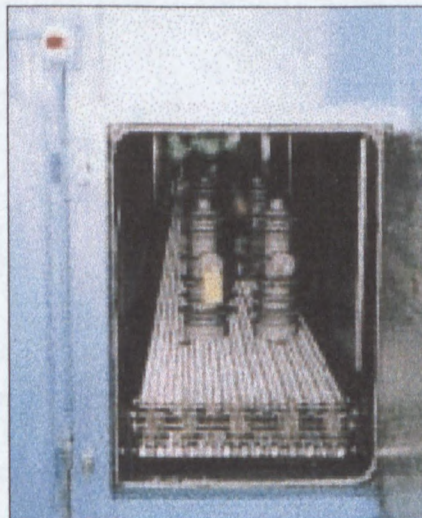
Figure 3.2 – CE insulators in the annealing oven

	Conventional Casting	Automatic Pressure Gelation
Mould temperature	Mix temperature 80-100 ^{0}C	Up to 70 ^{0}C higher than the mix temperature. Typically in the range 130 ^{0}C – 150 ^{0}C
Reactivity of mix	Low – stage cures can be required	High
Demolding time	3 – 6 hours	10 – 40 minutes
Annealing/Cure conditions	10 hours @ 140 ^{0}C	8 hours at 140 ^{0}C
Heat capacity	High	High
Application of pressure to inlet gate during gelation phase	No pressure applied to the mould system during gelation	1-3kg/cm^2. Complicated shapes requiring higher pressures.

Table 3.2 – Comparison between the conventional and APG process

In order to produce a molding, the accelerated resin mixture is fed under pressure (0.5 – 3 bar) through a casting valve with an injection nozzle that is strategically placed within the mould. Most moulds are filled from below in order to eliminate any unnecessary turbulence that could cause voids during the filling injection process. The mould is maintained at a constant temperature that corresponds to the curing temperature of the resin mix employed.

During the curing process, a constant holding pressure of between 3 – 6 bar is maintained in the injection nozzle. This allows for continuous resin injection into the mould, should shrinking of the curing resin mixture take place. The areas of shrinkage will be augmented by the application of more resin to the areas of shrinkage, thus allowing good dimensional accuracy of the cast object.

The cast object is allowed to gel in the mould and is removed after sufficient time has elapsed – approximately 40 minutes, thus allowing the mould to become available for the next casting process. The gelled (or set) casting is then removed to an annealing oven where final cure takes place at elevated temperature and extended time.

3.3 Features of the APG Process [2]

- Efficient mass production through the shortening of cycle times
- Positive control over the exothermic cure reaction
- Narrow tolerances in castings as a result of accurate mould design
- Cast parts have clearly defined mechanical and electrical properties
- Flexibility of cast design
- Low energy consumption
- Low levels of environmental pollution due to the nature of the totally enclosed processing system

Areas for concern in the APG Process:

- Flash-line
- Uneven distribution of filler
- Mould release agent
- Voids
- Hollow castings

a) Flash-line: CE insulators are cast in moulds – the moulds consist of two sections that are hydraulically pressed together to ensure a tight fit and resultant dimensional stability, and to enable the gelled cast object to be removed. As a result, a flash-line is formed along the line where the two halves of the mould meet. The flash-line is characterized by its rough and raised appearance (Chapter 7, Figure 7.1).

b) Uneven distribution of filler: This factor is admittedly more of a concern with the casting of larger CE objects. During the time taken for the resin system to enter the mould and for gelation to begin, there is some gravitational settling of the filler within the resin system. This is partly as a result of the low viscosity of the resin system.

c) Mould release agent: Due to the superior coupling / bonding qualities of CE resin systems, a mould release agent is employed to facilitate the removal of the gelled casting from the mould. The mould release agent provides the CE insulation with initial optimistic performance in respect of polluted conditions, until it is removed by natural weathering.

d) Voids: Voids are potentially the most harmful defects that CE insulation can contain. Voids are caused by inadequate wetting of the filler (by the resin), inadequate production processes where all trapped gas is not removed in the degassing plant; and by intricate mould designs that do not allow total wetting and optimal injection nozzle placement. CE insulation containing voids, when subjected to high voltage applications, suffer the negative consequences of partial discharge behavior and the resultant aging and failure typical of this condition.

Figure 3.3: CE casting containing voids

e) **Hollow castings:** Hollow castings are a rare occurrence. They are caused by the incorrect application of pressure of the resin system supply to the mould during the gelation period. During the gelation period, a 'holding pressure' of 3 –6 bar is maintained in the mould. If the 'holding pressure' is insufficient, or removed, the resin system within the mould will run out. Due to the nature of the mould design i.e. the part of the mould in contact with the resin system begins to gel the outer regions of the cast object first (much like boiling an egg). The resultant hollow castings to all purposes resemble a normal CE insulator, yet posses no electrical or mechanical integrity.

Figure 3.4: Hollow Casting

3.4 Typical Resin System Specification

Resin system specifications are dealt with here, and not Chapter 2, as they are so dependant on the process employed to produce the final product: the APG Process.

Manufacturers of resin systems provide users with comprehensive specifications for their systems that are valid only when mixing ratios and curing conditions are strictly adhered to. These specifications include the following:

- Flexural strength   (MPa)
- Deflection   (mm)
- Tensile strength   (MPa)
- Elongation   (%)
- Impact resistance (mJ/mm^2)
- Compressive strength   (MPa)
- Glass transition temperature (^0C)
- Linear coefficient of thermal expansion $(10^{-6}/K)$
- Thermal conductivity   (kJ/mhK)

- Water absorption   (% wt.)
- Specific volume resistance   (Ωcm)
- Surface resistance   (Ω)
- Dielectric strength   (kV/mm)
- Dielectric dissipation factor
- Permittivity

Degree of Cure

These specifications are dependent on the degree of cure that the CE has experienced. During the early stages of cure, when all reagents have been combined and the CE system is placed in the mould and gelation has begun – the resin system exists as a thermoplastic resin: all the molecules able to react and combine into chains have not had the opportunity to do so (not a high degree of cross-linking has taken place).[4] The resin is fairly solid, but fragile and soluble in various solvents. It is at this point that the CE insulator is removed from the mould and is placed in the annealing oven.

The CE insulator that has been placed in the annealing oven is characterized by an incomplete degree of cure: the cure reaction has been initiated at widely separated points within the reactive mass (low level of cross-linking); and with additional cure / annealing the degree of cross-linking is allowed to progress and become general.

In some CE systems, the initial cure temperatures determine the type of bonds present in the cured system, and hence, the properties. Practical limits for total cure are determined by the degree of cross-linking required to provide optimal physical properties from the resin system – for a specific application.

Summarizing, two significant mechanisms are involved during cure:

- conversion
- cross-linking

Conversion is characterized by the disappearance of reactive groups within the resin system. Cross-linking denotes the coupling of the molecules into 3-dimensional networks through reactive sites to form thermoset resins of the desired characteristics.[4]

Brief description of the specification

a) Flexural strength (ISO 178): Flexural strength is the resistance of a material to a bending stress. A sample is subjected to center loads of increasing magnitude until permanent deformation or failure is observed.

b) Deflection temperature (ISO 178): The deflection temperature is a useful indicator of cross-linking density.

c) Tensile strength (ISO 527): Tensile strength is a measure of the force required to break a sample of material – it is calculated by recording the force at failure, and dividing this force by the cross-sectional area of the sample at the point of failure.

d) Impact resistance (ISO 179): Impact resistance is a measure of the ability of a material to withstand sudden loading. The test is conducted by placing the test specimen in cantilever mode, and breaking the specimen by impacting it with a force at a fixed distance from the point of cant.

e) Compressive strength (ISO 604): Compressive strength of a material is a measure of its resistance to a crushing force. The compressive strength is of value when it is indicative of the force at which fracture occurs. In flexible and elastic materials, if deformation continues without fracture – it is of more value to record compressive yield – the point at which elongation of the material occurs without additional load.

f) Glass transition temperature (IEC 1006): The glass transition temperature of thermosetting plastics is indicative of the point at which the properties of the material change from those of a glassy hard material, to a resilient material. The glass transition temperature allows predictions to be made as to the behavior of the material in relation to temperature. In the glass transition zone the following physical changes occur in the material:

- decrease in the mechanical strength of approximately 10–20 percent.[2]
- increase in the dissipation factor, tan delta
- increase in the permittivity (ε_r)
- increase in specific heat capacity
- increase in elongation
- increase in coefficient of thermal expansion
- decrease in modulus of elasticity

Additionally, deviations from the suggested mixing ratios or insufficient annealing (cross-linking density) can be detected by changes in the glass transition temperature.

g) Linear coefficient of thermal expansion (DIN 53462): Thermal expansion characteristics are a function of the resin, curing agent, modifiers and fillers present in the system. Generally, the more flexibilized the system – the greater the degree of thermal expansion. As a result – fillers reduce both shrinkage and coefficients of thermal expansion of CE resin systems. This is of great importance in CE insulation containing metal inserts – matching of the coefficients of thermal expansion is highly desirable in order to reduce stress within the insulator. A stress-free system is not obtainable – increasing the filler loading shifts the stress from the metal–resin interface to the microscopic level, between the filler particles and the bulk resin.[1]

h) Thermal conductivity (DIN 52612): Thermal conductivity is a measure of the ability of a material to conduct heat, and can indicate the efficiency of the degassing plant in removing gas from a filled CE. Fillers increase the thermal conductivity of CE's, but cannot match the thermal conductivity of metals.[1]

i) Specific volume resistance (IEC 93): Volume resistivity is referred to as the resistance between the opposite faces of a unit cube of material.

$\rho_v = R.A/\ell$

where: R = measured resistance between the faces
A = the area of the faces
ℓ = the distance between the faces

j) Surface resistance (IEC 93): Surface resistivity is defined as being the resistance between the opposite edges of a unit square. Practically, two concentric rings of different radii are used for the measurement of surface resistance.

$\rho_s = 2.\pi.R.\ln(r_2/r_1)$

where: r_1 = radius of the inner electrode
r_2 = radius of the outer electrode

k) Dielectric strength (IEC 243): The dielectric strength of a material is the ability of that material to withstand a voltage, and is derived from the voltage required to cause electrical breakdown of a given thickness of the material.

l) Dielectric dissipation factor (IEC 250): The dielectric dissipation factor is the product of the power factor and the dielectric constant for a given material, and is a quantitative measure of power loss.

$\tan\delta = \varepsilon''/\varepsilon' =$ (energy dissipated per cycle)/(energy stored per cycle)

where $\tan\delta$ is called the dielectric loss tangent.

m) Permittivity (IEC 250): Permittivity is also known as the dielectric constant and is the ratio of the capacitance of a given material of known dimensions relative to the capacitance of a vacuum of similar dimensions.

Conclusion

By drawing a comparison between the processes of manufacturing glass, porcelain and CE insulators it can be seen that there are significant advantages to manufacturing the latter:

- repeatable quality raw ingredients are easily available
- smaller and self-contained premises for manufacture
- environmentally friendly (relative to the large scale porcelain and glass works)
- response time to demand is in the order of hours (porcelain could be in the vicinity of weeks if stock is not available)

- repetitive products of stable dimensions and properties (assuming identical manufacturing processes)

However, the APG process is extremely sensitive to any changes to the specification:

- a 5% difference in any of the constituent materials of the CE resin system results in non-standard and non-endorsed properties of that system
- the resin system specification is only valid if process constraints are diligently observed and applied
- due to the nature of the process, various defects can be difficult to detect (voids, hollow castings etc.)
- the inclusion of metal objects in the cured resin mass can be the source of internal stress, due to differences in coefficients of thermal expansion or electric field enhancement / re-profiling - resulting in the possible failure of CE insulation

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CHAPTER 4

EXPERIMENTAL PHILOSOPHY AND ANALYSIS TECHNIQUES

Chapters 2 and 3 served as introduction to the qualities of epoxide resins, the APG process for the manufacturing of CE insulation; and its associated advantages and disadvantages.

A typical CE resin system has stringent process constraints that determine the qualities of the final product. The high voltage outdoor insulation environment is a particularly strenuous environment, especially in respect of polluted conditions – and dictates the use of the best-suited products.

Chapter 4 accepts that the manufacturers of resin systems and CE insulation have tailored their production processes to provide the customer with the best possible product, and embarks on a philosophy of experimentation to discover whether CE insulation is a viable alternative in respect of South African environmental conditions.

Chapter 4 is directed towards discovering the effects of natural aging on CE insulation, by subjecting the test specimens to a battery of tests (electrical and material); and evaluating an industry probe.

4.1 Experimental Philosophy

The philosophy employed in the experimental analysis of CE insulation was chosen to provide for:

- fair test conditions that are specified by the relevant International Electrotechnical Commission (IEC) test standards [1-11]
- representative test configurations – the test insulators were subjected to the electrical tests under mounting and conductor connection conditions similar to those employed in the field.
- repeatable and reliable results

4.2 Analysis Techniques

The donated insulators (Chapter 4.4) were subjected to a variety of tests, broadly categorized into electrical and material analysis techniques. The electrical analysis techniques concentrated on the effect of aging on the electrical performance of the insulators. The material analysis techniques concentrated on the effects of various isolated aging mechanisms on the aging of the material that constitutes a typical CE insulator. Additionally, a questionnaire was sent to industry and responses were obtained as to their experiences with the product.

4.2.1 Electrical Analysis Techniques

a) AC Dry Flashover Test
b) AC Wet Flashover Test
c) Lightning Impulse Withstand Test
d) Clean Fog: Pre-deposited Pollution Test
e) Salt Fog Test
f) Mould Release Resiliency Test
g) IEC 1109 Voltage Test

4.2.2 Material Analysis Techniques

a) Epoxide System Identification
b) Ultraviolet-Light Aging in a QUV Aging Chamber
c) Water Hydrolysis Test
d) Filler Content Evaluation
e) Salt Deposit Density Test (SDD)

4.2.3 Independent Utility Questionnaire

a) Utility A: Sub-Tropical Coastal Region
b) Utility B: Temperate Coastal Region
c) Utility C: Sub-Tropical Plateau Region

4.2.1 Electrical Analysis Techniques

Tests with Alternating Voltage

The test voltage applied to the test insulators was of an alternating sinusoidal nature, frequency 50Hz, supplied from a 150kVA 0-350kV single-phase step-up transformer. This allows for a rated load current of 428mA at rated voltage. The tests were performed in accordance with the relevant specifications. [5]

a) Dry Disruptive Discharge Voltage Tests

The test voltage was applied to the test object and slowly raised until a disruptive discharge occurred. The test was repeated three times and the average of the disruptive discharge voltages was recorded.

b) Wet Disruptive Discharge Voltage Tests

The wet disruptive discharge test was designed to simulate the effect of natural rain on external insulation, and assists in establishing the 'rain-friendliness' of a given insulator profile.

The test object was sprayed with water of prescribed resistivity and temperature. Care was taken to ensure that the water was deposited as droplets and not as spray or mist on the surface of the test object.

Frequent measurements using standardized collecting vessels were taken to ensure that the correct quantity of water drops were impinging upon the test object surface.

Average Precipitation Conditions for Standard Wet Tests		
Average Vertical Precipitation Rate	mm / minute	1.0 to 2.0
Average Horizontal Precipitation Rate	mm / minute	1.0 to 2.0
Tolerance	mm / minute	± 0.5 from average
Water Temperature	Degrees Celsius	Ambient temperature ± 15 ^{0}C
Water Resistivity	Ω meter	100 ± 15

Table 4.1: Average precipitation conditions for IEC standard wet tests [5]

The test object was pre-wetted for 15 minutes under standard conditions, prior to testing. The conditions were monitored and assured to be stable for the duration of the test.

c) Tests with Lightning Impulse Voltages

The standard lightning impulse is a full impulse having a front time of 1.2 µs and a time to half-value of 50 µs and is generated by a 1600 kJ, 1.4 MV Marx generator (Philips).

Figure 4.1: Graphical display of a typical lightning impulse wave shape [5]

The standard lightning impulse is permitted (by the specification) to differ from the nominal values by the following:

- Peak Value (U):   ± 3%
- Front Time (T1):   ± 30%
- Time-to-half Value (T2): ± 20%

Peak value measurements were observed by using 500 mm standard sphere gaps, and a backup measurement was performed using a resistor-divider network coupled to an oscilloscope.

Fifteen impulses of the specified shape and polarity were applied to the test object. The test object passed the test if not more than two failures (out of the 15 applied impulses) were recorded at that peak voltage level in the self-restoring insulation (air surrounding the test object), and no indication of failure was present in the non-self-restoring insulation (epoxide body).

d) The Clean Fog Withstand Test [2]

The clean fog test was designed to provide information as to the performance of outdoor insulation under inland pollution conditions. The test procedure used for all clean fog testing was: 'wetting after energization'.

The clean fog was produced by boiling water in a large-volume electrically heated kettle. The clean fog kettle was placed upon the ground of the chamber, situated at least one meter from the insulator under test. The flow of steam from the kettle was directed away from the test insulator to prevent abnormal wetting of the insulator surface.

The steam input rate into the clean fog chamber was zero until the test object had been energized with the applicable test voltage, and was controlled to a constant rate of steam input thereafter. The steam input rate was monitored to be 50g / m^3 / hour $\pm$ 10g / hour per cubic meter of test chamber volume.

The test voltage was maintained until flashover of the insulator occurred. All insulators were connected to the test voltage via explosive fuses in order to protect the high voltage source from damaging over current conditions, and to provide visible disconnection of the test insulator once the fuse failed (typical fuse characteristic: failure at 600 mA rms).

In cases where flashover did not occur, energization of the test insulator and steam input into the clean fog chamber continued for 100 minutes from the start of the test; or until measured leakage currents across the insulator surface declined to 70% (due to the steam washing the conductive pollution layer from the insulator surface) of their maximum peak value recorded during the test.

The Pre-deposited Pollution Clean Fog Withstand Test [2]

A standard suspension of binding agent, water and salt was prepared. The suspension was applied by submersing the dry test insulator in the suspension. The insulator with the applied pollution layer was left to dry.

The standard suspension is clearly defined by IEC 507 and is as follows:

- 40 gram Kaolin
- 1000 gram water of conductivity < 0.5 mS/cm
- an amount of NaCl (table salt) to provide the required suspension volume conductivity (Table 4.2).

e) The Salt Fog Test [2]

The salt fog test was designed to provide information as to the performance of outdoor insulation under coastal pollution conditions.

The salt fog is produced in a chamber by atomizing a salt/water solution with compressed air. The chamber contains a number of salt-spray nozzles that project a stream of saltwater solution into a jet of compressed air.

The test object was placed within the test chamber, was completely wetted and then energized at rated voltage. Once the insulator was energized, the solution and compressed air was directed towards the nozzles. The test was accepted as begun once flow rates were noted as being according to specification.

The test object was subjected to ever increasing severities of salt fog. Salt fog severities are determined by the mass of salt (NaCl) in kilograms per kiloliter of water, or by the solution conductivity (Table 4.2 and Figure 5.1).

Specific Creepage Distance	Artificial Pollution Tests Severity Withstand Values at the Phase-to-Phase Voltage		
	Salt Fog Method	Solid-layer Methods	
mm/kV	kg/m^3	SDD mg/cm^2	Layer Conductivity μS
16	5 – 14	0.03 – 0.06	15 – 20
20	14 – 40	0.10 – 0.20	24 – 35
25	40 - 112	0.30 – 0.60	36
31	> 160	-	-

Table 4.2: Relation between pollution levels and artificial pollution tests.[3]

Two independent conductivity meters were used to determine the severity of the salt fog. One conductivity meter was permanently placed in the line of flow of the salt solution being directed towards the nozzles, whilst the second conductivity meter was used to periodically check the function of the permanently installed meter.

The test object was judged to pass the test if the peak current measured over the surface of the insulator did not exceed 600 mA within an hour interval.

f) Mould Release Resiliency Test

A reference insulator and a modified insulator were simultaneously evaluated in the salt fog chamber. Other than the removal of the mould release agent, the reference insulator and the modified insulator were entirely identical: geometrically and materially, and were exposed to identical electrical and environmental conditions for the duration of the test.

The purpose of the test was to establish the time taken to degrade the mould release agent under salt fog conditions - until conduction over the reference insulator was noted.

g) IEC 1109 Voltage Withstand Test [1]

Samples were prepared from 5 representative test insulators. The test insulators were delivered to an independent engineering concern to precision-cut the exact IEC 1109 sample dimension from the insulator bulk. Special care was taken to ensure that all cutting took place under water and that no hydrocarbon contamination of the sample could occur. The samples were finished to a fine semi-gloss surface with 'water-paper'.

The samples were placed in individual glass beakers containing distilled water and 0.1% salt (NaCl) by weight – so as to minimize the possibility of cross-contamination between samples of different chemical constitutions.

The samples were boiled for 224 hours, with monitoring at 24-hour intervals.

The samples were subjected to a 12 kV (equivalent to 0.4 kV/mm) alternating voltage (50 Hz), using the IEC 1109 suggested electrode construction, and the current flowing through the samples was recorded.

Additional measurements taken at the time of the voltage test were:

- Change in mass
- Change in Current (IEC 1109 Test requirement)
- Relative Permittivity (εr)

4.2.2 Material Analysis Techniques

a) Epoxy System Identification

Test samples from various manufacturers were submitted for experimental analysis and identification. A manufacturer was known to be using a specific epoxy system, and all other test samples were referenced to this sample using Photoacoustic Spectroscopy (PAS) analysis.

The PAS instrument utilizes the principle of detecting light absorption by using sound, and has been in use for approximately 20 years. The PAS device is designed to be used in conjunction with most Fourier Transform Infrared (FTIR) devices, and is simply placed in the FTIR sample-tray area.

The compartment containing the specimen is sealed using a potassium bromide (KBr) window. The KBr window is used to allow the testing of samples under various gaseous atmospheres, the most common being Helium and air.

An infrared beam is generated and passes through the KBr window and impinges upon the sample, causing the sample to heat up. The heat generated within the samples diffuses towards the surface of the sample and heats the gas contained in the compartment. The action of heating up the gas layer in contact with the sample surface causes a heat wave to be generated within the gas, and it is this heat wave that is detected by the PAS device.

The PAS device is a microphone (developed from hearing aids) and acts as a transducer – translating the heat wave (acoustic) energy into electrical energy.[12] The plot of the electrical energy with regard to the optical path difference of the FTIR device provides the interferogram, which is then Fourier transformed to provide the IR spectrum of the test sample.

The PAS FTIR method of sample evaluation can be performed at different depths within the sample, the following equation allowing for depth calculations [12]:

$$L = \sqrt{[D/(2.\pi.v.w)]}$$

Where:

L = sampling depth in cm
D = sample thermal diffusivity (cm^2/s)
v = moving mirror velocity (cm/sec)
w = Wave number of IR radiation

When increasing the sampling depth, it is important to note that the evaluation concerns the entire volume of material included in that depth (surface to sample depth) and that care should be exercised in the evaluation of the results.[12, 13]

b) Ultraviolet Light Aging

Representative samples of cycloaliphatic epoxy were exposed to UV–B light by using the QUV fluorescent-UV/ condensation tester.

The samples were mounted within the tester and exposed to UV light and condensation for 2000 hours. The test cycle consisted of 11 hours of UV light and 1 hour of condensation repeated continuously during the 2000-hour test.

The UV light was generated by using fluorescent UV–B 313 lamps having a peak spectral output wavelength of 313 nanometers. The condensation was generated by

heating a bath of water situated below the test samples, and allowing the pure condensate to collect, cleanse and run off the samples.

Weekly observations of the test samples were made and the following measurements were taken:

- Surface roughness
- Hydrophobicity

Hydrophobicity

The static contact angle measurement was the method used to characterize the hydrophobicity of the surface of the test samples. A single 5 micro-liter water droplet was placed upon the horizontal surface of the test sample, and was examined using a traveling microscope.

The dimensions of the droplet of distilled water were measured after allowing the droplet to equilibrate for a period of one minute at 20 °C. The positions of the right and left sides of the water droplet, Dr and Dl respectively, were recorded. The level of the sample surface and the height of the water droplet were measured as z_0 and z_i.[14]

The contact angle was computed by applying the following equation to the measured quantities:

$\theta = \pi/2 + \arcsin [(z_0 - z_i) / r]$, where:

- z_0 and z_i are the droplet and insulator surface heights respectively
- r is the radius of the water droplet

Surface Roughness and the Atomic Force Microscope (AFM)

Surface roughness measurements were made using an Atomic Force Microscope (AFM), first applied to the examination of insulation surfaces in 1985.[15] The AFM primary mechanism consists of a micro-cantilever with a tip / stylus. The stylus is scanned over the sample surface by utilizing feedback mechanisms to enable the piezo-electric scanners to maintain the stylus at a constant height or force. Information regarding the height profile of the sample can be obtained by maintaining a constant force on the stylus; or atomic force measurements can be obtained by maintaining a constant height above the sample.

The deflection of the cantilever-stylus arm is detected by projecting a optical beam onto a mirrored surface on the back of the cantilever arm, and interpreting the reflection onto a position-sensitive photo-detector.

The AFM can typically be operated in three different modes:

1. Contact mode – the general mode of operation for AFM studies. The stylus is set to the sample with a repulsive force of 10^{-9} N.[16] The force is provided by applying the cantilever to the sample surface using a piezo-electronic positioning element. The AFM cantilever deflection is monitored and compared in a DC feedback amplifier to a reference magnitude of deflection. The voltage applied by the feedback amplifier to the piezo-electronic crystal is utilized to provide the height axis of the sample and its surface features, and is displayed as a function of the lateral (x and y axis) position of the sample. Limitations of the contact method are typically the occurrence of excessive tracking forces between the probe and the sample.

2. Non-contact mode – the mode used where contact between the stylus and the sample surface could result in damage to the sample. The stylus is controlled to hover above the sample (50-150 Angstrom). The attractive Van der Waals forces between the stylus and the sample are detected. Due to the fact that the attractive Van der Waals forces are significantly weaker than the forces detected in contact mode, the stylus is made to oscillate. The oscillation of the stylus allows for AC detection methods to assign a surface image by measuring changes in amplitude, phase and frequency in response to differing force gradients on the sample surface.

3. Tapping mode – the mode used to overcome friction, adhesion and electrostatic forces and to limit damage to very sensitive sample surfaces. The stylus is made to oscillate at a frequency of 50 000 to 500 000 cycles per second, and contacts the surface of the sample. The action of lightly contacting or 'tapping' the sample surface permits the recording of surface information without causing damage.

c) Hydrolysis – Boiling Water

The test was conducted by placing the test object in boiling water for a period of 4 weeks.

When an ion reacts with water, H^+ and OH^- ions may result – this is known as hydrolysis. Water itself tends to ionize in a slight way to produce H^+ and OH^- ions, but it is the reaction of the water with the base constituents and molecules of the CE system that is of concern.[17]

The water affects the entire CE system – the resin matrix, the resin-filler interface and the filler. The plasticization process affects the van der Waals bonds between ethers, secondary amines and the hydroxyl groups. Polymers containing ketones are more resistant to hydrolysis as they possess relatively fewer polar groups, thus reducing their moisture sensitivity.

The ingress of moisture into the polymer system causes deterioration to the physical properties as the polymer/filler interfaces are destroyed due to the damage done to the polar bonds between the polymer matrix and the filler.

The degradation of the test objects was monitored by measuring changes in the hydrophobicity of the samples.

d) Filler Evaluation

The filler used in CE insulation determines many of the characteristics of the final product. Test samples were taken from representative field and reference insulators to determine the filler loading. Raw filler was obtained from suppliers in order to observe the filler shape, size and purity.

The samples were subjected to the following tests:

- Thermal Gravimetric Analysis – to determine filler loading
- Scanning Electron Microscopy – to determine filler shape and size
- Energy Dispersive X-ray – to determine the purity of the filler

Thermal Gravimetric Analysis (TGA)

Test samples were submitted for TGA analysis to determine the filler content. The filler content is expressed as a percentage of the total mass of the molded epoxy test sample.

TGA analysis measures the amount and rate of change in the weight of a test sample as a function of temperature and time in a controlled atmosphere. The TGA test can provide the following information about the test sample:

- Chemical composition of multicomponent systems
- Thermal stability of materials
- Oxidative stability of materials
- Estimated lifetime of a product
- Decomposition kinetics of materials
- Then effects of corrosive or reactive atmospheres on materials
- Moisture and volatile content of materials

Measurements are used primarily to determine the composition of materials and to predict their thermal stability at temperatures of up to $1000\ ^0C$. TGA can characterize materials that exhibit weight loss or gain due to decomposition, oxidation or dehydration during the application of heat and selected gaseous atmospheres.

Scanning Electron Microscopy (SEM)and Energy Dispersive X-ray (EDX)[18]

Chemical analysis of materials can be performed by directing a focused electron beam towards a material that is to be examined - causing the excitation of electrons within the orbits of the atoms of that material. The excitation of the electrons within the orbitals of the atoms results in the 'migration' of electrons from an orbital of lower energy – to an orbital of higher energy.
When the electron returns to its original position, the energy released in the process is released in the form of an X-ray. The energy of the X-ray is the difference in energy

between the two successive orbital positions of the 'migrating' electron – the reflected X-ray signal is made to exit the electron optical chamber and strike an analyzing crystal.

The X-ray energy is limited to the energy supplied by the electron beam. If the electron beam has a energy of 20keV then this is the upper limit of the X-ray energies. Similarly, there is a lower limit to the detection of X-ray energies – determined by the beryllium window that protects part of the device (X-ray detector) from contamination. The beryllium window effectively blocks the X-rays from the lighter elements (typically elements below sodium in the periodic table).

By using Braggs law: [18]

$$n.\lambda = 2.d.Sin\theta$$

where:

n is an integer n = 1,2,3...
λ the X-ray wavelength
d the interplanar spacing of the crystal
θ the angle of incidence of the X-ray on the crystal

The X-rays are reflected from the specimen to the crystal, and are then diffracted and detected by a proportional counter. The X-ray intensity as a function of crystal angle is used to compute the wavelength of the reflected signal, and by applying the Mosley relationship – a plot of reflected wavelengths relative to elements present in the electron optical chamber can be obtained.

Alternatively – the X-rays are reflected towards a (secondary) detector that transposes the X-ray energies into a format that is applicable for display on a cathode ray screen.

e) Salt Deposit Density Tests

IEC 507[2] describes artificial pollution tests for insulation applied to high voltage systems. The SDD test is a development on the 'solid layer methods' described in Section 4.

The rationale for performing the SDD test being to establish the change in the CE surface and its ability to 'trap' or retain pollution - before, during and after aging has taken place. CE insulation that has been exposed to the elements undergoes aging and the surface becomes rougher. Due to the nature of the ingredients employed to create the solid layer contamination – the size of the particles being small enough (Table 4.3) to be trapped in the changing CE surface topography – it is possible to determine a relative aging index when evaluating the results of the SDD test.

If the CE surface topography is such that the roughness is greater than 1 μm, then 50% of the kaolin suspension is available for the analysis (cumulative distribution: Table 4.3).

Type of Inert Material	Weight Composition %				Granulometry Cumulative Distribution μm			Volume Conductivity
	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	H$_2$O	16%	50%	84%	mS/cm
Kieselguhr	70-90	5-25	0.5-6	7-14	0.1-0.2	0.4-1	2-10	0.015-0,2
Kaolin	40-50	30-40	0.3-2	7-14	0.1-0.2	0.4-1	2-10	0.015-0.2
Tonoko	60-70	10-20	4-8	-	0.8-1.5	3-5	8-15	0.02-0.1

Table 4.3: Characteristics of the materials employed in solid layer pollution suspensions [2]

Additionally, IEC 507 provides information regarding the actual recorded SDD for reference glass cap and pin discs (vertically stacked). – permitting a direct comparison between the SDD of a well-known standard, and CE insulation.

4.2.3 Independent Utility Questionnaire

A questionnaire requesting the experiences of CE insulation was sent to six independent utilities. The questionnaire consisted of the following questions:

1. When were the insulators installed?

2. Who manufactured or supplied the insulators?

3. What type of insulator has been installed:

   - post type
   - pin type
   - suspension type
   - horizontal shed
   - slanted shed etc

4. A <u>rough</u> estimate of the quantity of cycloaliphatic insulators installed?

5. What is the specification of the insulators?

   - voltage level
   - basic insulation level (BIL)
   - power frequency flashover Voltage
   - cantilever strength etc

6. What is the creepage length (in millimeters) of the insulator?

7. What is the type of pollution in the area of application?

   - industrial
   - agricultural
   - marine
   - desert (IEC 815 pollution classification attached)

8. What is the severity classification of the pollution in the area of application?

   - light
   - medium
   - heavy
   - very heavy (IEC 815 pollution classification attached)

9. What is your mean annual rainfall (in millimeters): summer, winter or both seasons?

10. Is the area of application an area of high lightning occurrence?

11. What is the performance of the insulators to date?

   - good
   - bad
   - satisfactory

12. Have there been specific mechanical defects associated with the insulators?

13. Have the insulators experienced any physical changes?

   - color
   - roughness etc

14. Would you recommend the continued use of CE insulators in your area, based on your field experience of the unit?

4.3 Test Methodology for the Field-aged Insulators.

A test methodology had to be established in order to abide by the criteria of:

   - fair test conditions
   - representative test conditions
   - repeatable and reliable results,

since the donated insulators originated from actual utility service conditions, and had all experienced some degree of aging. The aim of the thesis is to describe the surface conditions of the donated insulators with respect to field aging mechanisms – so any laboratory work that could result in the artificial aging of the field-aged surfaces had to be approached methodically, and with care.

The action of applying an artificial pollution layer to a field-aged insulator, and then energizing the insulator could modify the surface conditions because of the high density of leakage current and electrical discharge activity in contact with the insulator surface. The test methodology was designed so that the electrical analysis techniques would not interfere with the results of one another. For this reason, the following test sequence was adopted as the test methodology:

1. AC dry flashover test
2. Lightning impulse withstand test
3. AC wet flashover test
4. Clean fog pre-deposited pollution test
5. Salt fog test

With respect to the test methodology:

- The AC dry flashover and lightning impulse withstand tests are more of an evaluation of the breakdown strength of the air surrounding the insulator. As a result of this characteristic, these tests tend to impact the surface and surface condition of the insulators under test far less than the remaining tests.

- The AC wet flashover test involves the application of water to the surface of the insulator. The action of the water running over the surface of the insulator, in conjunction with the applied voltage, tends to cause the electrical discharge to take place much nearer to the insulator surface (compared to the previous two tests). The heat and energy involved in the discharge could possibly modify the surface condition of the field-aged insulators.

- The clean and salt fog tests both require the use of artificial contaminants to be placed on the surfaces of the insulators. The clean fog test is significantly less stressful to the insulator surface than the salt fog test – due to the fact that the clean fog test is the evaluation of one pollution layer pre-applied to the insulator surface and wetted by steam, where the salt fog test is the evaluation of the insulator surface constantly being wetted by a barrage of conductive air-borne pollution. Both the artificial pollution tests cause the conduction of leakage currents over the surfaces of the insulators and cause significant aging of these surfaces. This necessitates that the artificial pollution tests be performed after all the other tests have been completed – with the salt fog being the last artificial pollution test method because of its aging severity with respect to the clean fog test.

4.4 The Selection of Test Specimens

Test specimens were collected from four donors. Care was taken to obtain test insulators from different climatic regions from within the RSA, in order to provide a sound basis for a holistic interpretation of the effects of both climate and pollution type on the performance of CE insulation. Details of the regions are given in Table 4.4 and Figure 4.2 :

Donor	Geographical Region	Pollution Classification (IEC 815 Table 1)	Aging Factor of Interest
Donor A	North-west South Africa	Marine – High Severity	Marine and UV
Donor B	Central South Africa	Agricultural – Light to Medium Severity	UV
Donor C	East South Africa	Agricultural – Medium to Heavy Severity	UV
Donor D	North-east South Africa	Agricultural/Industrial – Light to Medium Severity	UV

Table 4.4: Summary of test specimen zone of origin and pollution type
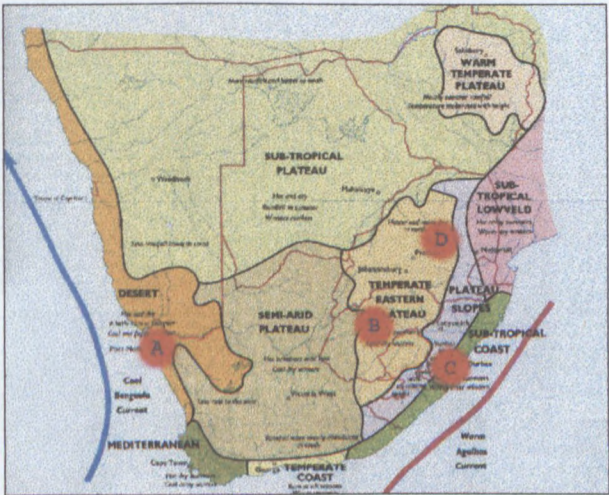
Figure 4.2: Climatic regions in Southern Africa, including donor locations [19]

Details of the insulators received from the respective donors are as follows:

a) Received from Donor A

Number of Insulators:	8
Date of Installation:	1996
Date of Donation:	2000
Report Identification Numbers:	Donor A1 – A8
Pollution Classification:	Desert - Marine
Insulator Profile:	LPIS 22 – Line Post Insulator Slanted Shed Configuration
Nominal Creepage Length:	27 mm/kV

b) Received from Donor B

Number of Insulators:	5
Date of Installation:	1987
Date of Donation:	1999
Report Identification Numbers:	Donor B1 – B5
Pollution Classification:	Temperate Eastern Plateau – Agricultural
Insulator Profile:	LPI 22 – Line Post Insulator Horizontal Shed Configuration
Nominal Creepage Length:	19 mm/kV

Number of Insulators:	8
Date of Installation:	1985
Date of Donation:	1999
Report Identification Numbers:	Donor B6 – B13
Pollution Classification:	Temperate Eastern Plateau – Agricultural
Insulator Profile:	LPI 22 – Line Post Insulator Horizontal Shed Configuration
Nominal Creepage Length:	19 mm/kV

Number of Insulators:	4
Date of Installation:	1987
Date of Donation:	1999
Report Identification Numbers:	Donor B14 – B17
Pollution Classification:	Temperate Eastern Plateau – Agricultural
Insulator Profile:	LPI 22 – Line Post Insulator Horizontal Shed Configuration
Nominal Creepage Length:	21 mm/kV

c) Received from Donor C

Number of Insulators:	6
Date of Installation:	1994
Date of Donation:	1999
Report Identification Numbers:	Donor C1 – C6
Pollution Classification:	Sub Tropical - Agricultural
Insulator Profile:	LPI 22 – Line Post Insulator Horizontal Shed Configuration
Nominal Creepage Length:	21 mm/kV

d) Received from Donor D

Number of Insulators:	4
Date of Installation:	1990
Date of Donation:	1999
Report Identification Numbers:	Donor D1 – D4
Pollution Classification:	Temperate Eastern Plateau - Agricultural/Industrial
Insulator Profile:	LPI 22 – Line Post Insulator Horizontal Shed Configuration
Nominal Creepage Length:	21 mm/kV

Number of Insulators:	4
Date of Installation:	1990
Date of Donation:	1999
Report Identification Numbers:	Donor D5 – D8
Pollution Classification:	Temperate Eastern Plateau - Agricultural/Industrial
Insulator Profile:	LPIS 22 – Line Post Insulator Slanted Shed Configuration
Nominal Creepage Length:	27 mm/kV

Number of Insulators:	4
Date of Installation:	1994
Date of Donation:	1999
Report Identification Numbers:	Donor D9 – D12
Pollution Classification:	Temperate Eastern Plateau - Agricultural/Industrial
Insulator Profile:	LPIS 22 – Line Post Insulator Slanted Shed Configuration
Nominal Creepage Length:	27 mm/kV

e) Reference Insulators

Identical insulators were requested from the manufacturers in order to compare the naturally aged specimens, Donor's A – D, with new insulators direct from the APG mould. These insulators were labeled "reference" insulators.

Conclusion

- An experimental philosophy was established for the electrical and material analysis techniques based on relevant IEC standards, representative test configurations (electrical) and repeatability.

- A detailed and transparent (clearly defined and accepted) set of analysis techniques was chosen to provide a comprehensive account of the abilities of the product, and the insulators were tested according to a test methodology.

- Test CE insulators were received from five donors widely distributed across the RSA, subject to different climates and pollution types.

- An impartial questionnaire was presented to independent utilities, to afford them the chance for input based on their experience with the product.

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CHAPTER 5

RESULTS OF EXPERIMENTAL AND ANALYSIS TECHNIQUES

In Chapter 4, analysis techniques applicable to determining a quantitative evaluation of the effects of aging on the performance of CE insulation were discussed.

The donated sample insulators were subjected to the experimental procedures discussed in Chapter 4, and the results of these tests are presented in Chapter 5. The test procedures were conducted at the University of Stellenbosch, High Voltage and Artificial Pollution Laboratories – while the material tests were conducted by the Department of Polymer Sciences.

5.1 Reference Insulators

In order to quantify the effects of field aging on CE insulators, a reference needed to be determined that is representative of new (reference) CE insulators. Field-aged CE insulators were selected from various geographical locations throughout the RSA (Chapter 4.4) and were representative of various CE insulator designs, profiles and dimensions (Appendix B).

New CE insulators, identical to the field-aged insulators, were provided by the manufacturers of the field-aged insulators. The new CE insulators were renamed 'reference' insulators and were subjected to the exact same electrical analysis techniques as the field-aged insulators.

The basis for determining the effects of field aging on CE insulators lies in the direct comparison of performance data between the field-aged and reference insulators, and this data is presented in Chapter 5.

The Convention for Identifying the Reference Insulators

The following convention is used to identify the reference insulators throughout this chapter:

1. The reference insulator serial is in the format:

   R(number a)(letter b)-(number c)

   - R denotes reference insulator
   - (Number a) denotes the specific creepage distance of the insulator
   - (letter b) denotes the type of insulator configuration where 'H' and 'S' indicate 'Horizontal shed' and 'Slanted shed' configuration, respectively
   - (Number c) denotes the specific identity of an insulator

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2. The specific creepage distance given by the following relationship:

- Specific creepage distance (mm/kV) = nominal creepage distance / U_{max}
- In this equation, U_{max} (the specified maximum system phase-to-phase voltage) = 24 kV for 22 kV networks in the RSA
- The nominal creepage distance is the actual length over the external insulator surface, from the conductor mount to the dead-end metal-ware. In the case of insulators without metal-ware dead-end spindles, the distance was calculated from the conductor mount to the point on the dead-end that connects physically to support structures.

The Reference Insulator Dry and Wet Power Frequency Flashover and Lightning Impulse Withstand Results

The results of the dry and wet AC flashover and lightning impulse withstand voltage tests conducted on the reference insulators are presented in Table 5.1. Some tests were previously performed on similar insulators by the South African Bureau of Standards (SABS), and these results are identified by the 'SABS' suffix.

Serial	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand kV
R19H-1	90.5	75.4	133.1
R19H-2	86.2	74.8	129.0
R19H-3	86.5	77.1	131.7
R19H-average	87.7	75.8	131.3
R27S-1	99.6	79.2	160.0
R27S-2	94.8	78.2	161.9
R27S-3	100.7	78.1	154.1
R27S-average	98.4	78.5	158.7
R19H-SABS	89.0	76.0	136.0
R21H-SABS	97.0	80.0	157.0
R27S-SABS	90.0	70.0	166.0

Table 5.1: Results for dry and wet AC flashover and lightning impulse withstand tests on the reference insulators.

The following conclusions can be summarized from these results:

- The R19H-average wet AC flashover voltage is 86.4% of the respective dry AC flashover voltage.
- The R27S-average wet AC flashover voltage is 79.8% of the respective dry AC flashover voltage.
- Insulator R21H could not be evaluated as it is no longer manufactured, hence the reference to SABS results of similar tests: R21H-SABS wet AC flashover voltage is 82.5% of the respective dry AC flashover voltage. [1]
- The R27S-SABS dry and wet AC voltages appear to be incorrect, possibly because of the omission of the correction factor for altitude and temperature (SABS tests are performed in the Gauteng region at a height of 1694 meters).

However:

1. a comparison can still be drawn between the results – if similar conditions are applied to the time of both tests, the atmospheric correction factors cancel in the comparison between the wet and dry AC withstand voltages. The wet AC flashover voltage is 77.8% of the respective dry AC flashover voltage.
2. if altitude correction factors are applied to both the dry and wet AC flashover voltages, the results are 99.9 kV and 77.7 kV respectively – a favorable comparison to R27S-average.

- The lightning impulse voltages are roughly proportional to the relative dry arc distances of the insulators:

1. R19H-average = 131.3 kV (dry arc distance of R19H = 190 mm)
2. R21H-SABS = 157 kV (dry arc distance of R21H-SABS = 228 mm)
3. R27S-average = 158.7 kV (dry arc distance of R27S = 263 mm)

The Reference Insulator Pollution Classification and Artificial Pollution Tests

The insulator pollution classifications, in accordance with IEC 815, are:

1. R19H: light pollution classification
2. R21H: medium pollution classification
3. R27S: heavy pollution classification

Figure 5.1 presents the relationship between the volume characteristics and the sodium chloride content (salinity) of a saline solution as used in the salt fog artificial pollution test. Figure 5.1 also indicates the pollution salinity boundaries of the specified pollution classes (IEC 815) and the specified creepage distances applicable to those classes.
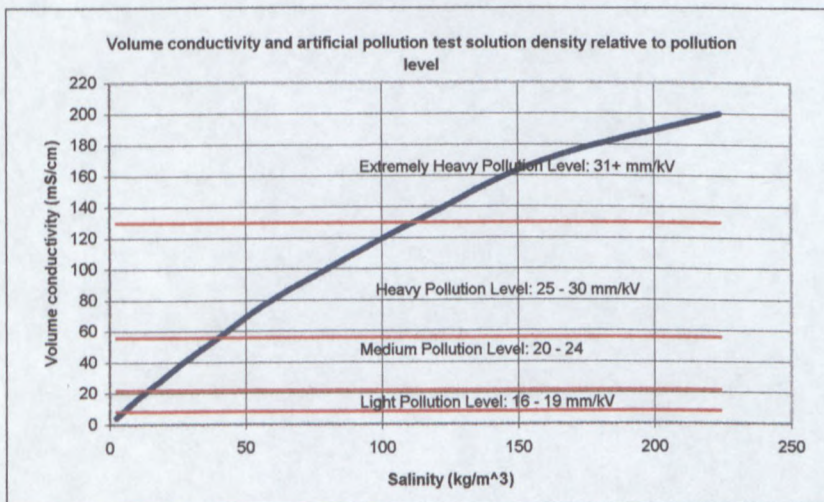
Figure 5.1: Volume conductivity and artificial pollution test solution density relative to pollution level

The results of clean and salt fog tests performed on reference insulators are presented in Table 5.2.

Reference Insulators: Clean and Salt Fog Performance Data

Serial	Clean Fog Peak Current mA	Salt Fog Peak Current mA
R19H-1	0	0
R19H-2	0	0
R19H-3	0	0
R21H-1	0	0
R27S-1	0	0
R27S-2	0	0
R27S-3	0	0

Table 5.2: Results for the clean and salt fog tests performed on the reference insulators.

From this table the following should be noted:

- With respect to the clean fog test, the mould release agent forms a highly hydrophobic layer on the insulator surface and prevents the clean fog kaolin/salt pre-contamination layer from adhering to it and forming a continuous pollution layer that readily permits conduction.
- With respect to salt fog test, the mould release layer similarly prevents the salt fog from adhering to the surface of the insulator hence no conduction of current (see Figure 5.2).
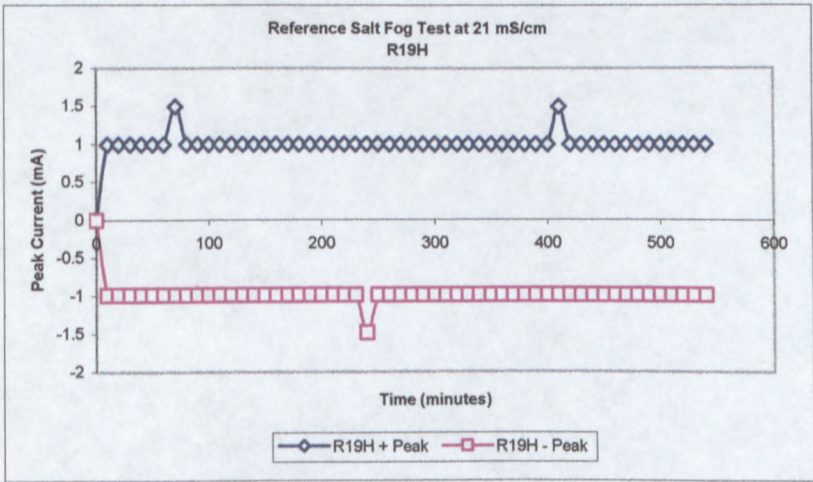
Figure 5.2: An example of leakage current over a reference insulator during a salt fog test

Figure 5.2 indicates the result of a salt fog test on a R19H insulator – as an example as to the effect of the hydrophobic mould release layer. The test and results are summarized as follows:

1. Insulator: R19H
2. Salt fog solution conductivity: 21 mS/cm (medium)
3. Duration of test: 540 minutes (9 hours)

The following observations can be made:

- The three 1.5 mA peak currents are spurious results and of no consequence or value for the test period.
- The standard salt fog test is 1 hour, whereas this test continued for 9 hours without conduction over the test insulator.
- The mould release layer prevents the flow of leakage current, even during 9 hours of continuous salt fog.

The effect of the mould release layer is comprehensively examined in Chapter 5.4.

Salt Fog Tests to Compare CE, Porcelain and Glass Cap and Pin Insulation

The data in Table 5.2 and Figure 5.2 provide an indication as to the resiliency of the mould release layer in preventing leakage current conduction on reference insulators. The test method adopted for the salt fog evaluation of CE insulators is the IEC 507 method. IEC 507 does not make provision for insulators retaining mould release layers on their surfaces, so the test to compare porcelain to CE insulation was devised. The test parameters were:

- A porcelain and CE insulator of identical dimensions and profile were selected for the test.
- The CE insulator was cleaned with methanol in order to remove the mould release layer.
- The CE and porcelain insulator were exposed to salt fog tests of increasing salinities, simultaneously.

Figure 5.3 illustrates the peak leakage current flowing over the surface of CE and porcelain insulators of identical dimensions, with glass cap and pin insulators included as reference to a widespread and known insulation type (U120B).

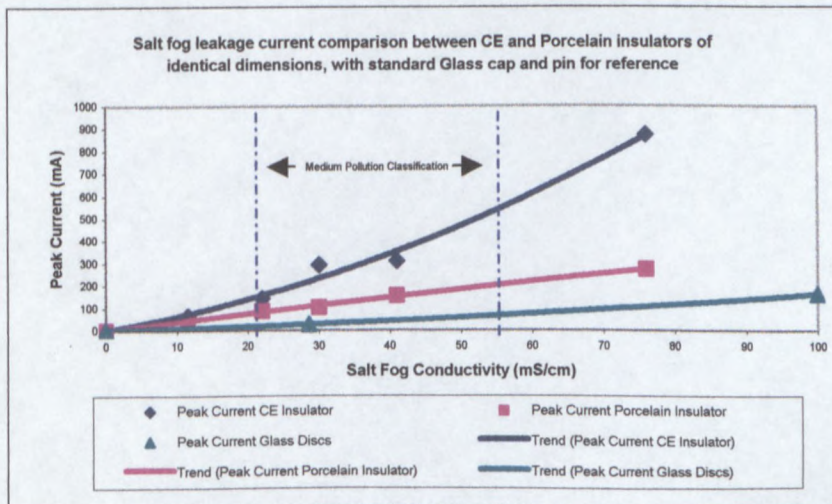**Figure 5.3: A comparison between CE and porcelain insulators of identical dimensions under salt fog conditions, including glass-cap-and-pin insulators as reference.**

Second order polynomials were fitted to the data of figure 5.3. A degree of correlation in the range of 97 to 99% was obtained for the trend lines. The trend lines are denoted by 'Poly' in the figures throughout this section of the thesis.

- CE insulator trend line equation: Peak current = $0.0799x^2 + 5.3512x$
- Porcelain insulator trend line: Peak current = $-0.0023x^2 + 3.7736x$
- Glass cap and pin insulator's trend line: Peak current = $0.0186x^2 - 0.1415x$
- The CE and Porcelain insulators are of identical dimensions and profile, but demonstrate a large difference in peak leakage current performance under salt fog conditions:

    1. At 22 mS/cm, The CE insulator is conducting 143.6 mA, as against 87.6 mA for the Porcelain insulator. The two trends are divergent and the CE insulator continues to perform worse for all salt fog solution conductivities.
    2. The glass cap and pin insulators perform well because of the concentration of current in the pin-zone providing heat and adequate dry bands of high impedance, thus limiting the current flow over the insulator surface. The profile in the under-shed region – the inclusion of ribs – assists in the formation of dry bands during the salt fog test.

A detailed interpretation of the relative performance between the CE and porcelain insulators of identical dimensions is discussed in Chapter 6.4, where a hypothesis is developed to explain the differences in the recorded performances under salt fog conditions.

5.2 Naturally Aged Insulators

With reference to Chapter 4 (Experimental Philosophy and Analysis Techniques), insulators were obtained from donors and were subjected to the electrical tests specified and discussed.

The results are presented in table-form in subsections specific to the area of initial deployment of the insulators, and are discussed individually.

5.2.1 Donor A: Northwest RSA

27 mm/kV Slanted Shed Insulators

- The average AC dry flashover voltage (Table 5.3) of the naturally aged (A27S-1 to 8) insulators is acceptable and compares well with the R27S-average of 98.4 kV, the difference being -1.32%.
- The average AC wet flashover voltage of the naturally aged insulators represents a 15.7% reduction of withstand ability when compared to the R27S-average of 78.5 kV.
- The average lightning impulse (LI) withstand capability of the naturally aged insulators compares favorably with the R27S-average of 158.7 kV. The result represents a reduction of 1.64% [*].

Serial Number	Age Years	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand Test kV
A27S-1	5	93.0	66.9	150.2
A27S-2	5	96.6	66.9	161.9
A27S-3	5	100.8	68.5	161.9
A27S-4	5	95.5	70.4	156.1
A27S-5	5	97.3	65.2	152.2
A27S-6	5	98.8	61.9	152.0
A27S-7	5	96.2	68.4	154.1
A27S-8	5	98.6	61.7	160.0
average	5	97.1	66.2	156.1

Table 5.3: AC dry and wet power frequency and lightning impulse performance data for 27 mm/kV slanted shed insulators

* losses or gains of less than 3% are of little importance with respect to measured lightning impulse voltages, as this tolerance is within the best resolution of the applicable measuring devices (SABS 1063).

Clean Fog Performance Data

- A clean fog pre-deposit contamination solution of 97 mS/cm represents a mid-heavy pollution classification. The leakage current (Table 5.4) over this contamination layer falls in the range: $92.8 \leq I_{leakage} \leq 316.5$ mA.
- Similarly, a clean-fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current range is: $225.1 \leq I_{leakage} \leq 450.4$ mA.
- The insulators withstand the 139 mS/cm clean fog test.

Serial Number	Age Years	Clean fog 97 mS/cm Artificial Peak current mA	Clean fog 139 mS/cm Artificial Peak current mA
A27S-1	5	128.7	271.7
A27S-2	5	256.4	450.4
A27S-3	5	193.8	258.9
A27S-4	5	202	225.1
A27S-5	5	221.3	313.5
A27S-6	5	92.8	284.9
A27S-7	5	316.5	327.5
A27S-8	5	267.2	326.1

Table 5.4: Clean fog performance data for 27 mm/kV slanted shed insulators

Salt fog performance data

- A salt fog contamination solution of 52 mS/cm represents a low-heavy pollution classification. The leakage current (Table 5.5) over this contamination layer falls in the range: $286.7 \leq I_{leakage} \leq 693.2$ mA.

- The insulators, A27S-1 to 8, fail at 52 mS/cm.

Serial	Age Years	Salt fog 52 mS/cm Solution conductivity Peak current mA
A27S-1	5	602.8 *
A27S-2	5	504.4
A27S-3	5	630.4
A27S-4	5	693.2
A27S-5	5	655.8
A27S-6	5	286.7
A27S-7	5	649
A27S-8	5	642.6

* Currents in red indicate failure of test insulator

Table 5.5: Salt fog performance data for 27 mm/kV slanted shed insulators

5.2.2 Donor B: Central RSA

19 mm/kV Horizontal Shed Insulator

a) Insulators B19H-1 to B19H-5:

- The average AC dry flashover voltage (Table 5.6) of the insulators is acceptable and compares well with the R19H-average of 87.7 kV.
- The average AC wet flashover voltage represents a 21.1% loss of withstand ability when compared to the R19H-average of 75.8 kV.
- The average lightning impulse (LI) withstand capability compares favorably with the R19H-average of 131.3 kV. The result represents a loss of 0.7%.

b) Insulators B19H-6 to B19H-13:

- The average AC dry flashover voltage (Table 5.6) of the insulators is acceptable and compares well with the R19H-average of 87.7 kV.
- The average AC wet flashover voltage represents a 10.7% reduction in withstand ability when compared to the R19H-average of 75.8 kV.
- The average lightning impulse (LI) withstand capability compares favorably with the R19H-average of 131.3 kV. The result represents a reduction of 1.5%.

Serial	Age Years	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand Test kV
B19H-1	13	90.9	58.7	132.1
B19H-2	13	83.1	60.6	127.9
B19H-3	13	93.2	58.7	132.1
B19H-4	13	91.1	64.4	127.9
B19H-5	13	98.5	56.7	132.1
Average	13	91.4	59.8	130.4
B19H-6	15	82.7	69.4	129.0
B19H-7	15	86.7	70.2	133.1
B19H-8	15	92.1	64.8	131.7
B19H-9	15	80.6	60.7	129.0
B19H-10	15	89.5	71.1	123.5
B19H-11	15	89.9	68.2	133.1
B19H-12	15	86.9	69.1	129.0
B19H-13	15	95.4	68.1	126.3
average	15	88.0	67.7	129.3

Table 5.6: AC dry and wet power frequency and lightning impulse performance data for 19 mm/kV horizontal shed insulators

Clean Fog Performance Data

a) Insulators B19H-1 to B19H-5:

- A clean fog pre-deposit contamination solution of 42 mS/cm represents a mid-medium pollution classification. The leakage current (Table 5.7) over this contamination layer falls in the range: $95.2 \leq I_{leakage} \leq 138.6$ mA.
- Similarly, a clean-fog pre-deposit contamination solution of 60 mS/cm represents a low-heavy pollution classification. The leakage current range is: $225.3 \leq I_{leakage} \leq 299.8$ mA.
- A clean fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current over this contamination layer falls in the range: $385.6 \leq I_{leakage} \leq 907.8$ mA.
- The insulators fail the clean fog test at 139 mS/cm.

b) Insulators B19H-6 to B19H-13:

- A clean fog pre-deposit contamination solution of 42 mS/cm represents a mid-medium pollution classification. The leakage current (Table 5.7) over this contamination layer falls in the range: $135.7 \leq I_{leakage} \leq 343.5$ mA.
- Similarly, a clean-fog pre-deposit contamination solution of 60 mS/cm represents a low-heavy pollution classification. The leakage current range is: $202.8 \leq I_{leakage} \leq 392.3$ mA.
- A clean fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current over this contamination layer falls in the range: $659.8 \leq I_{leakage} \leq 834.2$ mA.

- The insulators fail the clean fog test at 139 mS/cm.

Serial	Age Years	42 mS/cm Artificial Peak current mA	60 mS/cm Artificial Peak current mA	139 mS/cm Artificial Peak current mA
B19H-1	13	113.9	266.5	434.3
B19H-2	13	135.9	225.3	738.9
B19H-3	13	98.2	273	385.6
B19H-4	13	138.6	299.8	757.1
B19H-5	13	95.2	289.3	907.8
B19H-6	15	170.8	308	705.8
B19H-7	15	150.5	202.8	822.9
B19H-8	15	235.9	289	786.6
B19H-9	15	193.5	275	834.2
B19H-10	15	135.7	244	757.5
B19H-11	15	343.4	247.5	806.5
B19H-12	15	213.4	268.2	659.8
B19H-13	15	247.3	392.3	727

Table 5.7: Clean fog performance data for 19 mm/kV horizontal shed insulators

Salt fog performance data

a) Insulators B19H-1 to B19H-5:

- A salt fog contamination solution of 8 mS/cm represents a low pollution classification. The leakage current (Table 5.8) over this contamination layer falls in the range: $251.1 \leq I_{leakage} \leq 316.1$ mA.
- A salt fog contamination solution of 20 mS/cm represents a upper-low pollution classification. The leakage current over this contamination layer falls in the range: $347.6 \leq I_{leakage} \leq 594.4$ mA.
- A salt fog contamination solution of 28 mS/cm represents a lower-medium pollution classification. The leakage current over this contamination layer falls in the range: $656.3 \leq I_{leakage} \leq 841.3$ mA
- The insulators, B19H-1 to B19H-5, fail at 28 mS/cm

Serial	Age Years	8 mS/cm Peak current mA	20 mS/cm Peak current mA	28 mS/cm Peak current mA
B19H-1	13	265.7	558.5	656.3
B19H-2	13	282.7	594.4	679.3
B19H-3	13	251.1	521.7	769.7
B19H-4	13	254.5	426.2	841.3
B19H-5	13	316.1	347.6	836.9

Table 5.8: Salt fog performance data for 19 mm/kV horizontal shed insulators

b) Insulators B19H-6 to B19H-13:

- A salt fog contamination solution of 20 mS/cm represents an upper-low pollution classification. The leakage current (Table 5.9) over this contamination layer falls in the range: $361.2 \leq I_{leakage} \leq 543.5$ mA
- A salt fog contamination solution of 28 mS/cm represents a low-medium pollution classification. The leakage current over this contamination layer falls in the range: $380.6 \leq I_{leakage} \leq 941.3$ mA
- A salt fog contamination solution of 35 mS/cm represents a middle-medium pollution classification. The leakage current over this contamination layer falls in the range: $629.6 \leq I_{leakage} \leq 807.0$ mA
- The insulators begin to fail at 28 mS/cm, and complete failure of the batch occurs at 35 mS/cm.

Serial	Age Years	20 mS/cm Peak current mA	28 mS/cm Peak current mA	35 mS/cm Peak current mA
B19H-6	15	409.7	628.1	←
B19H-7	15	451.9	562.2	740
B19H-8	15	399.5	669.6	←
B19H-9	15	413.1	380.6	629.6
B19H-10	15	362.2	407.1	807
B19H-11	15	520.2	941.3	←
B19H-12	15	361.2	533.7	730
B19H-13	15	543.5	552.9	731.6

Table 5.9: Salt fog performance data for 19 mm/kV horizontal shed insulators

21 mm/kV Horizontal Shed Insulator

Insulators B21H-1 to B21H-4:

- The average AC dry flashover voltage (Table 5.10) of the insulators is acceptable and compares well with the R21-SABS of 97 kV.
- The average AC wet flashover voltage represents a 15.7% reduction in withstand ability when compared to the R21-SABS of 80 kV.
- The average lightning impulse (LI) withstand capability compares favorably with the R21-SABS of 157 kV.

Serial	Age Years	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand Test kV
B21H-1	13	98.5	73.7	165.0
B21H-2	13	97.3	61.3	161.2
B21H-3	13	101.2	71.3	163.6
B21H-4	13	99.2	63.1	158.7
average	13	99.1	67.4	164.3

Table 5.10: AC dry and wet power frequency and lightning impulse performance data for 21 mm/kV horizontal shed insulators

Clean fog performance data

Insulators B21H-1 to B21H-4:

- A clean fog pre-deposit contamination solution of 139 mS/cm (Table 5.11) represents a high-heavy pollution classification. The leakage current over this contamination layer falls in the range: $454.4 \leq I_{leakage} \leq 595.5$ mA.
- The insulators withstand the clean fog test at 139 mS/cm.

Serial	Age Years	139 mS/cm Artificial Peak current mA
B21H-1	13	595.0
B21H-2	13	563.5
B21H-3	13	454.4
B21H-4	13	524.6

Table 5.11: Clean fog performance data for 21 mm/kV horizontal shed insulators

Salt fog performance data

Insulators B21H-1 to B21H-4:

- A salt fog contamination solution of 17 mS/cm represents a mid-low pollution classification. The leakage current (Table 5.12) over this contamination layer falls in the range: $316.5 \leq I_{leakage} \leq 502.6$ mA
- A salt fog contamination solution of 22 mS/cm represents an upper-low pollution classification. The leakage current over this contamination layer falls in the range: $425.4 \leq I_{leakage} \leq 1012$ mA
- A salt fog contamination solution of 28 mS/cm represents a low-medium pollution classification. The leakage current over this contamination layer falls in the range: $586.6 \leq I_{leakage} \leq 611.1$ mA
- The insulators begin to fail at 22 mS/cm, and complete failure of the batch occurs at 28 mS/cm.

Serial	Age Years	17 mS/cm Peak current mA	22 mS/cm Peak current mA	28 mS/cm Peak current mA
B21H-1	13	316.5	425.4	611.1
B21H-2	13	448	512.4	586.6
B21H-3	13	502.6	689.3	←
B21H-4	13	486	1012.0	←

Table 5.12: Salt fog performance data for 21 mm/kV horizontal shed insulators

5.2.3 Donor C: East RSA

21 mm/kV Horizontal Shed Insulators

Insulators C21H-1 to C21H-6:

- The average AC dry flashover voltage (Table 5.13) of the insulators is acceptable and compares well with the R21-SABS of 97 kV.
- The average AC wet flashover voltage represents a 11.8% reduction in withstand ability when compared to the R21-SABS of 80 kV.
- The average lightning impulse (LI) withstand capability compares favorably with the R21-SABS of 157 kV.

Serial	Age Years	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand Test kV
C21H-1	6	98.9	77.3	163.6
C21H-2	6	94.6	71.1	165.0
C21H-3	6	92.4	69.4	159.4
C21H-4	6	106.6	59.2	149.6
C21H-5	6	96.3	73.3	158.0
C21H-6	6	95.5	73.5	163.6
average	6	97.4	70.6	159.9

Table 5.13: AC dry and wet power frequency and lightning impulse performance data for 21 mm/kV horizontal shed insulators

Clean fog performance data

Insulators C21H-1 to C21H-4:

- A clean fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current (Table 5.14) over this contamination layer falls in the range: $231.4 \leq I_{leakage} \leq 375.0$ mA.
- The insulators withstand the clean fog test at 139 mS/cm.

Serial	Age Years	139 mS/cm Artificial Peak current mA
C21H-1	6	375.0
C21H-2	6	231.4
C21H-3	6	290.0
C21H-4	6	366.5

Table 5.14: Clean fog performance data for 21 mm/kV horizontal shed insulators

Salt fog performance data

Insulators C21H-1 to C21H-4:

- A salt fog contamination solution of 14 mS/cm represents a mid-low pollution classification. The leakage current (Table 5.15) over this contamination layer falls in the range: $340.5 \leq I_{leakage} \leq 583.6$ mA
- A salt fog contamination solution of 22 mS/cm represents an upper-low pollution classification. The leakage current over this contamination layer falls in the range: $412.7 \leq I_{leakage} \leq 715.3$ mA
- A salt fog contamination solution of 28 mS/cm represents a low-medium pollution classification. The leakage current over this contamination layer falls in the range: $637.7 \leq I_{leakage} \leq 639.1$ mA
- The insulators begin to fail at 22 mS/cm, and complete failure of the batch occurs at 28 mS/cm

Serial	Age Years	14 mS/cm Peak current mA	22 mS/cm Peak current mA	28 mS/cm Peak current mA
C21H-1	6	340.5	715.3	←
C21H-2	6	352.3	412.7	639.1
C21H-3	6	382.6	459.3	637.7
C21H-4	6	583.6	634.7	←

Table 5.15: Salt fog performance data for 21 mm/kV horizontal shed insulators

5.2.4 Donor D: Northeast RSA

21 mm/kV Horizontal Shed Insulators

Insulators D21H-1 to D21H-4:

- The average AC dry flashover voltage (Table 5.16) of the insulators is acceptable and compares well with the R21-SABS of 97 kV.
- The average AC wet flashover voltage represents a 11.6% reduction in withstand ability when compared to the R21-SABS of 80 kV.

- The average lightning impulse (LI) withstand capability compares favorably with the R21-SABS of 157 kV.

Serial	Age Years	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand Test kV
D21H-1	10	98.4	72.4	150.7
D21H-2	10	99.9	70.9	171.1
D21H-3	10	100.6	69.6	155.9
D21H-4	10	98.9	69.8	167.6
average	10	99.5	70.7	161.3

Table 5.16: AC dry and wet power frequency and lightning impulse performance data for 21 mm/kV horizontal shed insulators

Clean fog performance data

Insulators D21H-1 to D21H-4:

- A clean fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current (Table 5.17) over this contamination layer falls in the range: $560.3 \leq I_{leakage} \leq 703.4$ mA.
- The insulators fail the clean fog test at 139 mS/cm.

Serial	Age Years	139 mS/cm Artificial Peak current mA
D21H-1	10	630
D21H-2	10	703.4
D21H-3	10	560.3
D21H-4	10	641.4

Table 5.17: Clean fog performance data for 21 mm/kV horizontal shed insulators

Salt fog performance data

Insulators D21H-1 to D21H-4:

- A salt fog contamination solution of 14 mS/cm represents a mid-low pollution classification. The leakage current (Table 5.18) over this contamination layer falls in the range: $244.0 \leq I_{leakage} \leq 541.9$ mA
- A salt fog contamination solution of 22 mS/cm represents an upper-low pollution classification. The leakage current over this contamination layer falls in the range: $561.5 \leq I_{leakage} \leq 794.9$ mA
- A salt fog contamination solution of 28 mS/cm represents a low-medium pollution classification. The leakage current over this contamination layer falls in the range: $I_{leakage} = 601.3$ mA
- The insulators fail the salt fog test at 22 mS/cm.

Serial	Age Years	14 mS/cm Peak current mA	22 mS/cm Peak current mA	28 mS/cm Peak current mA
D21H-1	10	244	621	←
D21H-2	10	360.3	794.9	←
D21H-3	10	533	561.5	601.3
D21H-4	10	541.9	626.4	←

Table 5.18: Salt fog performance data for 21 mm/kV horizontal shed insulators

27 mm/kV Slanted Shed Insulators

a) Insulators D27S-1 to D27S-4:

- The average AC dry flashover voltage (Table 5.19) of the insulators is acceptable and compares well with the R27S-average of 98.4 kV.
- The average AC wet flashover voltage represents a 11.8% loss of withstand ability when compared to the R27S-average of 78.5 kV.
- The average lightning impulse (LI) withstand capability compares favorably with the R27S-average of 158.7 kV.

b) Insulators D27S-5 to D27S-8

- The average AC dry flashover voltage (Table 5.19) of the insulators is acceptable and compares well with the R27S-average of 98.4 kV.
- The average AC wet flashover voltage represents a 9.3% loss of withstand ability when compared to the R27S-average of 78.5 kV.
- The average lightning impulse (LI) withstand capability compares favorably with the R27S-average of 158.7 kV.

Serial	Age Years	Power Frequency AC Dry Flashover kV	Power Frequency AC Wet Flashover kV	Lightning Impulse Withstand Test kV
D27S-1	10	102.1	66.6	165.8
D27S-2	10	101.1	70.4	157.4
D27S-3	10	102.5	75.0	169.4
D27S-4	10	98.3	64.8	160.2
average	10	101.0	69.2	163.2
D27S-5	6	99.4	72.3	160.2
D27S-6	6	101.3	68.4	167.3
D27S-7	6	100.5	72.4	157.4
D27S-8	6	100.8	70.3	157.4
average	6	100.5	70.9	160.6

Table 5.19: AC dry and wet power frequency and lightning impulse performance data for 27 mm/kV slanted shed insulators

Clean fog performance data

a) Donor D27S-1 to D27S-4:

- A clean fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current (Table 5.20) over this contamination layer falls in the range: $170.5 \leq I_{leakage} \leq 214.4$ mA.
- The insulators withstand the clean fog test at 139 mS/cm.

b) Donor D27S-5 to D27S-8:

- A clean fog pre-deposit contamination solution of 139 mS/cm represents a high-heavy pollution classification. The leakage current (Table 5.20) over this contamination layer falls in the range: $43.2 \leq I_{leakage} \leq 168.9$ mA.
- The insulators withstand the clean fog test at 139 mS/cm.

Serial	Age Years	139 mS/cm Artificial Peak current mA
D27S-1	10	200.9
D27S-2	10	170.5
D27S-3	10	206.1
D27S-4	10	214.4
D27S-5	6	97.9
D27S-6	6	43.2
D27S-7	6	168.9
D27S-8	6	67.8

Table 5.20: Clean fog performance data for 27 mm/kV slanted shed insulator

Salt fog performance data

a) Donor D27S-1 to D27S-4:

- A salt fog contamination solution of 54 mS/cm represents an upper-medium pollution classification. The leakage current (Table 5.21) over this contamination layer falls in the range: $390.6 \leq I_{leakage} \leq 878.1$ mA
- A salt fog contamination solution of 67 mS/cm represents a lower-high pollution classification. The leakage current over this contamination layer falls in the range: $277.8 \leq I_{leakage} \leq 605.7$ mA
- A salt fog contamination solution of 80 mS/cm represents a mid-high pollution classification. The leakage current over this contamination layer is: $I_{leakage} = 875.4$ mA
- The insulators begin to fail the salt fog test at 54 mS/cm, and total batch failure occurs at 80 mS/cm – representing a large deviation.

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b) Donor D27S-5 to D27S-8:

- A salt fog contamination solution of 54 mS/cm represents an upper-medium pollution classification. The leakage current (Table 5.21) over this contamination layer falls in the range: $287.7 \leq I_{leakage} \leq 572.3$ mA
- A salt fog contamination solution of 67 mS/cm represents a lower-high pollution classification. The leakage current over this contamination layer falls in the range: $431.3 \leq I_{leakage} \leq 518.8$ mA
- A salt fog contamination solution of 80 mS/cm represents a mid-high pollution classification. The leakage current over this contamination layer is: $443.8 \leq I_{leakage} \leq 791.9$ mA
- A salt fog contamination solution of 94 mS/cm represents a mid-high pollution classification. The leakage current over this contamination layer is: $414.9 \leq I_{leakage} \leq 734.5$ mA
- The insulators begin to fail the salt fog test at 80 mS/cm, and total batch failure occurs at 94 mS/cm.

Serial	Age Years	54 mS/cm Peak current mA	67 mS/cm Peak current mA	80 mS/cm Peak current mA	94 mS/cm Peak current mA
D27S-1	10	613.2	←	←	←
D27S-2	10	878.1	←	←	←
D27S-3	10	448.5	277.8	875.4	←
D27S-4	10	390.6	605.7	←	←
D27S-5	6	287.7	501.9	443.8	414.9
D27S-6	6	497.9	471.6	638.5	←
D27S-7	6	361.1	431.3	791.9	←
D27S-8	6	572.3	518.8	569	734.5

Table 5.21: Salt fog performance data for 27 mm/kV slanted shed insulator

5.3 IEC 1109: One-hundred Hour Voltage Test

Various samples were tested according to the IEC 1109 protocol. Samples D, X, J, P and R were taken from different insulators and different manufacturers. The samples were placed in boiling water containing 0.1% NaCl (sodium chloride or table salt) for the required 100 hours (IEC 1109), and continued until 192 hours once the IEC 1109 requirements had been satisfied.

The change in leakage current due to the application of 12 kV AC, and the change in capacitance in time were monitored on a Tettex Schering Bridge.

IEC 1109 Voltage Test (Current Measurement)

- Sample J exhibits the best performance (Table 5.22) during the 100 hour IEC 1109 Voltage Test - and is closely followed by Sample R. The order of merit for the remaining samples is: Samples D, X and P.

Time hours	Test Voltage kV	Sample D Current mA	Sample J Current mA	Sample P Current mA	Sample R Current mA	Sample X Current mA
0	12	0.0111	0.0109	0.0110	0.0112	0.0111
24	12	0.0112	0.0109	0.0112	0.0111	0.0109
48	12	0.0110	0.0110	0.0114	0.0113	0.0111
72	12	0.0115	0.0112	0.0116	0.0113	0.0113
96	12	0.0117	0.0111	0.0121	0.0115	0.0118
120	12	0.0124	0.0113	0.0126	0.0119	0.0128
144	12	0.0124	0.0115	0.0146	0.0127	0.0156
168	12	0.0127	0.0120	0.0460	0.0131	0.0900
192	12	0.0129	0.0118	0.5020	0.0320	0.7800

Table 5.22: IEC 1109 voltage test data

- If the test is extended to 192 hours, Samples J and D exhibit remarkable stability (Figure 5.6). Samples P and X deteriorate to a large degree, Sample R less so. The order of merit (best to worst) for the 192 hour test is: Sample J, D, R, P and X.
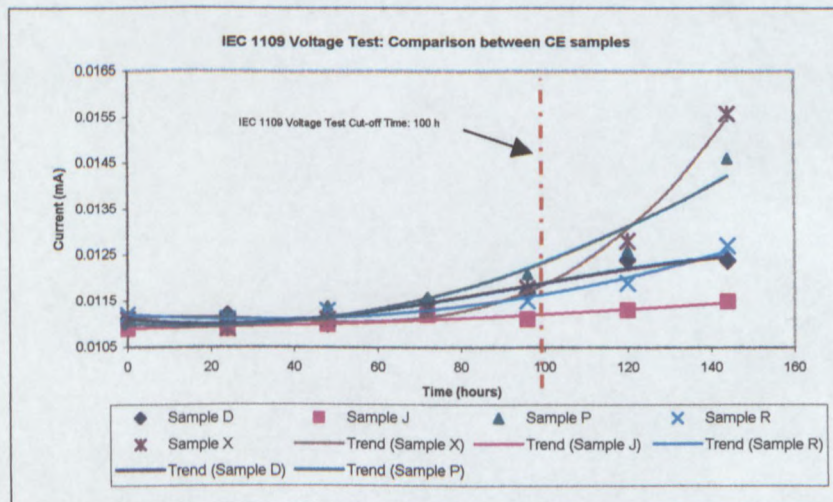
Figure 5.4: IEC 1109 voltage test data

IEC 1109 Voltage Test (Relative Permittivity Measurement)

In order to establish some form of reference, with regards to the effect of elevating the temperature of the solution that the samples were submersed in, two samples (Samples D and X) were submersed in identical solutions at ambient laboratory temperature (Figure 5.5).

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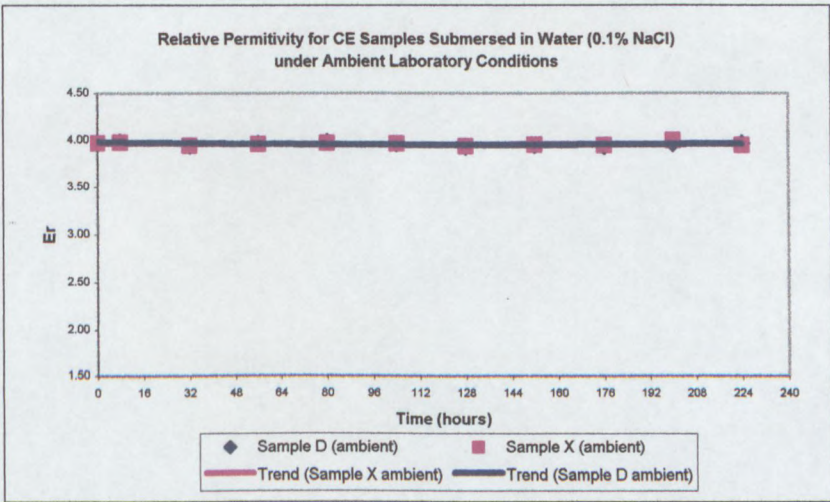
Figure 5.5: Relative permittivity for CE samples submersed in water (0.1% NaCl) under ambient laboratory conditions.

- The relative permittivities for Samples D and X submersed in 0.1% NaCl water solution indicate similar stability of the materials at ambient laboratory temperatures.
- The samples behave similarly for the first 100 hours – and there is not much deviation up to 160 hours of submersion in 0.1% NaCl solution boiling water (Figure 5.6).
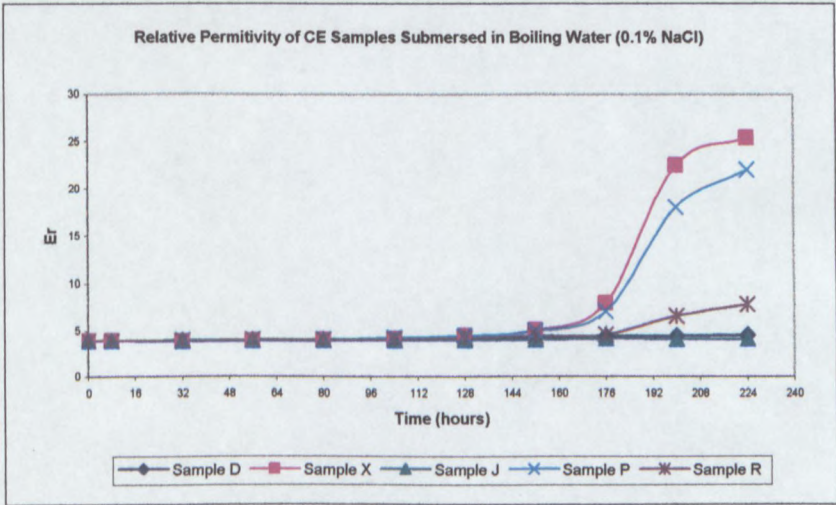

Figure 5.6: Relative permittivity of CE samples submersed in boiling water (0.1% NaCl).

- Samples J and P perform best, with minimal deviation during the entire test period of 224 hours. Sample R shows significant deviation (Er = 7.8) after 224 hours.
- Samples P and R demonstrate advanced deterioration during this test, by attaining values of relative permittivity of 22 and 25 respectively.

The significance of the IEC 1109 Voltage Test is further discussed in Chapter 6.3.

5.4 Mould Release Tests

The superior bonding or adhesive qualities of CE's dictate the use of mould release agents during the casting process. The mould release agent is applied to the mould to assist in the de-molding of the cast object, and as a result, remnants of the release agent are left on the surfaces of CE insulators when shipped to customers.

There have been discussions and suggestions made as to the effect of the release layer on the performance of CE insulation, and the following mould release tests were designed to quantify the exact effect under laboratory conditions.

The tests were designed to compare the CE insulator as received from the manufacturer, to the modified insulator - the modified insulator simply being a representative insulator without the mould release layer (removed by washing the insulator surface in a non-abrasive manner with methanol).

The mould release layer is a low-viscosity silicon-based oil and thus imparts a certain degree of water repellency to any surface it is applied to. The aim of the mould release tests was to determine the length of time the mould release layer could resist high voltage (rated insulator voltage) under salt fog pollutions.

Initially, due to the excellent hydrophobicity of the layer, the CE insulators should not register any leakage current over their surfaces. There should be an indication of leakage current once the mould release layer degenerates to such a degree that the insulator surface becomes hydrophilic

a) Mould release test: 38 mS/cm salt fog on 29 mm/kV insulator

The 29 mm/kV CE insulator falls in the heavy pollution classification range and should be suitable for salt fog pollution severities of $56 \le$ mS/cm ≤ 130. A salt fog severity of 38 mS/cm was chosen in order to evaluate the mould release layer under reduced stress conditions. A 38 mS/cm salt fog conductivity represents a medium pollution classification (Figure 5.1).

The Modified insulator – peak current profile

- The modified insulator begins to conduct leakage current over its surface after 120 minutes (Figure 5.7). This is due to the difficulty in completely removing the mould release layer from the surface of the insulator.

- However, once leakage current conduction has begun, the current quickly assumes a significant value in the order of 200 mA.
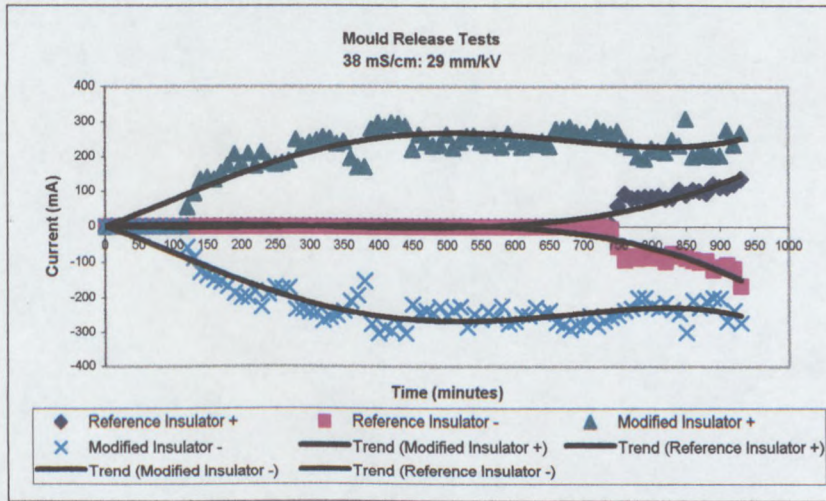
Figure 5.7: Mould release tests at 38 mS/cm on 29 mm/kV slanted shed CE insulator

The Reference insulator – peak current profile

- The reference insulator blocks surface leakage current conduction (Figure 5.7) for 740 minutes.
- Within 20 minutes of leakage current conduction, the leakage current has increased from 5 mA to approximately 100 mA. The trend indicates a deteriorating condition and the insulator continues to achieve surface conduction levels similar to the Modified insulator.
- No recovery of surface condition is achieved through allowing the insulator to 'rest' by disconnecting it from the power source and removing it to a non-polluted atmosphere. The damage to the mould release layer appears to be permanent.

b) Mould release test at 21 mS/cm on 19 mm/kV insulator

The 19 mm/kV CE insulator falls in the light pollution classification range and should be suitable for salt fog pollution severities of $6 \leq$ mS/cm ≤ 22. A salt fog severity of 21 mS/cm was chosen in order to evaluate the mould release layer under optimal stress conditions. A 21 mS/cm salt fog conductivity represents the upper limit that the insulator should withstand.

This test represents the 'legal' limit for a fair examination of the insulator and any mould release layer evident on the surface, and should result in the rapid reduction of any hydrophobic qualities.

The Modified insulator – peak current profile

- The modified insulator begins to conduct leakage current over its surface immediately (Figure 5.8).
- The current assumes a significant and stable peak value of 475 mA for the duration of the test. The damage done to the modified insulator surface is in the form of tracking and erosion (Figure 5.9).
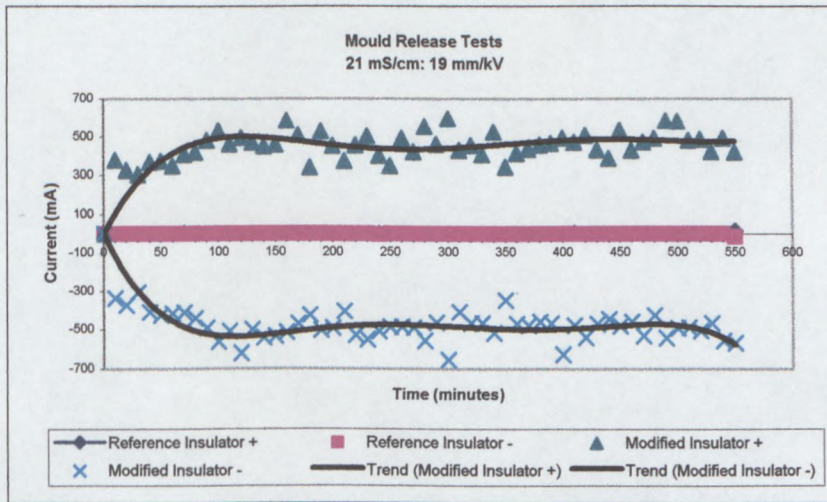
Figure 5.8: Mould release tests at 21 mS/cm on 19 mm/kV horizontal shed CE insulator

The Reference insulator – peak current profile

- The reference insulator blocks surface leakage current conduction for 540 minutes (Figure 5.8).
- No recovery of surface conditions is achieved through allowing the insulator to 'rest'.
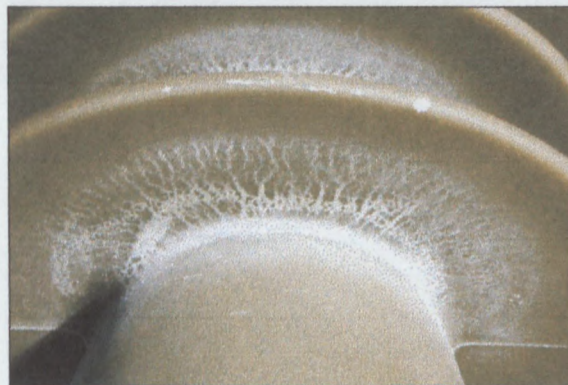

Figure 5.9: Effects of 9 hour mould release test (leakage current) on CE insulator surface

c) Mould release tests at 10 mS/cm on 27 mm/kV insulator

The 27 mm/kV CE insulator falls in the heavy pollution classification range and should be suitable for salt fog pollution severities of $56 \leq mS/cm \leq 130$. A salt fog severity of 10 mS/cm was chosen in order to evaluate the mould release layer under extremely low stress conditions. A 10 mS/cm salt fog conductivity represents a very low pollution severity classification (Figure 5.1). Accordingly, the insulator should not experience any indications of electrical stress, and leakage currents should be low.

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The Modified insulator – peak current profile

- The modified insulator begins to conduct leakage current over its surface immediately and achieves a peak current level of 75 mA for the duration of the test (Figure 5.10).
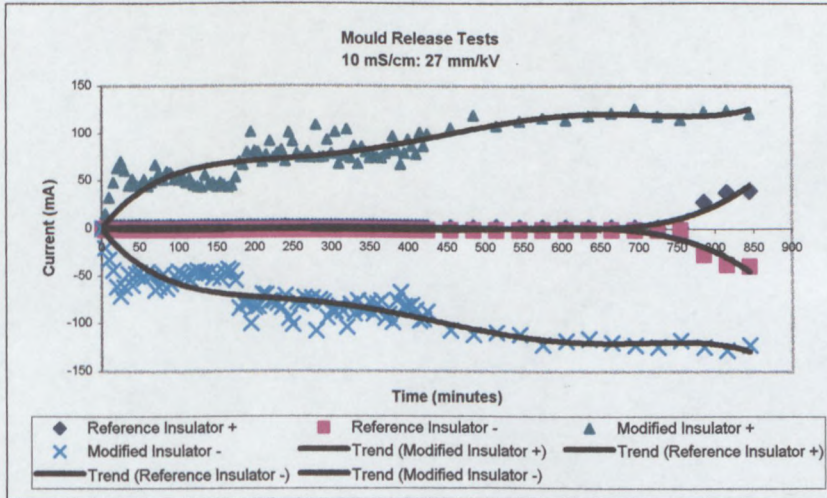

Figure 5.10: Mould release tests at 10 mS/cm on 27 mm/kV slanted shed CE insulator

The Reference insulator – peak current profile

- The reference insulator blocks surface leakage current conduction for 755 minutes (Figure 5.10).
- No recovery of surface conditions is achieved through allowing the insulator to 'rest'.

The mould release tests reveal that the mould release seriously impacts the performance of CE insulators with respect to the IEC 507 salt fog test. The relevance of the mould release tests are discussed in Chapter 6.2.1.

5.5 Material Identification Study

In the RSA there are two predominant CE resin systems applied to the manufacture of CE insulation. Tests performed at the Koeberg Insulator Pollution Test Station (KIPTS) in 1998 indicated that the use of different resin systems could result in the different behavior of the CE insulators in respect of polluted conditions. The material identification study was performed in order to determine the identity of resin systems employed to manufacture the test specimens.

The basic components:

- accelerator
- hardener
- resin
- filler

- mould release

constitute a complete resin system. The basic ingredients were individually analyzed in the FTIR-PAS device, and the spectra were compared to an electronic spectra library for correlation and identification. Any confidence level over 90% is regarded as a reasonable correlation or identification of the specimen. The analysis excluded any additives (Chapter 2.9) that the manufacturer might add to the resin system, as the additives tend to be regarded as trade secrets and were purposely not supplied by the manufacturers.

Resin Systems

- Resin System A and Resin System 1 are very similar, except for the accelerator (Table 5.23). Resin System A incorporates an amine-based accelerator while Resin System 1 utilizes an acid-type (Lewis) accelerator. The use of an amine accelerator allows for the identification of the two systems by observing their odor as the amine-based system delivers a pungent odor when stressed mechanically, or electrically.
- There is a slight difference in the confidence of correlation between the hardeners, yet the basic constitution of the hardeners is similar (both being aliphatic / aromatic anhydrides).

Component	Resin System A	Resin System 1
Accelerator	Tertiary aliphatic/aromatic amine (99% confidence)	Acid type
Hardener	Aliphatic / aromatic carboxylic acid anhydride (81% confidence)	Aliphatic / aromatic carboxylic acid anhydride (91% confidence)
Resin	Hexahydropthalic acid diglycidyl ester (99.4% confidence)	Hexahydropthalic acid diglycidyl ester (94% confidence)
Filler	Silicone dioxide (SiO_2)	Silicone dioxide (SiO_2)
Mould Release	QZ13	QZ13

Table 5.23: Resin system identification

Mould Release: Gas Chromatography

By comparing the dominant retention time areas obtained by performing a gas chromatograph test (Table 5.24), it appears that the mould release agents are similar or contain similar solvents or constituent chemicals.

Retention Time (minutes)	Resin System A (% area of peak)	Resin System 1 (% area of peak)
4.160	15.7	9.9
4.705	12.0	9.3
6.289	7.8	7.9
6.651	9.9	11.5

Table 5.24: Mould release system identification GC: essential retention time peak areas

5.6 Water Immersion Tests (Absorption and Desorption Curves)

Insulation applied in outdoor conditions is subjected to wetting by various sources of condensation: dew, fog, mist or rain. The occurrence of condensation can be sporadic (typical of seasonal rainfall patterns in the RSA), or occur regularly in a cyclic pattern (nocturnal dew formation at KIPTS).

Additionally, it is a well known fact that hydrolysis due to the action of water on CE's is one of the most significant relevant aging mechanisms, hence the decision to use the water immersion test as an indicator of the relative performance of CE samples – the ability to resist the ability of water to hydrolyze (effectively de-cross-link) the CE matrix.

The test employed was based on the IEC 1109 specification for the immersion of insulation in water: "the water diffusion test". The test involved the monitoring of the changes in mass and the ability of the sample to withstand a specified AC voltage.

The tests were performed at three different temperatures:

1. Ambient temperature (20 degrees Celsius)
2. 50 degrees Celsius
3. 100 degree Celsius

In order to perform the test, the dimensions of the test samples need be accurately known (Table 5.25). The actual dimensions are specified in IEC 1109 and are meant to be 3.5 cm (diameter), and 3 cm (height).

Serial Number	Height cm	Diameter cm	Surface Area cm^2	Volume cm^3	Density g/cm^3
D	3.007	3.482	51.938	28.634	1.877
D - ambient	2.999	3.501	52.238	28.870	1.886
J	3.001	3.417	50.556	27.520	1.899
P	3.003	3.515	52.569	29.140	1.893
R	3.019	3.515	52.745	29.296	1.884
X	3.011	3.366	49.637	26.793	1.890
X – ambient	2.999	3.512	52.463	29.052	1.912

Table 5.25: Physical dimensions of water immersion test samples (IEC 1109)

The dimensions were measured using an accurate digital vernier and checked with an analog equivalent. The accurate CE sample dimensions permitted the densities of the samples to be calculated: by dividing the measured mass of the sample by the volume. An important artifact of the APG process was detected when comparing the relative densities of the samples.

In order to obtain a representative comparison between ambient and elevated temperature tests, two samples were cut from insulators D and X. In both cases there are differences in densities of the samples – indicating gravitational settling of the (more dense) filler within the resin system. The gravitational settling (sedimentation) of filler, especially in larger cast objects requiring longer cure times, has been noted and recorded to be up to a 21% difference in the bottom CE layer (see Chapter 6, Table 6.8).[2]

IEC 1109: Ambient Temperature Water Immersion Absorption Data

The CE samples were placed in the IEC 1109 solution, and both the mass increase per unit surface area and unit volume were monitored. The mass increase per unit surface area was chosen as the criteria for evaluation since any mass increase per unit volume must penetrate the surface area of the sample, and logically, the surface area dictates the rate at which absorption initially takes place.

The volume has an effect on the rate of absorption once a fair degree of material saturation has taken place – since the absorbed water cannot occupy a space or volume already occupied by polymer material, filler or other substances.

- Samples D and X were immersed in ambient temperature (laboratory) 0.1% sodium chloride (NaCl) solution in order to serve as monitors for both the 50 ^{0}C and 100 ^{0}C immersion tests.
- Although both samples indicate minimal increase in mass-per-square-unit surface area over the entire test period, Sample D performs better than Sample X (Table 5.26).
- The most significant increase in mass for both samples takes place within 50 hours of immersion (Figure 5.11). The percentage mass increase of the final attained mass-per-square-unit surface area for 25% (56 hours) of the test period is:

  1. Sample D: 56%
  2. Sample X: 56%

Serial	Δmass mg	Δmass / volume mg / cm^3	Δmass/ surface area mg / cm^2
Sample D – ambient	16.7	0.57845	0.32
Sample X - ambient	19	0.654001	0.36

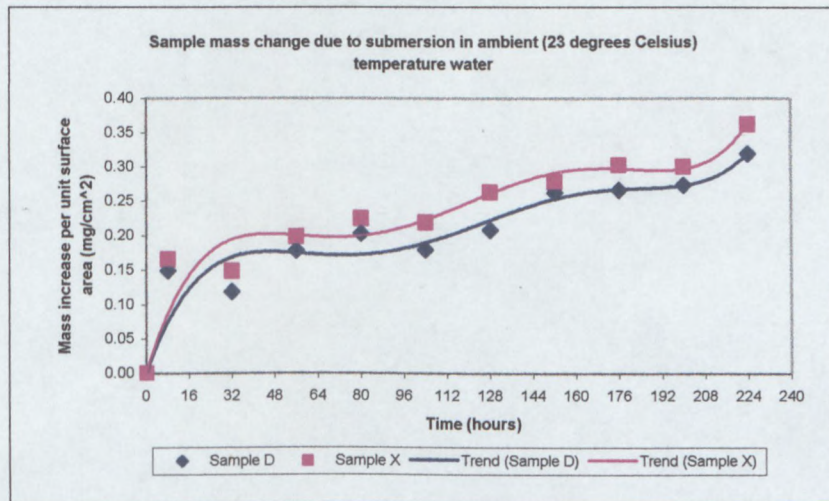Table 5.26: Ambient temperature water immersion tests: monitors

Figure 5.11: Sample mass change per unit surface area due to submersion in ambient temperature water

IEC 1109: 100 ⁰C Water Immersion Absorption Data

- The relative performance of the samples from best to worst is: Samples J, D, P, X, R respectively (Table 5.27).
- In 25% (roughly 50 hours) of the total test time, the increase in mass-per-unit-surface-area is (Figure 5.12):

  1. D = 40%
  2. X = 31.5%
  3. J = 44%
  4. P = 33%
  5. R = 35%

- The gradient of increase in mass-per-unit-surface-area indicates that Sample J is the most stable material, while Sample X is the least stable material.

Serial	Δmass mg	Δmass / volume mg / cm^3	Δmass/ surface area mg / cm^2
Sample D	249.7	8.720426	4.81
Sample J	165.8	6.024745	3.28
Sample P	383.5	13.16041	7.3
Sample R	402.2	13.72898	7.63
Sample X	372.5	13.90264	7.5

Table 5.27: Mass increase in CE samples submersed in boiling water
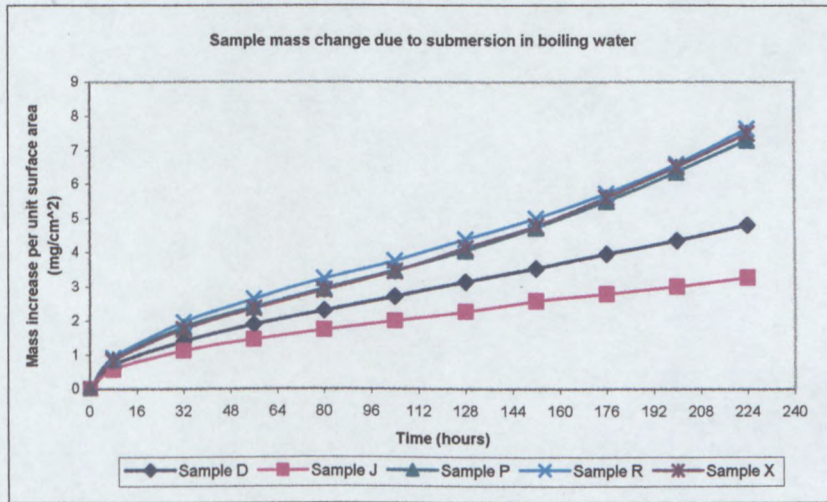
Figure 5.12: Sample mass change per unit surface area due to submersion in boiling water

IEC 1109: 50 °C Water Immersion Absorption Data

- The relative performance of the samples, from best to worst is: Sample R, D, P, X, J (Table 5.28).
- The percentage increase in mass-per-unit-surface-area in 20% of the total test time is (Figure 5.13):

  1. D = 31%
  2. X = 35%
  3. J = 67.3%
  4. P = 38%
  5. R = 38.5%

- Sample J exhibits a curious increase in the amount of absorbed water relative to the other samples, and previous submersion tests – being an entire order-class more absorbent. However, upon closer examination of the trend lines for the absorbance, the following is noted:
- The trend line equations for the samples, plotted from the 48 hour interval reveals interesting information as to the relative stability of the materials:

  1. Sample J: $y = 0.0019.t + 0.712$
  2. Sample D: $y = 0.0026.t + 0.121$
  3. Sample X: $y = 0.0027.t + 0.142$
  4. Sample P: $y = 0.0023.t + 0.1523$
  5. Sample R: $y = 0.0024.t + 0.1278$

Sample J has a large offset quantity (0.712), yet the gradient for the increase in mass-per-unit-surface-area is significantly less than for all the other samples:

a. $0.0023 \leq \text{gradient} \leq 0.0027$ (D, X, P, R)
b. $\text{gradient} = 0.0019$ (J)

This would seem to indicate that Sample J would assume a better level of material stability in time, yet is compromised by an initial short-term susceptibility to moisture ingress.

Serial	Δmass mg	Δmass / volume mg / cm^3	Δmass/ surface area mg / cm^2
Sample D	32.9	1.4417	0.7263
Sample D – ambient	16.7	0.57845	0.32
Sample J	50.1	2.5379	1.1962
Sample P	32.9	1.4522	0.7285
Sample R	26.5	1.7346	0.7207
Sample X	36.4	1.5664	0.7942
Sample X - ambient	19	0.654001	0.36

Table 5.28: Mass increase in CE samples submersed in 50 degrees Celsius water
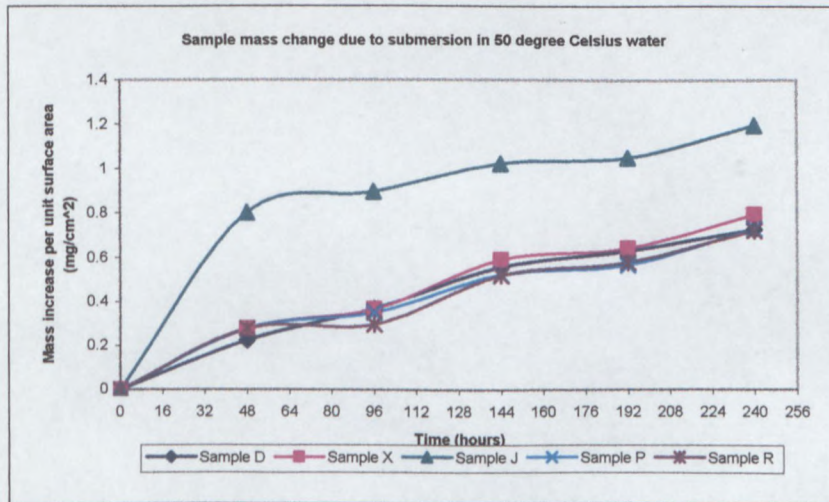
Figure 5.13: Sample mass change per unit surface area due to submersion in 50 degree Celsius water

IEC 1109: 100 ^{0}C Desiccation Desorption Data

The samples exposed to the 100 ^{0}C water immersion mass increase experiment were placed in an oven and baked at 100 ^{0}C in order to determine the desorption curves (Figure 5.14).

The trend line equations for the samples:

- Sample J: $y = 0.0000108.x^2 - 0.0021253.x + 0.1704089$
- Sample D: $y = 0.0000226.x^2 - 0.0039616.x + 0.2705424$
- Sample X: $y = 0.0000244.x^2 - 0.0042581.x + 0.3320156$
- Sample P: $y = 0.0000234.x^2 - 0.0040513.x + 0.3259371$
- Sample R: $y = 0.0000210.x^2 - 0.0038647.x + 0.3430149$

Figure 5.14 indicates that the samples exposed to the water immersion tests do not return to their original masses before immersion.
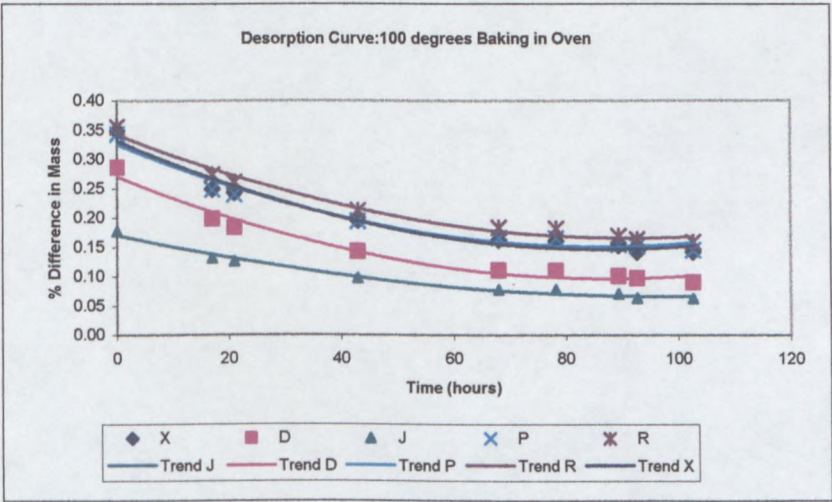
Figure 5.14: Desorption curves for CE samples baked in oven at 100 ^{0}C

5.7 Thermal Gravimetric Analysis

Measurements of the filler content were specifically taken in the bulk material of the insulator body – the general mass constituting the insulator. This was done in order to get the most representative sample of the insulator - from which to perform TGA analysis. Another set of samples was taken from the CE insulator mould line zone – in order to compare the filler densities between the bulk and mould line.

- TGA 1-4 are random sample measurements taken from donated insulators (bulk material)
- Samples D,X,J,P and R represent insulator bulk material samples and indicate a notable variation in filler content: $59.4 \leq$ filler $\% \leq 69.6$ (Table 5.29).
- In general, the filler content for CE utilized as outdoor electrical insulation should be approximately 59–61%. The TGA results indicate a wide range of results: $56.6 \leq$ filler $\% \leq 72.1$
- The flash line is characterized by less filler content when compared to the bulk material of the insulator: 62.1% filler in the mould line compared to 71.5% for the bulk insulator material.

Serial / Identity	TGA Filler Content In Percent (%)
TGA-1	56.6
TGA-2	72.1
TGA-3	70.3
TGA-4	57.1
Sample R	69.6
Sample P	69.0
Sample J	59.4
Sample X	61.9
Sample D	64.1
Insulator (Bulk)	71.5
Insulator (Mould Line)	62.1

Table 5.29: TGA analysis for CE samples

5.8 Hydrophobicity changes due to Water Hydrolysis

The samples were placed in sealed glass beakers and boiled continuously in deminerilized water for the indicated period of time. Samples were monitored at the time intervals (Table 5.30).

- There is a reduction in surface hydrophobicity characteristics for the submersion of CE samples in boiling water. Sample D and X both present a total loss of hydrophobicity of 30% relative to their respective reference (0 hour) values for contact angle (Figure 5.15).
- By comparing the gradients of the trend lines, Sample D performs better than Sample X:

Trend line Sample D: contact angle = -0.0518.t + 105.4
Trend line Sample X: contact angle = -0.0399.t + 87.2

Time Hours	Sample X degrees	Sample D degrees
0	103	92
168	101	77
336	88	70
504	76	66
672	72	64

Table 5.30: Changes in hydrophobicity on samples D and X due to water hydrolysis
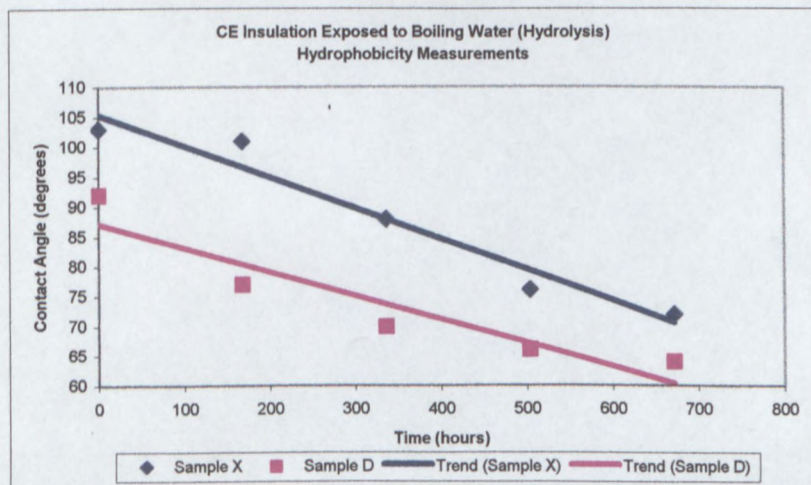

Figure 5.15: Hydrophobicity measurements on CE exposed to boiling water

5.9 Hydrophobicity changes due to QUV exposure

A sample was placed in the QUV device and exposed to the UV and wetting cycles. The sample was monitored at the stated time intervals (Table 5.31).

There is a reduction in surface hydrophobicity characteristics due to the combined effects of exposure to UV and condensation typical of the QUV test, and the sample shows a reduction in the contact angle over time (Figure 5.16):

contact angle = -0.0142.t + 110.8

Time (hours)	Sample (degrees)
0	108
168	112
336	106
505	97
672	107
1008	98
2016	81

Table 5.31: Hydrophobicity changes due to QUV exposure
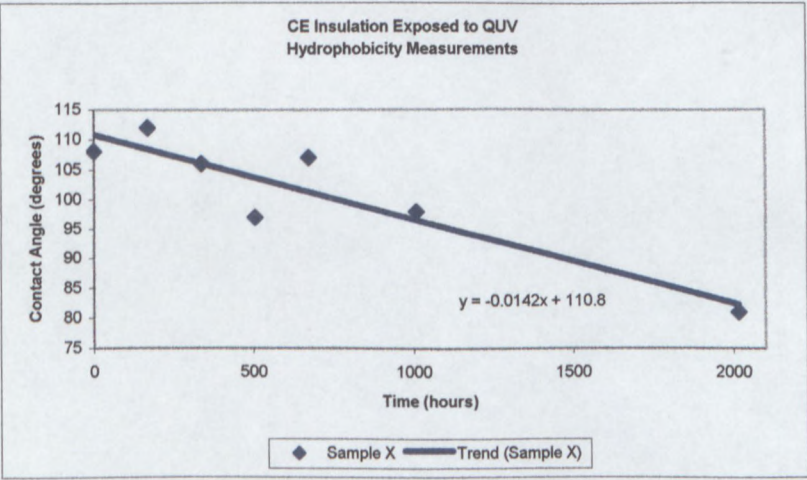
Figure 5.16: Changes in hydrophobicity due to QUV exposure

5.10 Scanning Electron Microscopy of Fillers

It is a well known fact that the addition of filler to the CE resin system influences the physical properties of the final product (Chapter 2.9). However, the shape and size of the filler particle itself plays a significant role in determining these properties.

- On average, Supplier 2 filler is physically smaller when compared to the Supplier 1 filler (Figures 5.17 and 5.18).
- The particle size varies from very small fragments (less than 1 micron) to large fragments (greater than 50 micron) for both filler suppliers
- Both suppliers fillers are not smooth, and consist of many fragments and jagged edges.
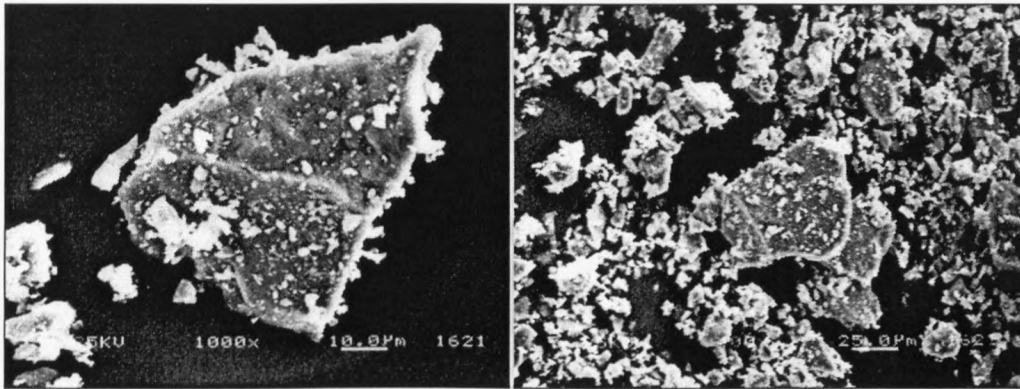
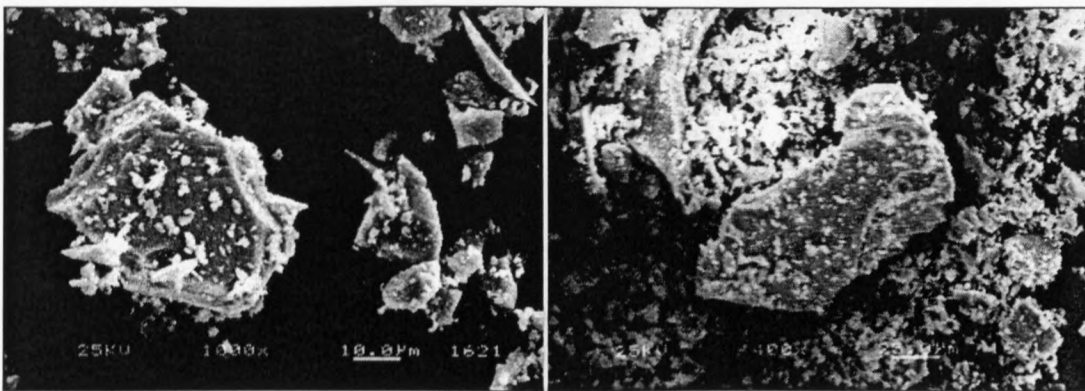Figure 5.17: 10 and 25 micron SEM of Supplier 1 filler

Figure 5.18: 10 and 25 micron SEM of Supplier 2 filler

5.11 Energy Dispersive X-ray Analysis of Fillers

The fillers of the two prominent CE resin systems employed in the RSA were analyzed using EDX, in order to determine the material quality of the fillers and detect any impurities. The fillers should, according to specification, consist entirely of silicon-based compounds (Chapter 2.9).

- Both fillers, within the detection range of the EDX instrument, appear to be consistent and pure – consisting entirely out of silicon or silicon based compounds (Figures 5.19 and 5.20).
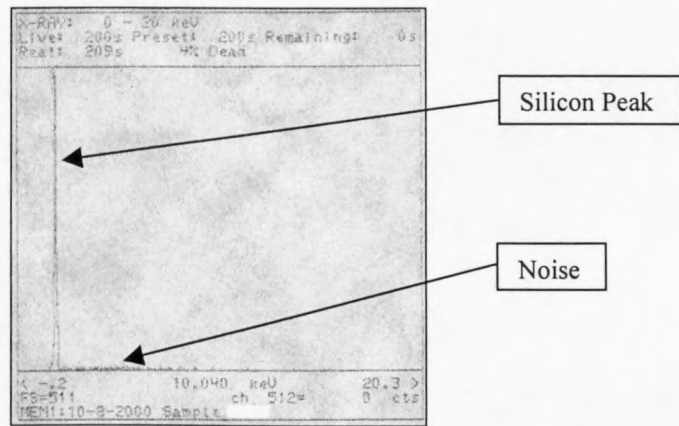
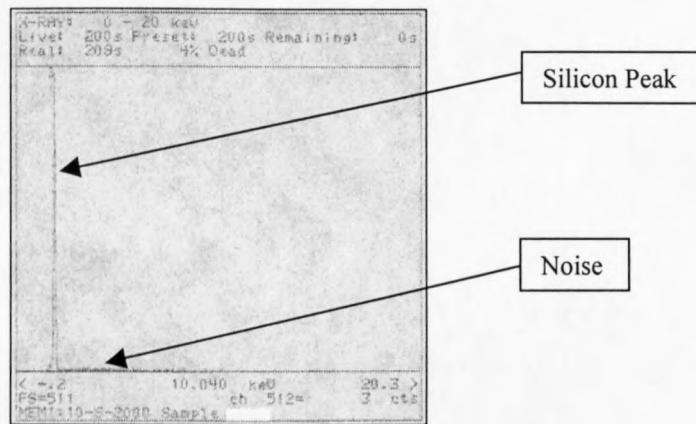**Figure 5.19: EDX of Supplier 1 filler**

Figure 5.20: EDX of Supplier 2 filler

5.12 AFM: Surface Area and Roughness Measurements due to UV radiation

Many studies have been conducted that indicate that CE samples become rougher with exposure to solar UV radiation (Chapter 6). An attempt was made to simulate the roughness process by exposing CE samples to laboratory generated UV radiation in the UV-B range of the spectrum.

Surface Area Changes and the Surface Area Index (Hypothesis: Chapter 6.2.2)

The changes in the surface areas of the CE samples were monitored (Figure 5.21). The CE sample was examined using the AFM, and a surface area was calculated at various aging time intervals (Table 5.32).

- The Surface Area Index (SAI) is determined by the following equation:

  SAI = [Projected Surface Area] / [User Selected Scan Surface Area]
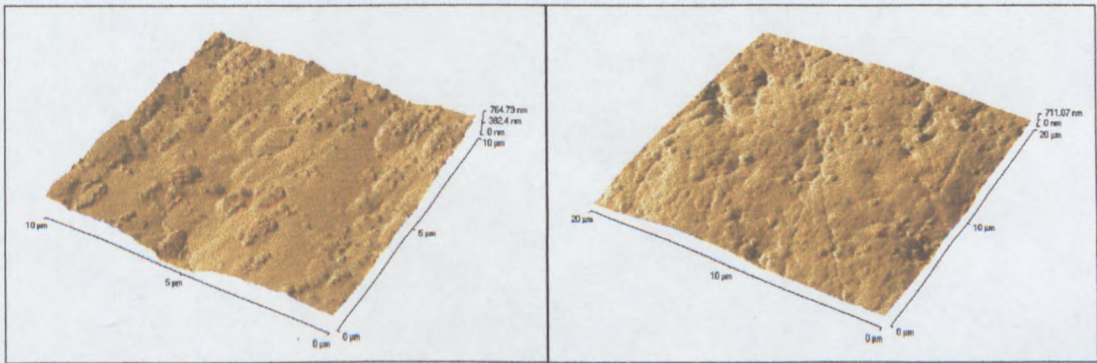
Figure 5.21: AFM images of a control and QUV2000 aged CE sample

Serial	QUV Exposure Time (hours)	Surface Height nano-meters	Surface Area Index Ψ_{SA}
UV 0000	0	1573.9	1.1852
UV 0500	500	1443.4	1.0793
UV 1000	1000	1287.2	1.0517
UV 1500	1500	996.0	1.0359
UV 2000	2000	694.9	1.0260

Table 5.32: CE surface changes due to QUV radiation

The AFM scans a pre-determined (by the user) surface area, denoted by the x and y Cartesian co-ordinates – referred to as the two-dimensional surface area. The three dimensional surface area includes the height (z coordinate). The theory is that the aging of CE samples affects the height (z) profile of the CE sample.

The pre-determined surface area remains as a constant as it is the user defined scan area. The change in height (z) of the CE sample is the only variable and is thus incorporated into the three dimensional measurement.

The advantages of using this method of surface change analysis are:

1. Extreme accuracy – determined by the resolution of the AFM
2. By incorporating a height measurement into a specific area, the possibility of individual high peaks giving an incorrect roughness measurement is reduced – as the very nature of a high peak is a structure typical of a small surface area.
3. 3-D data images for visual inspection of the measured area

By analyzing the data in Figure 5.22 for changes in surface area:

- CE samples exposed to UV radiation and condensation cycles of 11 and 1 hours respectively show a reduction in the Surface Area Index.
- The most significant surface change took place within the first 1000 hours of QUV exposure, followed by a 'plateau' region of reduced aging rate for the remaining 1000 hours.
- The trend line equation for the first 1000 hours of aging is:

$$\Psi_{SA} = 156.4167 \times 10^{-9}.t^2 - 289.9167 \times 10^{-6}.t + 1.185167 \ (0 < t < 2000 \ h)$$
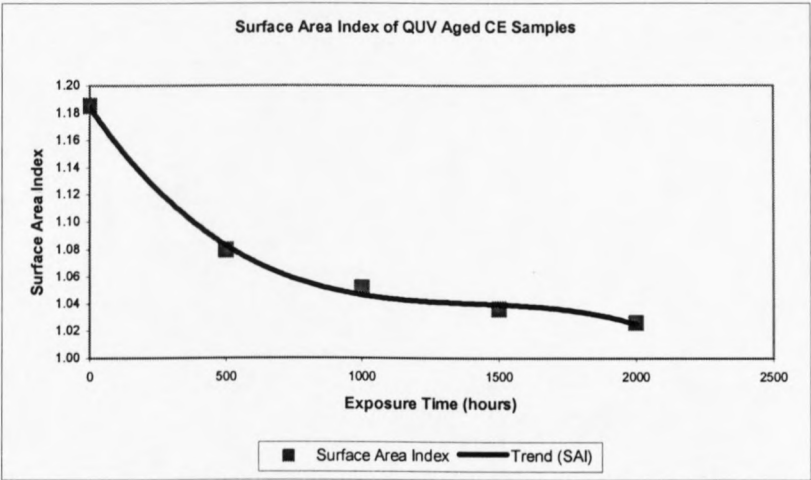

Figure 5.22: Surface Area Index for QUV aged CE

Surface Roughness Changes

- The trend line (Figure 5.23) indicates that the samples become less rough (smoother) with 2000 hours of exposure to ultraviolet light and condensation in the QUV device.
- The trend line equation, with a high degree of correlation, is:
  $$y = -136.0407 \times 10^{-6}.t^2 - 169.02 \times 10^{-3}.t + 1572.1493095238 \ (0 < t < 2000 \ h)$$
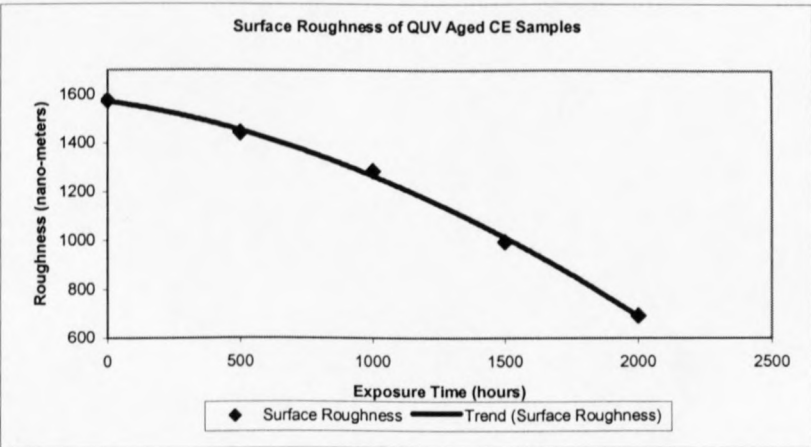

Figure 5.23: Surface roughness for QUV aged CE

The surface roughness changes are an unexpected result and are further discussed in Chapter 6.2.2.

Field-aged Samples

Field samples were subjected to the same AFM analysis in order to determine the surface roughness and surface area index for naturally aged CE. Figure 5.24 provides

81

an indication as to the roughness, and Figure 5.25 provides an indication as to the surface area index. The samples ages and aging mechanisms are provided in Table 5.33.

From Figure 5.24 it is clear that all the samples are significantly rougher than the control sample (by a factor of 2). By determining the amount of change in surface roughness per year of exposure to the environment, the following sequence or ranking of samples is obtained:

1. C21H (415.2 nm/annum)
2. A27S (327.2 nm/annum)
3. D27S (175.6 nm/annum)
4. D21H (128.7 nm/annum)

Similarly, by determining the change in surface area index per annum, the following ranking of samples is obtained:

1. C21H (0.0665 units per annum)
2. D27S (0.05498 units per annum)
3. A27S (0.0194 units per annum)
4. D21H (0.0154 units per annum)

Serial Number	Age	Pollution Type	Average Roughness nm	Surface Area Index
D21H	10	UV (Agricultural / Industrial)	2860.8	1.339
A27S	5	Desert – Marine	3210.0	1.282
C21H	6	Agricultural (sub-tropic)	4064.9	1.584
D27S	8	UV (Agricultural / Industrial)	2978.3	1.625

Table 5.33: Average roughness and surface area index for selected field-aged CE samples
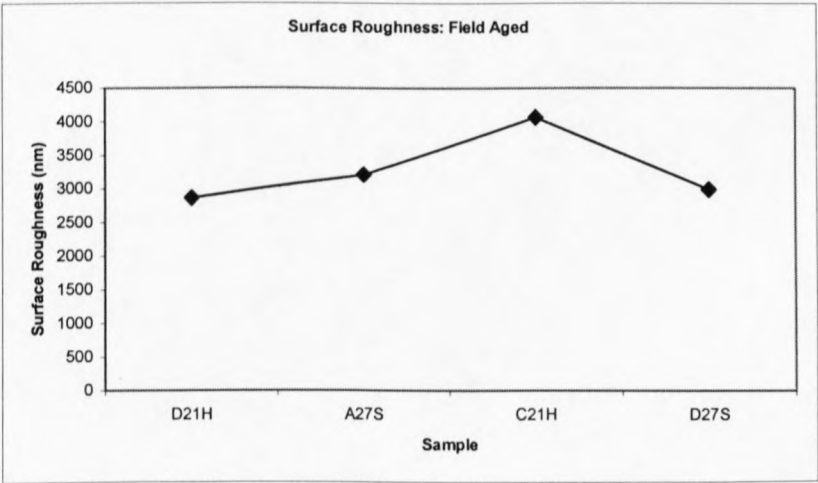

Figure 5.24: Average surface roughness for selected field-aged samples

However, in absolute terms and ranked from worst to best in Table 5.34:

Ranking	Surface Roughness	Surface Area Index
1 (worst)	C21H	D27S
2	A27S	C21H
3	D27S	D21H
4 (best)	D21H	A27S

Table 5.34: Absolute rankings of field-aged CE insulators according to surface roughness and surface area index
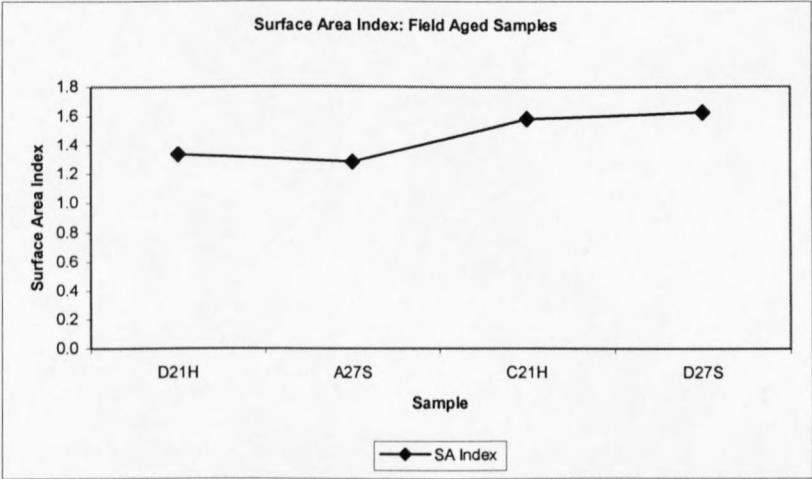

Figure 5.25: Surface area index for selected field-aged CE samples

The SAI and the surface roughness measurements do not correlate (Table 5.34). The results of the SAI, surface roughness and SDD tests are compared and comprehensively discussed in Chapter 6.

5.13 Salt Deposit Density Tests

A selection of insulators (Tables 5.35, 5.36) were subjected to the pre-deposited contamination test sequence, where the insulators were dipped in a kaolin-water-salt mixture. The insulators were allowed to dry and the equivalent salt deposit density (milligrams of NaCl per square centimeter) was determined for each of the insulators.

Serial Number	Pre-contamination Volume Conductivity mS/cm	SDD_{60} mg/cm^2	Pre-contamination Volume Conductivity mS/cm	SDD_{130} mg/cm^2
B21H-14	60	0.39	130	0.74
B21H-15	60	0.26	130	0.57
B19H-3	60	0.39	130	0.73
B19H-5	60	0.41	130	0.82
B19H-8	60	0.43	130	0.91
B19H-9	60	0.45	130	0.63
C21H-1	60	0.52	130	0.99
C21H-2	60	0.50	130	1.00
D21H-1	60	0.37	130	0.78
A27S-1	60	0.12	130	0.22
A27S-2	60	0.14	130	0.21
A27S-4	60	0.13	130	0.23
A27S-6	60	0.12	130	0.19
D27S-12	60	0.16	130	0.24
D27S-5	60	0.15	130	0.26
D27S-6	60	0.17	130	0.32
D27S-9	60	0.14	130	0.19

Table 5.35: SDD values for filed aged CE insulators

Serial Number	Pre-contamination Volume Conductivity mS/cm	SDD_{60} mg/cm^2	Pre-contamination Volume Conductivity mS/cm	SDD_{130} mg/cm^2
R19H-1	60	0.380	130	0.800
R21H-1	60	0.380	130	0.800
R27S-1	60	0.125	130	0.290

Table 5.36: SDD values for reference CE insulators

Table 5.37 is an extract from IEC 507 and is applicable to typical ceramic insulation – in this case horizontally arranged (suspension mounted) glass cap and pin insulators that were dipped in the indicated kaolin suspension.

Pre-contamination Volume Conductivity mS/cm	SDD mg/cm^2
10	0.025
14	0.035
20	0.050
28	0.070
40	0.100
56	0.140
80	0.200
112	0.280
160	0.400

Table 5.37: Approximate correspondence between the volume conductivity and SDD for vertically arranged reference glass discs [3]

By analyzing the data displayed in Figure 5.35:

Horizontal Shed Insulators

- The horizontal type insulators all indicate extreme levels of SDD which is a poor reflection on the insulator units. Due to a design peculiarity, there is a concentration of SDD in the shed-rim zone – caused by a depression in the run-off profile within this zone (Figure 5.26).
- This phenomenon supports the results obtained in the clean fog tests – where CE insulation of this design registers leakage currents lower than those to be expected from such high levels of SDD, as it is patently clear that the SDD is not uniformly distributed – but concentrated in concentric zones that have little bearing on the performance under clean fog tests, and the wetting mode inherent in such tests.

Figure 5.26: The concentration of contaminant on horizontal shed insulators in the rim-zone

- The horizontal type insulators exhibit further peculiarities when comparing the SDD magnitudes between reference (new) insulators and field-aged insulators. The surface-wetting mode is entirely dissimilar for these two extremes – the field-aged surface is rough and irregular and exhibits a hydrophilic nature,

while the new surface contains the mould release agent and exhibits a highly hydrophobic surface (Figure 5.27).

- The volume of conductive suspension contained in the large drops on the new surface is sufficiently large and results in the hydrophobic surface retaining nearly as much SDD as the field-aged surface. The important distinction being that the drops of contaminant on the new surface are isolated 'islands' of pollution, that do not permit the formation of conductive channels, and hence do not permit leakage currents to flow under clean fog test conditions (the drops are not connected to one another).

Figure 5.27: A highly hydrophobic CE insulator surface with wet contamination

Slanted Shed Insulators

- The slanted shed insulators perform marginally better than the IEC 507 specification. This is because the slanted surface (30^0 slope) assists in removing or reducing the volume of contamination on the wetted surface.
- The field-aged samples register less SDD than the new samples for similar reasons as the horizontal shed type insulators. However, as noted with the horizontal type insulators, the nature of the distribution of the contaminant differs widely between the two surface extremes: field-aged and new.
- The new insulators exhibit highly hydrophobic surfaces to the contamination and do not allow connection of the droplets, hence no leakage current measurements under clean fog conditions. The field-aged samples do however form a layer of connected contamination that provides a suitable medium for the formation of leakage current paths.

General

- The use of the SDD test, which is of a similar process to the clean fog test, is a debatable and complex issue when applied to initially hydrophobic surfaces that are not purposely modified (surface preparation by abrasion or wetting agents) by the researcher.
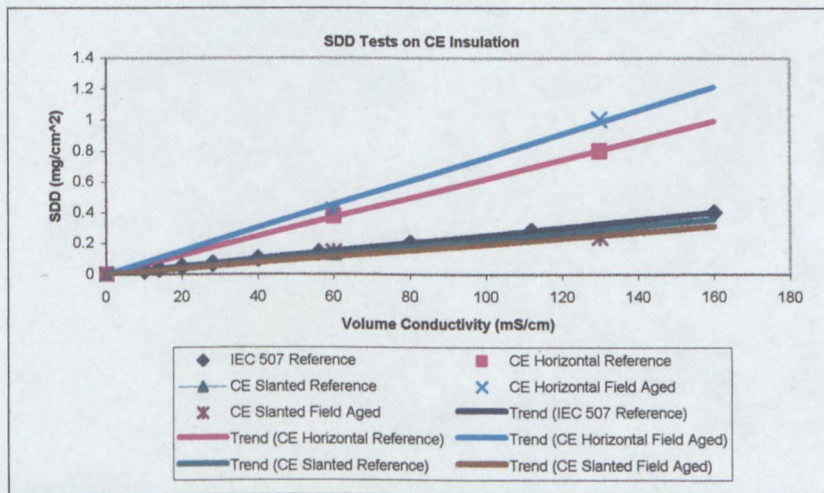
Figure 5.28: SDD Tests on CE insulation

5.14 Independent Utility Questionnaire

The questionnaire was sent (February, 2000) by facsimile to six utilities within the RSA, and three replies were received. The responses are tabulated in Table 5.38:

Parameter	Utility 1	Utility 2	Utility 3
Geographical Location	Pietermaritzburg	Durban	Port Elizabeth
Climate	Summer rainfall: 830 mm Inland: Sub-tropical	Summer Rainfall: 1003 mm Coastal: Sub Tropical	Variable rainfall: 611 mm Temperate Coast
Lightning Occurrence	High	High	Low
Pollution Type and Severity	Industrial Medium severity	Coastal Heavy severity	Coastal Heavy severity
Insulator Type	Predominantly pin-type	Predominantly pin-type	Post-type
Insulator Specification	11 kV BIL: 95 kV Creepage: 520 mm	11 kV [2]	22 kV BIL: 150 kV Creepage: 453 mm
Number of Insulators in Use	3000	12000	150
Date of Installation	1990	1989 / 1990	1990
Performance	Good	Bad	Bad [3]
Physical Changes	Insulator turns gray / white	Insulator turns gray / white with increase in surface roughness	Not available
Mechanical Failures	None	Puncturing	None
Recommendation	CE insulators recommended	Pin-type CE insulators are not recommended [1]	Post-type insulators not recommended for marine or industrial pollution areas

Table 5.38: Responses to the Independent Utility Questionnaire

[1] A significantly high number of the pin-type insulators failed due to puncturing
[2] Data not available
[3] The time until first failure was 3 months.

The results from the questionnaire are most illuminating regarding the application of CE insulation in respect of marine pollution conditions, and the difference between the experiences of Utilities 1 and 2. These two utilities fall in the same geographic and climatic region – yet experience different basic pollution types: inland sub-tropical versus coastal sub-tropical (respectively) – thus indicating the effects of coastal pollution on the performance of CE insulators.

Conclusion

- New and field-aged CE samples were obtained from the manufacturers and utilities, respectively – and were subjected to a battery of tests discussed in Chapter 4. Direct comparisons between field-aged and new (reference) CE insulation was made using the following test techniques:
1. AC dry versus the AC wet flashover voltage test
2. Lightning impulse withstand tests
3. Clean fog tests
4. Salt fog tests
5. SDD tests to determine the 'pollution-friendliness' of new and aged CE surfaces.
6. Atomic Force Microscopy of the sample surfaces (reference and field-aged) in order to determine the surface roughness and surface areas because of aging mechanisms.

- The salt fog test was also utilized to provide information as to the relative performance of identical CE and porcelain insulators under salt fog conditions (glass discs were included in the evaluation in order to provide the reader with a reference insulation type).
- Additional material studies were performed on both new and field-aged samples – in order to determine the reaction of the samples to suspected and well-known aging mechanisms, and to attempt to correlate the rates of reaction to the physical constitution of the samples:

1. IEC 1109 One Hundred Hour Voltage Test where the withstand strength of immersed CE samples was monitored, including the recording of material changes.
2. Mould release tests to determine the effect of the mould release agent on the performance of new CE insulators with respect to salt fog tests.
3. Material identification studies to determine the resin systems in use by manufacturers, including the mould release layer (for correlation with the mould release test)
4. Hydrophobicity changes due to the effects of UV radiation and condensation.
5. Scanning Electron Microscopy of fillers in order to determine the geometry and size distribution.
6. Energy Dispersive X-Ray analysis of the fillers in order to determine purity and quality.
7. Water immersion tests to determine the susceptibility of various samples to hydrolysis and temperature.

- A utility questionnaire was evaluated to determine the feelings and experiences of independent users of CE insulation from differing regions and climates.

The results were recorded, tabulated and graphically displayed in a concise, yet in-depth manner, and were partially discussed with reference to further discussion in Chapter 6: Discussion of Results.

References

1. EMC, **"EMC Insulators, Electrical Moulded Components (PTY) LTD"**, Product Brochure.
2. Isobe, S. et al., **"Large Capacity Class-H Resin Molded Transformer"**, IEEE Transactions on Electrical Insulation, Vol. EI-13, No. 6, December 1978, pp. 436 – 443.
3. IEC International Standard, IEC 507, **"Artificial Pollution Tests on High-Voltage Insulators to be Used on AC Systems"**, 1991-04.

CHAPTER 6

DISCUSSION OF RESULTS

Chapter 4 served as the test philosophy and methodology employed to obtain the results documented in Chapter 5.

The aim of Chapter 6 is to illustrate and expand on Chapter 5 (Results) in a logical and chronological order, ultimately leading up to Chapter 7 (Hypothesis for the Aging of CE Insulation).

6.1 The AC Wet and Dry Flashover Voltage Comparison

6.1.1 The Dry AC Flashover Test and Lightning Impulse (LI) Withstand Test

By referring to Chapter 5 (Results) it can be seen that there is no difference in AC dry flashover and lightning impulse withstand voltages between reference (new) and field-aged insulators. This is possibly because of the following reasons:

- The insulators have not deteriorated to such an extent that they cannot support AC or lightning impulse voltages under dry conditions. The dry AC and lightning impulse tests provide vital clues as to the quality of the unexposed dielectric. If the bulk CE dielectric contained weaknesses, trees or voids then failure could have occurred during these tests. None of the CE insulators, new or field-aged could be induced to fail during these tests.

- The field-aged insulator surface was devoid of electrically conductive pollution or CE debris (as a result of aging) and therefore surface contaminants did not interfere with the distribution of the applied AC or LI potential.

- The field-aged insulator surface was not characterized by electrical tracking (electrical tracking is similar to erosion of the insulator surface, but with an electrically conducting path due to carbon deposits etc.). Electrical tracking could assist in the redistribution of the applied AC and LI potential and thus initiate premature flashover and failure of the insulator during the dry tests.

These tests induce the breakdown of the air surrounding the insulator, and as such are somewhat independent of the insulator material – unless the defects as noted are of sufficient magnitude to influence the breakdown path or mechanism.

6.1.2 The Wet AC Flashover Test

The wet AC flashover tests were performed on the reference (new) and field-aged insulators, and the results were compared to the dry AC flashover tests in order to provide an indication as to the profile and dimensioning (Appendix B) of the insulators. In all cases regarding the reference insulators, the AC wet flashover voltage is significantly lower than the dry AC flashover voltage (Table 6.1):

Serial	AC Dry Flashover Voltage kV	AC Wet Flashover Voltage kV	% Reduction (AC wet / AC dry)
Reference 19H	87.7	75.8	13.6
Reference 21H	97.0	80.0	17.5
Reference 27S	98.4	78.5	20.2

Table 6.1: Comparisons between wet and dry AC flashover voltages for the reference insulators

The field-aged insulators were subjected to identical wet AC conditions and the wet AC flashover voltages were compared to the wet AC flashover voltages of the reference insulators (Table 6.2):

Serial	Reference AC Wet Flashover Voltage kV	Field-aged AC Wet Flashover Voltage kV	% Reduction (AC wet field-aged / AC wet reference)
Donor A (27S)	78.5	66.2	15.7
Donor B (19H)	75.8	67.7	10.7
Donor C (21H)	80.0	70.6	11.8
Donor D (21H)	80.0	70.7	11.6

Table 6.2: Comparison between reference and field-aged AC wet flashover voltages

The results obtained in Table 6.2 indicate that degradation of the insulator surface plays a significant role in the ability of the CE insulator to withstand AC under wet conditions, with all aged insulators (regardless of climate, pollution type or age) indicating a loss of wet AC flashover voltage. This finding is in stark contrast to the findings of other researchers who claim that the modification of CE insulator surfaces has no effect on the 50 Hz AC strength under wet conditions. [1,2]

To gain insight into the reasons for the decrease in the AC withstand capabilities under wet conditions, one must observe the behavior of water flow over the surfaces of the insulators under test (Figures 6.1, 6.2, 6.3 and 6.4). [3]

By observing the water flow patterns in Figures 6.1 and 6.2, the reason for the decrease in AC dry and wet flashover potential between reference and field-aged insulators is clear. The water flowing over the insulator surface during the AC wet test bridges a considerable portion of both the nominal creepage distance and the dry connecting length of the insulator (indicated by the red lines). This has the effect of short-circuiting the insulator thus reducing its capabilities to withstand AC voltages.
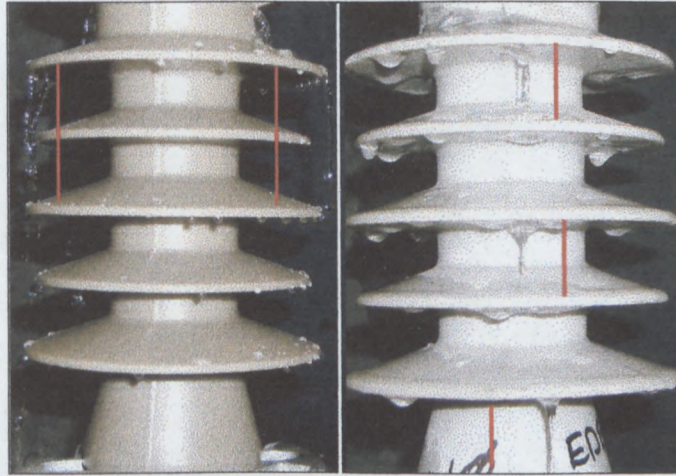
Figure 6.1 Water flow characteristic for a Reference and Field-aged insulator (horizontal configuration)

The degree of hydrophobicity, or water repellency, has a measurable and visible effect on the wet AC test.
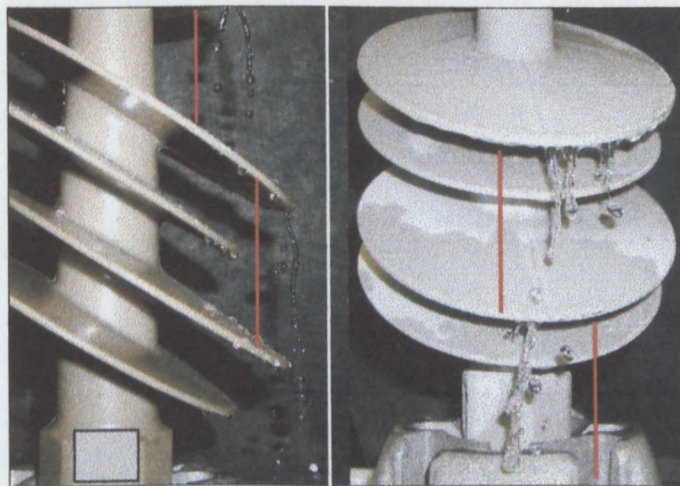

Figure 6.2 Water flow characteristic for a Reference and Field-aged insulator (slanted configuration)

By observing the nature of the run-off on the field-aged insulator in Figures 6.1 and 6.2, the following can be deduced relative to the reference insulator:

- the amount of run-off stored on the field-aged insulator surface is of greater volume: thus sustaining flow over the insulator rim for longer periods of time and reducing the surface conductivity of the insulator (due to the increased volume)
- the hydrophobic surfaces are characterized by a run-off that is composed of many individual droplets that possess a high kinetic energy in relation to the run-off on field-aged units, where the run-off is in the form of a substantial rivulet with a languid viscous appearance.

The Slanted Shed Insulator

The slanted shed insulator revealed further factors possibly resulting in the reduction in the ability of field-aged insulators to withstand AC under wet conditions:

- The role of geometry – the channeling of all the run-off into a specific direction and path (Figure 6.3).
- The effect of surface tension in conjunction with a dynamic fluid possessing kinetic energy (Figure 6.4).
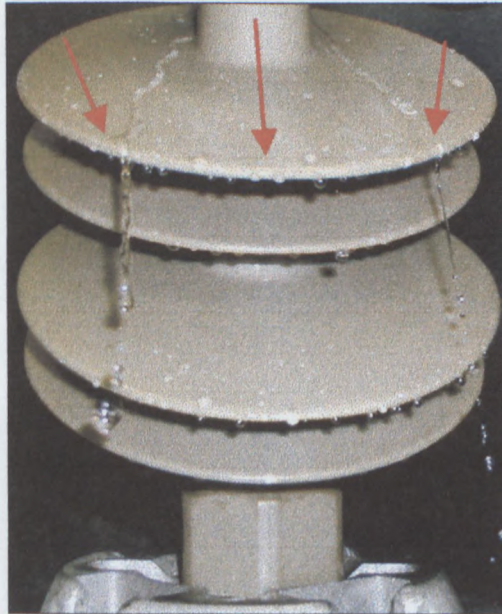

Figure 6.3: The channeling effect of the slanted shed profile (in red).

By incorporating a slanted (approximately 30^0) shed profile into the insulator design, the designer forces all the run-off resulting from condensation into one direction (the flow over the insulator surface, in this case, is governed by the force of gravity). The rationale behind the design principle is to promote self-cleansing of the insulator shed area by incorporating the slant and allowing the supposed pollutants to be transported rapidly from the surface under condensation conditions.[4]

The incorporation of the slant into insulator design indeed proves to be a wise decision in respect of pollution accretion (see Chapter 6.2: SDD Tests), however, the design has its drawbacks.

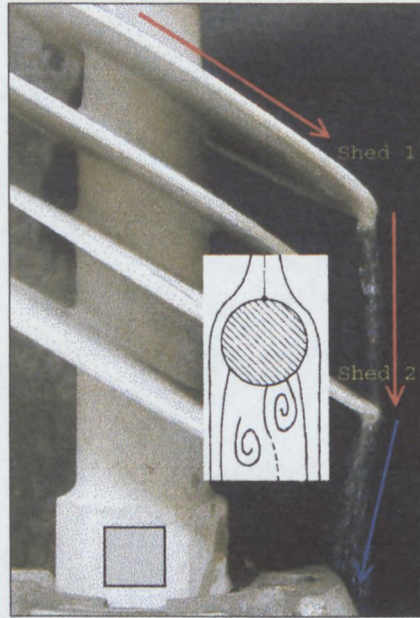By observing the phenomena in Figure 6.4:

Figure 6.4: The effect of surface tension in conjunction with a dynamic fluid

The curvature of the fluid that is evident on the second shed in Figure 6.4 is because of the combined effects of surface tension and the behavior of a fluid under dynamic conditions.[5, 6] The paths denoted by the red arrows indicate the areas where the fluid gains kinetic energy, specifically once the fluid has left the surface of shed 1 and falls towards shed 2. There are water droplets hanging beneath the rims of both sheds 1 and 2 that are in place because of the surface tension between the water and the CE insulator surface. The water droplet on shed 1 causes the fluid to slightly curl (due to the relatively low kinetic energy of the fluid at this point) under the shed and drop directly onto the surface of shed 2. If there were no surface tension effect and no droplet to influence the flow of the water, the run-off would not fall onto shed 2 (Figure 6.2: new).

As the fluid falls along the path denoted by the red arrow, it gains kinetic energy. The added kinetic energy, in conjunction with the droplet hanging below shed 2 (surface tension), causes the fluid to deviate from its path and significantly undercut shed 2.

The phenomenon can be compared to the effects of water flowing over weirs – and boundary layer separation (Figures 6.5).[6]
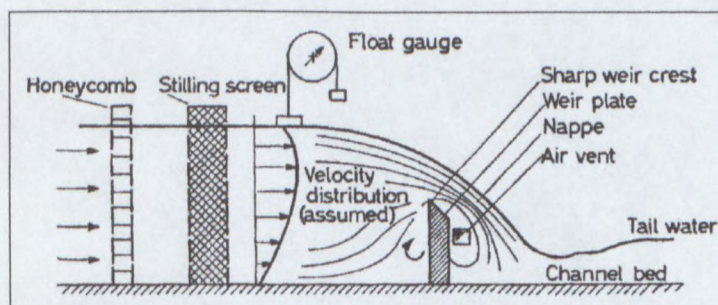

Figure 6.5: Water flowing over a sharp crested weir [6]

The fluid flowing over the weir plate exhibits a similar behavior (after the weir plate) to the phenomenon observed in Figure 6.4 – the turbulent curling of the fluid back towards the obstruction causing the turbulence.

This phenomenon could result in the short-circuiting of the insulator creepage if the run-off is allowed to curve back, and can be exaggerated with the assistance of wind. The effect would be worse if the insulator could physically store more water on it's surfaces, thus resulting in the increased kinetic energy of the run-off and this therefore has repercussions for insulators having the following characteristics:

- Multiple sheds stacked vertically allowing for increased condensation 'catch' (specifically rain) and increased run-off over the insulator

- Polluted or aged sheds that result in a larger volume of trapped condensation

This phenomenon is of specific importance to insulation employed in areas of rainfall similar to the RSA – where rain is often torrential and large volumes fall within short periods of time. The higher the density of the rain (mm/minute), the greater the volume of water that the insulator must channel from its surfaces.

6.2 Surface Changes due to Aging

6.2.1 The Mould Release Agent

The mould release tests serve as evidence to the resilience of the mould release agent – under artificial pollution contamination conditions. The mould release agent is a "low viscosity, solvent-containing silicone oil" that is applied to the APG moulds to assist with the demolding of the cast objects. [7]

The mould release agent provides the following characteristics to insulation employed in respect of polluted conditions:

- A highly hydrophobic surface to water and water-based pollution (Figure 6.5).

- A similar salt deposit density (SDD) compared to field-aged insulation due to the droplet-volume effect (Figure 6.6). The droplet-volume effect is the high volume of pollution contained within the many droplets that are formed on the hydrophobic CE surface. The SDD is however contained in isolated islands of pollution that are not electrically connected, and therefore not permitting the formation of electrically conductive paths over the surface of the insulator.

- A buffer to UV radiation, thus preventing aging of the CE surface due to the effects of UV radiation (see Chapter 6.2.2). [8]
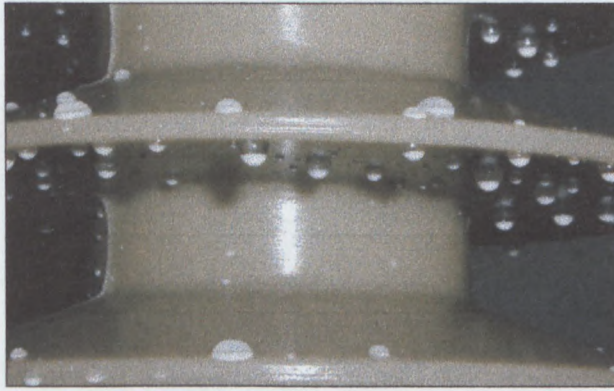
Figure 6.6: The droplet-volume effect – SDD pre-contamination on a hydrophobic surface

These characteristics combine to form an insulator that performs optimistically within the initial period of field application, until the mould release agent has been degraded to such a degree as to not afford any further protection to the actual CE surface that it effectively covers.

The mould release test ultimately results in the degradation of the mould release agent and its hydrophobic qualities. The manner in which the mould release agent degrades is not beneficial to the newly exposed CE insulator surface as the degradation is in the form of narrow channels characterized by a loss of hydrophobicity. The narrow channels of reduced hydrophobicity allow continuous pollution layers to form, thus permitting electrical current to flow over an initially small surface area.

This results in the accelerated aging of the newly formed current path, directly in contact with the CE insulator surface, because of the high leakage current density and resultant concentrated energy loss that manifests itself in immediate dry-band formation (Figure 6.7). Figure 6.7 is the first recorded peak leakage current oscillogram for a 27 mm/kV slanted shed reference insulator exposed to a very light salt fog of 10 mS/cm. It is interesting to note that the insulator immediately proceeded to form a dry band under such light artificial pollution conditions.
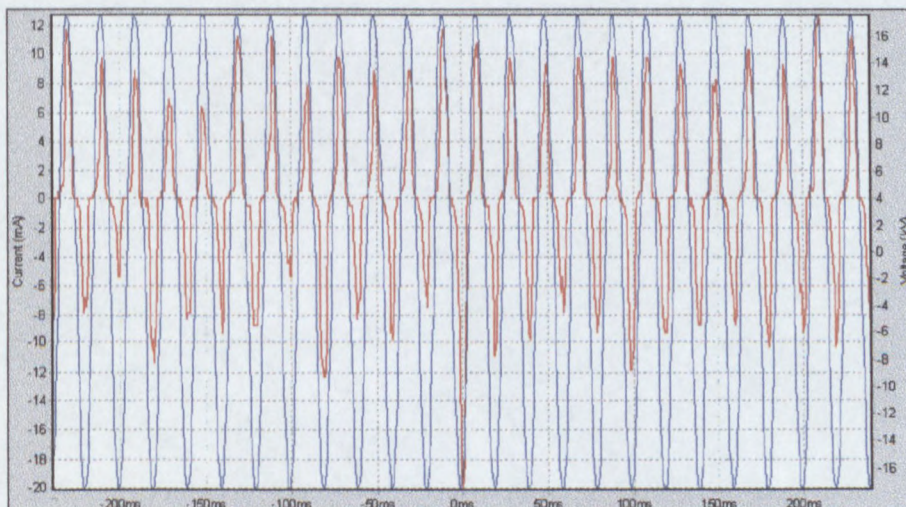

Figure 6.7: First peak current record on reference insulator during mould release test indicating immediate dry-band current profile (10 mS/cm test on 27 mm/kV insulator).

Gorur found that the leakage current and leakage current induced dry band activity is the primary cause for aging and aging related mechanisms in polymeric insulation.[9] The current waveform (red trace) in Figure 6.7 is characteristic of dry band activity as it distinctly indicates a non-linear characteristic typical of such activity, thus the insulator immediately started aging once leakage current conduction begun. By observing the negative peak current value at 0 ms on the x-axis, one can observe the following:

- the current does not increase linearly with the increase in voltage magnitude and appears to have a definite inception voltage.
- The current does not decrease linearly with a decrease in voltage magnitude and displays an extinction voltage.
- The positive and negative current magnitudes are not equal in magnitude – indicating a dynamic insulator surface condition (changing pollution volume conductivity).

The current that is permitted to flow over the surface of an energized and polluted insulator is governed by the resistance of the pollution layer, including any dry band areas in series with the conductive pollution layer. The non-linearity of the current is related to the inception and extinction voltages required to 'fire' and sustain conduction in the dry band, causing a local disruptive discharge in the dry band zone (the energy liberated by the dry band discharge process is responsible for the concentrated aging of the polymer, typical of dry band zones).

The mould release layer can be seen as being similar in form and function to a grease layer (typically applied to insulation in respect of extreme pollution conditions). Mähönen advises against the use of grease layers on CE insulation as it has been found that the high leakage currents that could flow through the degraded grease layer impacts the CE insulator surface negatively. [1]

6.2.2 Surface Roughening and the Surface Area Index (SAI)

Surface roughness measurements have been used to indicate the progression of aging of polymer surfaces in the past. It is, however, important to look closely at how an aged surface is, or should be defined. In the following section a new concept, the Surface Area Index is proposed to describe the surface condition.

The evolution of the Surface Area Index evaluation technique for hydrodynamic surfaces – a hypothesis

In electrical engineering and specifically studies involving electrical insulation, the surface roughness measurement is a dimensionless and inappropriate measure of the condition of a surface. The surface roughness measurement is a single dimension entity and does not indicate the dimensions/size or location of the rough area within the sample surface.

The measure of an insulation surface should be defined as the ability of the surface to repel or inhibit the accretion of conductive substances or matter to it. Most insulation

surfaces, no matter how closely approaching the ideal, allow some conductive matter to attach to their surfaces. If the conductive matter is continuous between the electrodes encompassing the insulation, then during the application of voltage the insulation will register pollution related leakage currents through the conductive medium. The leakage currents, upon reaching significant magnitudes, could therefore result in the failure of the insulation to perform its duties in respect of polluted conditions.

The surface roughness measurement provides little information as to the amount of conductive matter that could adhere to a polymer surface, however, it is a quantative measure of the expected ease that conductive matter will experience in being trapped by a surface.

Surface roughness measurements are prone to errors in interpretation. Figure 6.8 presents exactly identical surface roughness measurements, yet clearly present different surface areas.
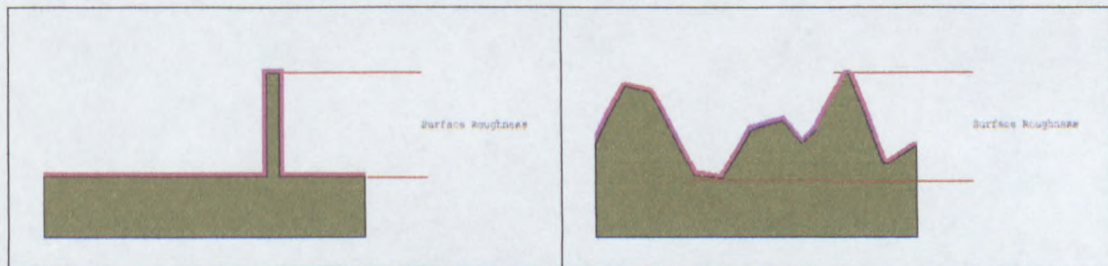

Figure 6.8: Surface area versus surface roughness (surface roughness kept constant)

The surface area measurement is defined by the topology of the sample, and is a function of the lateral sample dimensions and height profile (roughness). The purple layer closely following the surfaces of the shapes (Figure 6.8) represents the areas of possible conductive matter accretion, and is thus linked to the surface area of the sample. Thus, the larger the surface area of a sample, the more conductive matter is theoretically able to collect on the sample surface – assuming that the surface area is available for conductive matter accretion.

The use of a pollution index providing an equivalent salt deposit density is well known and has been in use for some time (IEC 507 and 815). Since the surface roughness and the surface area are a measure of a common entity, the surface condition of a sample, they are related. However, methods of correlating the surface roughness with the surface area were not available for application to polymeric insulator surfaces. Since the invention of the AFM, highly accurate measurements of sample surfaces have been possible. Figure 6.9 shows a typical AFM scan of a representative CE sample surface.
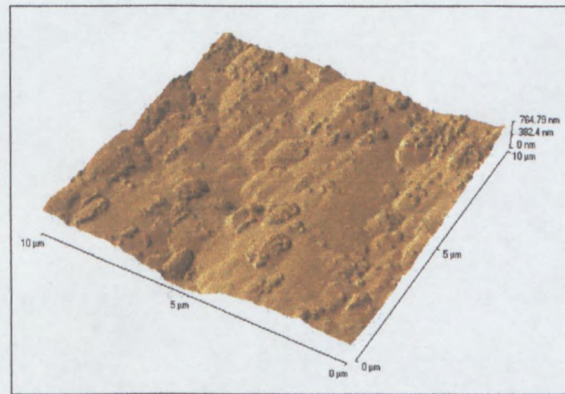
Figure 6.9: AFM scan of a CE sample surface

Included in Figure 6.9 are the following parameters:

- The absolute surface roughness (764.79 nm)
- The median surface roughness (382.4 nm)
- The linear dimensions of the actual scan area as selected by the user (10x10 μm)

The AFM software can provide additional parameters based on the actual database of surface measurements recorded during typical scanning. The parameter of interest is the 'Projected Surface Area' that is calculated from the Cartesian (x,y and z) coordinate record of the sample. Since the user based the original AFM scan on a user selected scan area (e.g. 10x10 μm), a SAI can be calculated by performing the following operation:

SAI = [Projected Surface Area] / [User Selected Scan Surface Area]

By evaluating the SAI for samples subjected to aging mechanisms, deductions can be made as to the effect of the mechanisms on the sample over predetermined time periods.

Figure 6.10 is a hypothetical example of a sample that presents an increasing SAI with exposure to aging mechanisms.

- Area1 is the 'user selected scan surface area'
- Area 2 is the 'projected surface area' after a certain time of aging
- Area 3 is the 'projected surface area' after further aging
- The arrows represent the effective 'growth' in the x and y co-ordinates required to increase the SAI with aging. Even though the 'user selected scan surface area' remains constant, the 'projected scan area' increases as the topology of the sample experiences change. If one were to flatten the surface topology contained within the 'user selected scan area' after the initial aging period (assuming uniform aging) – then 'Area 1' would be the area covered by the topology.
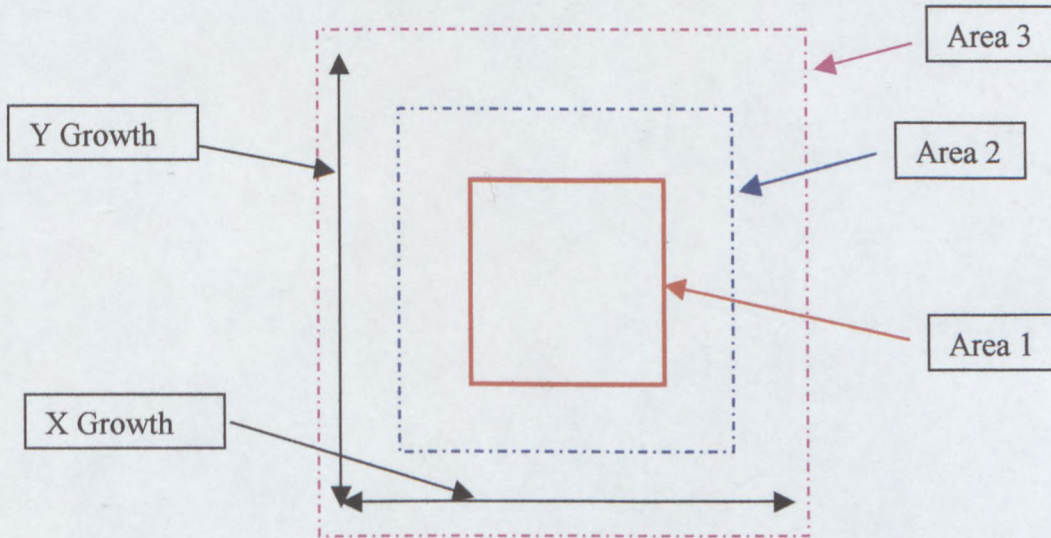
Figure 6.10: The growth of the surface area (increasing SAI) over the user-selected-scan-area

What is immediately apparent is that the projected surface area increases in size as aging progresses. However, the 'projected surface area' is still contained within the 'user selected scan surface area' that remains unchanged in size – since it is a clearly defined location on the sample.

In other words, due to the increase in the sample surface roughness as a result of aging, the effective area contained within the 'user selected scan area' is growing at a rate related to the rate of aging of the polymer sample surface – and is thus related to the SAI.

Since the insulator surface area increases as a result of aging, the following applies:

- As the insulator ages, more of the vulnerable polymeric surface is exposed to the harmful effects of UV radiation, condensation, leakage current activity, ozone etc. - thus resulting in the aging of increasing surface areas as time progresses.
- Assuming uniform aging over the sample surface, the nominal creepage distance of the insulator increases with the square-root of the SAI ($\sqrt{SAI}$) for a given surface area (Figure 6.10). This implies that a sample surface permits more conductive matter to attach to its surface, to the detriment of the nominal creepage length.

Surface Roughening and the Surface Area Index (SAI) of CE Samples

Surface roughening is the result of the exposure of insulators to the environmental and electrical mechanisms typically encountered during their application in utility networks. An attempt was made to simulate the effect of UV radiation and condensation on CE samples.

CE samples were exposed to ultra-violet (UV 313) light and condensation (11 hours dry UV, 1 hour condensation) inside the QUV device and monitored at 500-hour intervals for surface roughness and SAI. The tests for the SAI and surface roughness revealed a rather disturbing result – the longer the CE samples were subjected to artificial aging within the QUV device, the smoother their surfaces became (Figure 5.23). This is in agreement with work done by Ollier-Dereault and Gosse on anhydride cured resins aged by UV, and is in direct contrast to work done by Peyer.[10, 11]

When comparing the SAI to the surface roughness measurements:

- It is clear that the SAI indicates that the aging (reduction in SAI) is accelerated within the first 1000 hours, followed by a plateau region of reduced area increase in the 1000-2000 hour region (Figure 6.11).

- By observing Figure 5.23 it can be seen that the surface roughness is decreasing in a pseudo-linear fashion over the test interval of 2000 hours.
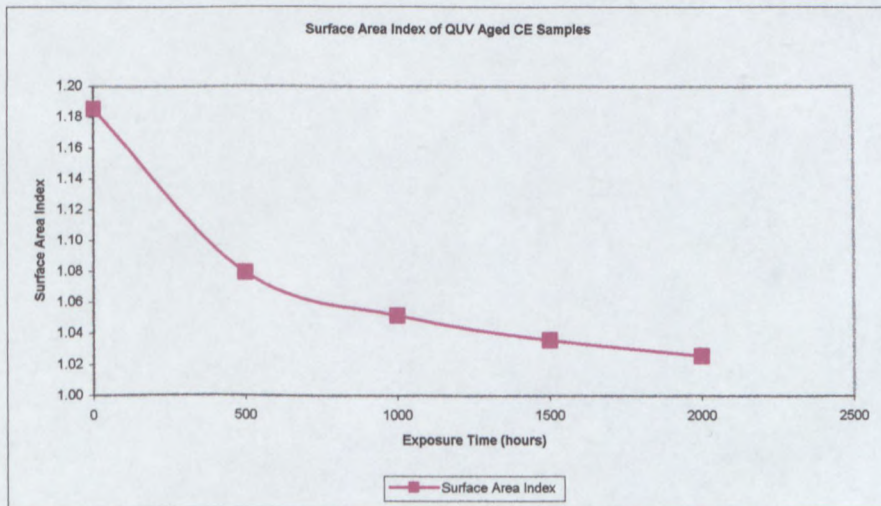
Figure 6.11: SAI for QUV aged CE

Both measurement results could be valid if:

- The plot of the change in SAI is providing an accurate account of the CE sample surface - that could become smoother because of the evolution and entrapment of the UV degraded material on the surface due to the inherent roughness of the sample area. The more the rough areas are reduced, the more material must naturally fill the CE sample surface area – if the QUV condensation cycle is not providing adequate mobility to the waste and removing it from the surface (Figures 6.12 and 6.13). The failure to remove the waste would result in the accretion of this waste on the CE sample surface, thus acting as a buffer to further QUV aging of un-aged surfaces – resulting in the reduction in aging rate as recorded by the SAI.
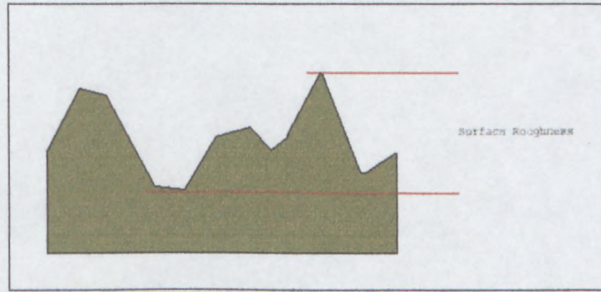
Figure 6.12: CE sample surface roughness before QUV aging

- Similarly, since the surface roughness measurement is an evaluation of the maximum CE sample physical peak structure and the minimum CE sample surface height, it is quite plausible that the aging could proceed in a pseudo-linear fashion as the peaks exposed to the QUV radiation remain so until eliminated. Ultimately, it is possible that if the test were extended indefinitely, that the surface roughness would indicate a reduction in the aging rate, as the rough surface assumes the median height of the CE sample surface - containing the waste products - and thus the physical peak structure begins competing with the median sample surface for QUV radiation exposure.

Figure 6.13: CE sample surface roughness after QUV aging

Although it was found that CE materials become smoother on aging when exposed to laboratory generated QUV radiation (313 nm), Figure 6.14 indicates that field-aged insulators show a definite and unambiguous roughening of their surfaces.

Figure 6.14: SAI for field-aged CE

This raises the following concerns regarding the laboratory aging of CE materials:

- Is laboratory aging a reasonable substitute for field UV-aging?

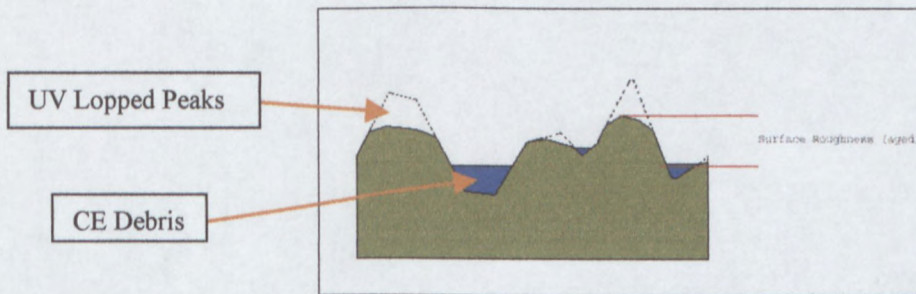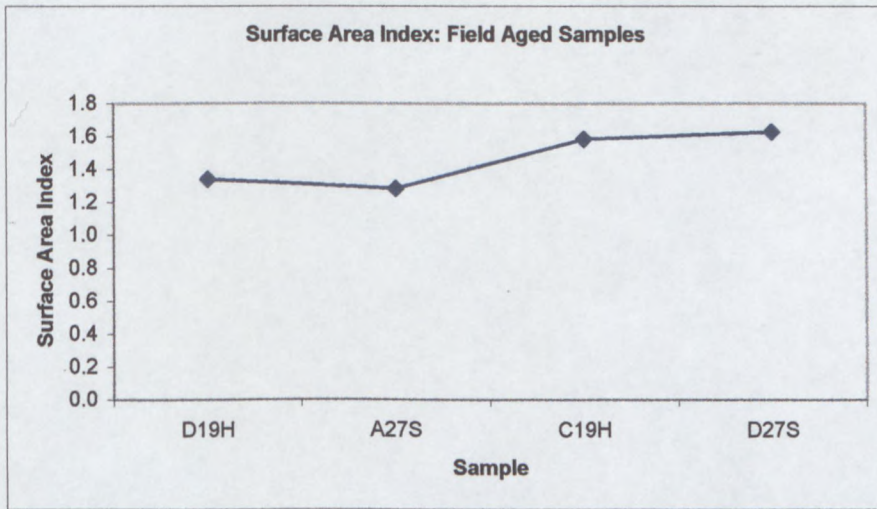- CE materials have a complex aging characteristic – perhaps field-aged CE insulators become smoother before advancing to a rough surface (needs investigation).

- UV aging is not solely responsible for the roughness of field-aged CE insulators – the roughening of the surfaces is due to some other mechanism or is aggravated by the combination of mechanisms (leakage current or chemical attack due to rain and contaminants). QUV aging is however responsible for the reduction in surface hydrophobicity characteristics (Figure 5.16), which is one of the first conditions and steps to produce modified CE insulator surfaces and aging.

The modification of CE insulator surfaces and the loss of hydrophobicity leads to aging of the insulator in respect of polluted conditions. An equivalent mechanism is apparent during the mould release tests on the modified insulators, where the hydrophobic mould release layer has been removed from the insulator surface prior to salt fog testing. The modified insulators immediately form conductive pollution layers that result in the accelerated aging of the insulator surfaces (Figures 5.8, 5.9 and 5.10).

6.2.3 Salt Deposit Density (SDD) Tests

The SDD test was developed in order to determine whether the changes in surface roughness or the SAI are related to the aging of an insulator surface.

SDD tests are a measure of the surface condition of the field-aged insulators. By comparing the measured surface roughness measured on field-aged insulators with the

cumulative distribution of the SDD pre-contamination solution, the following can be stated (by referring to Table 4.3):

- The average roughness measured on field insulators falls in the range: 2.98 < μm < 4.1
- 50% of the pre-contamination solution has a particle size less than 1 μm in diameter
- 84% of the pre-contamination solution has a particle size of between 2 and 10 μm.

Therefore, more than 50% of the particles contained in the pre-contamination solution are available for the SDD test – as their size is of such a nature that they will be accommodated by the rough field-aged surface. This indicates statistically that sufficient material is available through the pre-contamination solution for a sound result.

General SDD results

The results of the SDD tests (Figure 6.15) indicate that the CE insulators, with respect to the tests performed on glass cap and pin disc insulators in IEC 507, provide complex results:
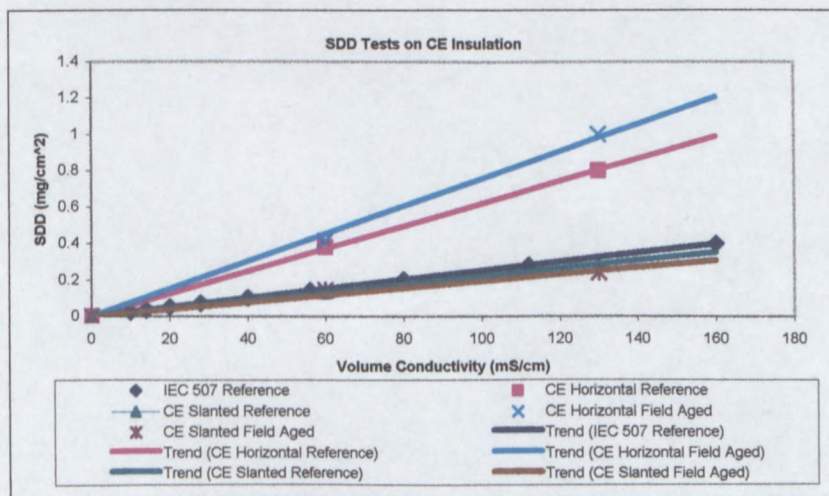
Figure 6.15: SDD Tests on CE insulation

- The hydrophilic field-aged CE insulators register a similar SDD to the equivalent hydrophobic reference insulators – this is due to the volume of pollution trapped within the droplets contained on the hydrophobic surface. The distinction between the aged and reference insulators being that the hydrophobic surface does not allow interconnection and thus conduction between the successive pollution droplets. By contrast, the field-aged insulators registering a similar SDD provide a continuous film of pollution readily accommodating conduction.

- The slanted shed insulators perform marginally better than the IEC 507 glass cap and pin disc insulators – this is due to the superior run-off characteristics of the slanted surface

- The horizontal shed CE insulators perform significantly worse than the IEC 507 glass cap and pin disc insulators

- The tests suggest that the SDD could either improve or worsen with intermediate aging (needs to be investigated) when the insulator experiences the crossover from hydrophobic to hydrophilic surface.

Correlation between the SDD tests and insulator surface conditions

The SDD test, surface roughness and SAI tests should indicate some form correlation as they essentially are a measure of an identical entity – the condition of the surface of the insulator.

Table 6.3 lists the insulators exposed to the SDD tests according to SDD/annum. This is to assist in ranking the insulators according to the SDD value and exposure to aging mechanisms, as the insulators are all of differing ages. This unfortunately assumes that the aging of CE insulators exposed to field conditions is a linear event, when all other data tends to indicate a more complex relationship between exposure time and ultimate aging (Figure 6.11).

Serial Number	Pre-contamination Solution Conductivity mS/cm	SDD mg/cm^2	Age Years	SDD/annum mg/cm^2/year
C-1	60	0.52	6	0.087
C-2	60	0.50	6	0.084
D-3	60	0.43	10	0.043
D-1	60	0.37	10	0.037
B-5	60	0.41	13	0.031
B-3	60	0.39	13	0.030
B-9	60	0.45	15	0.030
B-14	60	0.39	13	0.030
B-8	60	0.43	15	0.029
B-15	60	0.26	13	0.020

Table 6.3: SDD/annum for field-aged horizontal shed insulators

By observing the data in Table 6.3, and ranking the insulators according to SDD/annum, the following points are worth noting:

- The donated insulators arrange themselves according to geographical zone of deployment and age when comparing either the absolute SDD or the SDD/annum.

- Since the insulators are of the horizontal configuration and would thus tend to indicate similar aging characteristics under similar aging conditions – a relative ranking of the geographical region aging severities can therefore be obtained (even though some of the insulators are of different creepage distances, the SDD readings were taking from areas common to all the insulators). It appears that region C has the greatest aging effect on CE insulators, followed by region D and B.

There is an indication of correlation between the SAI and the SDD tests (Table 6.4).

Serial Number	Surface Roughness	Ratio	SAI	Ratio	SDD_{60}	Ratio	SDD_{130}	Ratio
C21H	4065	1.421 (4065/2861)	1.584	1.183 (1.584/1.339)	0.51	1.378 (0.51/0.37)	0.99	1.269 (0.90/0.78)
D21H	2861		1.339		0.37		0.78	
A27S	3210	1.078 (3210/2978)	1.282	0.789	0.12	0.750 (0.12/0.16)	0.22	0.815
D27S	2978		1.625	(1.282/1.625)	0.16		0.27	(0.22/0.27)

Table 6.4: The correlation between SDD's and the SAI

The insulators and data presented in Table 6.4 are identical to the insulators in Table 5.33. In order to determine if there is correlation between the SDD, surface roughness or SAI – the following calculations were performed:

- Ratio of the surface roughness for the horizontal and slanted shed configuration insulators was compared to the ratios of the SAI and SDD's for the same insulators.

- The ratios of the SDD's was chosen to be the criteria for evaluation of the ratios for surface roughness and SAI – as the SDD is ultimately the quantity that determines the performance of the insulator.

By comparing the results in Table 6.4 (values in brackets indicate methods for obtaining ratios):

- One ratio is possibly inaccurate – the ratio between the SDD_{60} of C19H and D21H of 1.378 appears to be high. However, the ratios between the SDD_{130} of the horizontal shed insulators and the SAI correlates.

- The surface roughness and SAI ratios indicate no correlation as the surface roughness and surface area index for the slanted shed insulators in Table 6.4 indicate inverse characteristics (the surface roughness ratio indicates that the insulators become rougher while the SAI indicates the insulators become smoother).

- The ratios between the SDD's and SAI correlate for the slanted shed insulators.

IEC 507 recommends that the deposition of SDD onto insulator surfaces, by pre-contamination methods, should indicate a correlation of 15% with the standard as determined on glass cap and pin insulators – for a solution of known conductivity and the ultimate recorded SDD. This level of tolerance was used to judge the variation in ratios of recorded SDD and SAI:

- The correlation between the horizontal shed insulators is problematic, because of the rim phenomena (Figure 5.26) providing error in reproducibility of the actual test conditions. The tolerance range is: $-7 \leq \%$ tolerance ≤ 16.5.

- The correlation between the SDD and the SAI on the slanted shed insulators falls well within the 15% tolerance of IEC 507: $-4.9 \leq \%$ tolerance ≤ 3.3.

The results indicate that the SDD and SAI are related, and that the surface roughness measurements do not correlate with either. Additionally, glass discs do not indicate any significant surface roughness characteristics – yet are used in the IEC 507 specification to serve as reference for the pre-contamination tests, thus further proving that insulators do not need to provide a rough surface to allow pollution to adhere to them.

Since the leakage current (and changes in the leakage current with time) flowing over the surface of an insulator surface is used as an aging criteria, and the leakage current is related to the conductivity of the pollution layer – the SAI, and changes in the SAI due to aging would therefore provide a more realistic aging index, as the SAI correlates with the amount of pollution measured on CE insulators.

6.3 Water Immersion Tests at 100 ^{0}C

Water diffusion, the spontaneous intermingling of the particles of two or more substances as a result of random thermal motion, always takes place in damp conditions.[1] The moisture can appear in molecular form between the macromolecules of the polymer (non-permanent changes), or cause polymer chain scission (hydrolysis) resulting in permanent damage to the material.

Thus, the water can exist in one of two conditions 1) the water appears freely in the polymer 2) the water appears as a chemical entity and is rigorously bonded and fixed within the structure of the hydroxyl group.[12]

The degree of water sorption in CE samples is related to the physical and chemical qualities unique to the sample. The IEC 1109 voltage test excludes the measurement of the solution sorption rates, yet the sorption rates are included within the context of this work. The sorption rates are affected by many factors, hence can provide information as to the quality of the CE samples.

Samples X,J,P and R were manufactured by the same manufacturer under identical process conditions and using identical resin systems, and are thus expected to provide reasonably similar results (the only variable for the manufacture of the samples being the date of manufacture). Deviations in the results of the IEC 1109 test, and the sorption rates can thus only be attributed to manufacturer process variations. CE

samples display certain characteristic sorption rates, and these are discussed with reference to:

- Electrical qualities (tan delta, relative permittivity and leakage current)
- Effect of filler shape, size and loading

IEC 1109 dictated the CE sample dimensions for the voltage test, and thus for the sorption test. The samples were cut from insulators and were typically 30 mm high, with a diameter of 35 mm. Accurate measurements of the samples allowed their densities to be calculated and correlated with the TGA and changes in the materials due to the sorption of solution into the samples.

The IEC 1109 Voltage Test

The IEC 1109 voltage test specifies that the samples be immersed in the boiling water-salt solution for a period of 100 hours before being exposed to an AC voltage of 12 kV for 1 minute. The successful sample should withstand the applied voltage for the full minute, without disruptive discharge, and simultaneously not allow the conduction of more than 1 mA of leakage current.

All CE samples evaluated using the IEC 1109 voltage test method performed admirably over the 100 hour period, with the highest recorded current being 12.1 μA in magnitude. Furthermore, the rate of increase in leakage current (for the 100 hour period) was characterized by a gradual increasing trend with little to distinguish the various samples, except for Sample X. Sample X begins to indicate signs of distress at the 70 hour mark, where the trend begins to deviate towards higher leakage current levels (Figure 5.4).

It was decided to continue the test for approximately 200 hours (Figure 6.16) in order to note the point where significant changes in the leakage current occur.
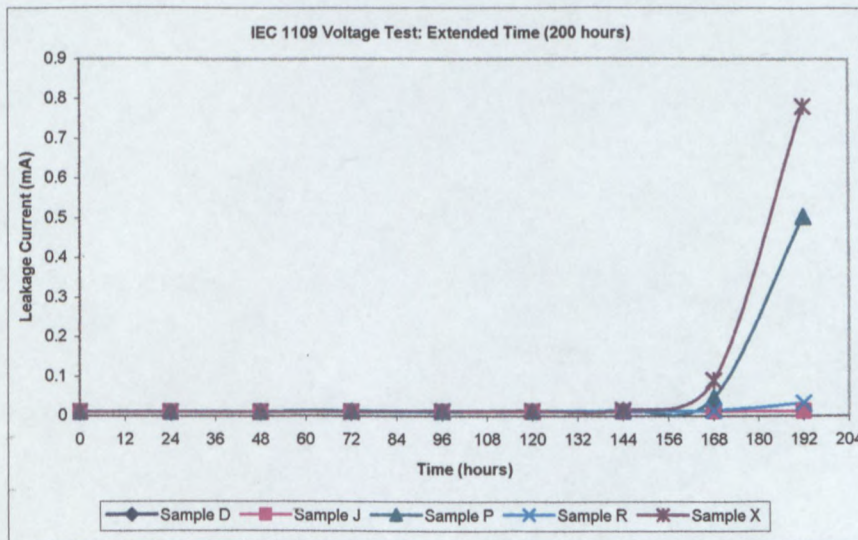

Figure 6.16: Extended IEC 1109 voltage test (200 hours)

Samples X and P reach leakage current knee-point conditions at the 165 hour interval, ultimately attaining leakage currents of 780 and 502 µA respectively. Sample R follows at 168 minutes, yet only attains an ultimate leakage current of 32 µA; followed by Samples D and J attaining 12.9 and 11.8 µA respectively.

For Figure 6.17, the p.u. values are:

- Leakage current: Sample P 1 p.u. = 502 µA
  Sample X 1 p.u. = 780 µA

- Mass increase per unit surface area: Sample P 1 p.u. = 6.355 mg/cm^2
  Sample X 1 p.u. = 6.509 mg/cm^2

- Relative permittivity: Sample P 1 p.u. = 17.93
  Sample X 1 p.u. = 22.52

- % Mass increase: Sample P 1 p.u. = 0.606 %
  Sample X 1 p.u. = 0.638 %
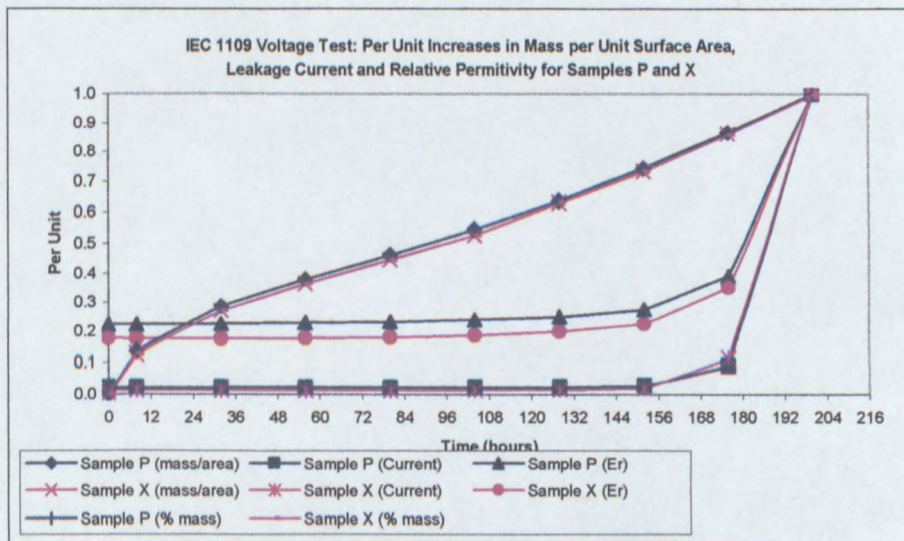
Figure 6.17: IEC 1109 voltage test: per unit increases in mass per unit surface area, leakage current and relative permittivity for Samples P and X

The mass increase per unit surface area due to water diffusion displays a characteristic that can be described as being quasi-Fickian in nature and is in agreement with the findings of Grave.[13]

The Frisch analysis of the Fickian Mechanism for Penetrants in Polymers

Frisch analyzed the Fickian diffusion of penetrants in polymeric materials with regards to the penetrant size, and the availability of free volume within the polymer to accept the penetrant. Fickian diffusion concerning the larger organic molecules is characterized by the following:

- Concentration dependant diffusion coefficients
- Temperature dependent energies of activation

The free volume associated with a polymeric material could be allocated a $F(V,T,c)$ distribution function, denoting the local free volume sizes less than 'V' at a temperature 'T' with a penetrant concentration 'c'.[14] The diffusion process theory is governed by the allocation of volume within the polymer: void and average free volume. If the void volume required for the dispersal of the penetrant is smaller than the average free volume – the diffusion mechanism progresses by filling local unfilled pre-existing voids larger enough to accept the penetrant molecules near the surface of the polymer.

Once these local pre-existing voids have been consumed by the penetrant, the diffusion of penetrant into bordering pre-existing voids proceeds by an activation step – where it is theorized that the activation step involves the co-operative motion of polymer chain segments.[14] The filling of the pre-existing voids continues until all voids are filled with penetrant – and the Fickian nature of diffusion then ceases to exist.

In the case of the IEC 1109 diffusion test, the penetrant is a lightly conductive solution and diffusion into the CE samples results in changes in the electrical properties.

Leakage Current Conduction due to Water Diffusion

In Figure 6.17, the leakage current is due to the conductance of the sample. Since the sample was placed in a very lightly conducting medium (0.1% NaCl water solution) at an elevated temperature, one can conclude the following:

- The increase in conductance is due to the effects of a conducting medium penetrating the sample, thus providing additional charge carriers to those already present and inherent in the material

- The action of hydrolysis at elevated temperature creates new compounds (due to polymer chain scission) that provide charge carriers, thereby effectively increasing the conductance of the sample.

It appears that the increase in the conductance of the sample is related to the amount of freely associated (not bound in rigid hydroxyl groups) conductive solution absorbed, since testing of the samples after superficial and incomplete room temperature desiccation revealed the return of the leakage current to original values. Additionally, this tends to indicate that the surface condition of the sample dictates the performance of the dielectric when evaluated to IEC 1109 parameters. Extensive desiccation in an oven is required to reduce the mass of solution contained within the CE sample bulk dielectric.

Furthermore, by taking mass measurements of the samples after extensive desiccation, it was noted that the samples do not return to their original mass recorded before the water immersion tests (Table 6.5).

Serial Number	Mass before Immersion (grams)	Mass after Immersion And Drying (grams)	% Difference
Sample D	53.7437	53.7919	0.090
Sample X	50.6400	50.7117	0.142
Sample J	52.2642	52.2966	0.062
Sample P	55.1565	55.2360	0.144
Sample R	55.1908	55.2778	0.158

Table 6.5: Mass of CE samples after water immersion tests and subsequent drying at elevated temperature

The resin system employed to create the CE samples dictates the performance of the samples during the diffusion test. The fillers added to cast CE objects affects the actual diffusion or sorption rates of CE samples exposed to moisture, thus requiring that the effect of the filler type, loading and proportions be studied.

The effect of filler shape, size and loading

Logically, the optimum filler shape should be spherical, as the greatest volume is achieved with the smallest surface area (Table 6.6), resulting in:

- Reduced interfacial polarization between the filler and the resin matrix because of the smaller surface area, yet larger volume resulting from the geometry.
- Reduced dipole losses as there is less water incorporated in the bonding between filler and resin matrix.
- Possibility of improved field tailoring within the CE object resulting in improved partial discharge behavior under voltage stresses.

Practically speaking, all filler shapes could be defined as falling in the range between sphere and cube – sphere and square being the defined limits of shapes incorporating all other derivatives (within practical limits).

Filler Morphology	Surface Area square units	Volume cubic units	Ratio Volume / Area
Sphere	$A = 4.\pi.r^2$	$v = 4/3.\pi.r^3$	0.333
Cylinder	$A = 2.\pi.r(r + h)$	$v = \pi/4.d^2.h$	0.250
Cube	$A = 6.r^2$	$v = r^3$	0.167

Table 6.6: Effect of general filler morphology on filler volume and surface area

The effect of filler shape is most significant when it comes to non-uniform filler shapes – a cylinder or square shape consisting of significantly different Cartesian dimensions could result in a shape of low volume, but significant surface area.

Sample	Date of Manufacture of the Sample	TGA % Filler	Filler Supplier	Resin System
Sample D	Not known	64.1	Supplier 1	System 1
Sample X	7 September 1999	61.9	Supplier 2	System A
Sample J	8 February 1999	59.4	Supplier 2	System A
Sample P	17 September 1999	69.0	Supplier 2	System A
Sample R	23 February 1999	69.6	Supplier 2	System A

Table 6.7: CE Sample filler shape, size and loadings

Both filler suppliers provide silane treated silicon oxide, yet Supplier 1 filler is characterized by a larger average particle size when compared to Supplier 2 (Figures 5.17 and 5.18). Samples X,J,P and R consist of identical components – the filler concentration and date of manufacture being the only variables – and are therefore useful to observe the effects of filler concentration on the performance of the samples during the water submersion test (assuming the remaining manufacturing conditions are similar) – in the process theoretically eliminating the physical and chemical characteristics from impacting the test result, due to this commonality/similarity of the resin systems.
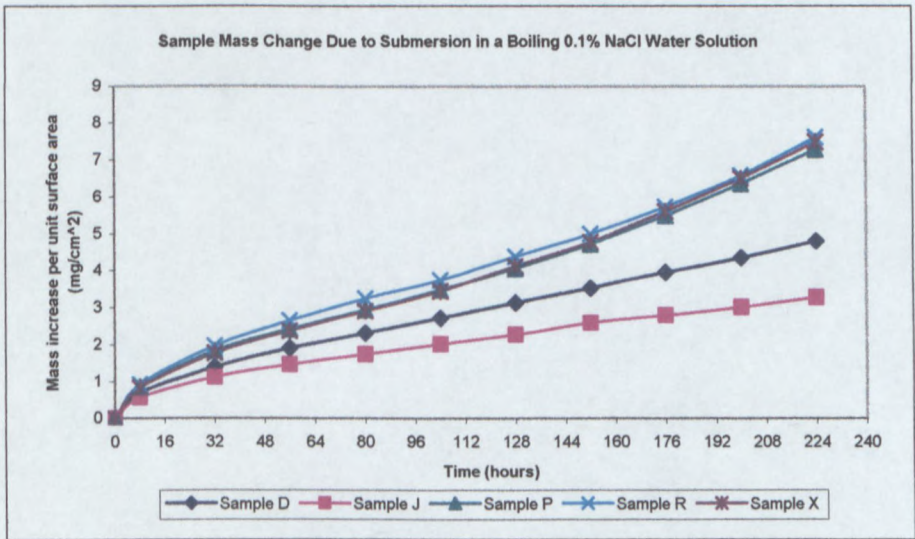
Figure 6.19: Sample mass change due to submersion in boiling 0.1% NaCl water solution

A glance at the quantities in Table 6.7, and the performance of the samples during the water immersion tests (Figure 6.19) immediately raises concern as the TGA and material changes do not correlate. van der Huir, Kramer and Yamanaka claim that variations in the filler (TGA) loadings affects the amount of moisture absorbed – the more filler, the less water absorbed as the filler itself is not able to absorb the water.[15, 16, 17]

This would imply that the degree of water absorption in Samples X,J,P and R (D omitted as it is not of similar resin system to X,J,P and R) should occur as follows,

least to most absorption: Sample R, P, X and J – if the TGA is used as the measure of filler content.

However, if the relative densities of the samples are calculated by accurately determining the mass and dimensions of each sample before submersion, a completely different account of events is revealed since the filler is the denser component of the resin system and determines the densities of the samples (Table 6.8).

The reason for the difference is related to the sampling method, and ultimately the sample size. The TGA analyzer accepts only small samples of the order of mg (10 to 20 mg), while the density calculations were performed on much larger samples (5000 times larger than for the TGA) – thus statistically encompassing a more representative measurement condition.

Simply stated – the TGA provided a highly accurate measurement on an inaccurate sample, while the density calculation provided a less accurate determination of equivalent filler composition on a more representative sample.

Sample	TGA %	Density of Sample g/cm³	Solution After Drying mg/cm²	Solution After Drying %	Solution Uptake mg/cm²	Solution Uptake %
Sample X	61.9	1.890	1.450	0.142	7.50	0.735
Sample J	59.4	1.899	0.641	0.062	3.28	0.317
Sample P	69.0	1.893	1.510	0.144	7.30	0.695
Sample R	69.6	1.884	1.650	0.158	7.63	0.729

Table 6.8: Table of dynamic quantities during water immersion tests, compared to TGA and density of the samples

By analyzing the data in Table 6.8, the following is obtained:

- The solution uptake (diffusion) should be governed by the filler content of the samples – yet the TGA series does not correlate with any data in the table. The TGA dictates a solution uptake sequence of: Sample R, P, X and J (best to worst) – the higher filler content should indicate reduced diffusion.

- The solution uptake (mg/cm²) correlates with the sample densities, which is a more representative indication of the filler loadings than the TGA. The sample densities dictate a sequence of: Sample J, P, X and R (best to worst).

- The remaining solution, after drying volume and surface characteristics (% and mg/cm²) correspond with one another, yet indicate no correlation with either the sample TGA or the densities.

- The solution uptake, volume and surface characteristic (% and mg/cm²), do not correlate with one another. Since the surface characteristic correlates with the filler loading as determined by the sample density – it appears the criteria to monitor for CE sample solution or penetrant sorption is the increase in mass per unit surface area.

The degrees of mass increase (surface characteristic) do not correlate with the TGA filler loadings of the samples, yet do correlate with the densities. An indication as to the degree of hydrolysis (within the limits of the experimental technique) can be extrapolated by observing the %mass difference of the samples after desiccation. The desiccation removes the less rigidly bound H_2O from the samples, but the rigidly bound hydroxyl groups remain, resulting in the recorded mass difference (Figure 5.14).

The determination of the degree of hydrolysis is an interesting approach to the mass measurement protocol typically employed during the water diffusion tests – and typically shows how much water is loosely associated within the sample (this is the component that evaporates on heating in a dry atmosphere) and the chemically bound water contained in the hydroxyl groups (this is the residual mass that cannot be reduced by sub-boiling point heating in dry atmospheres).

The degree of hydrolysis is an indication of the relative stability of the materials in respect of wet conditions. The sample that indicates the least hydrolysis is most stable and should not register as large deviations in electrical quantities in respect of polluted and moist conditions.

Correlation between CE sample constitution and electrical characteristics

Kramer found that the decrease in the dielectric quality of CE samples is not related to the filler loadings – it is a product of the amount of moisture that is located between the resin / filler interfaces that is providing the losses through interfacial polarization.[15]

The amount of water available for interfacial polarization was, best to worse: Sample J, P, R and X (related to the % water uptake of the samples). Sample R displays an uncanny stability when observing Figure 6.16.

The deviation of Sample R raises some concern – since the manufacturer claims that Samples X, J, P and R are of identical resin systems and manufactured according to specification. If this were so, then Sample X, J, P and R would tend towards providing similar data in response to the test methods employed to evaluate them.

Samples X, P and R take on equivalent quantities of solution during the IEC 1109 water diffusion test, yet display very different electrical manifestations or differences in relative permittivity and leakage current as a result of the diffusion. This would suggest that the difference in electrical quantities is not an absolute reflection of the amount of moisture absorbed.

The following phenomena could bring about the abnormal behavior of Samples X and P, since sample R performs in a relatively stable manner:

- The samples are not of the same resin system – a different resin system might provide a different response to the effects of water submersion

- The samples are based on Resin System A – an amine accelerated system – by incorporating more amine accelerator into the resin system than required by specification results in increased water absorption rates.[13]

- Samples P and X contain a filler with a defective or non-existent silane coating resulting in the increase of water absorption due to the inferior bond between the resin matrix and the filler.[1] Alternatively, Samples P and X contain a filler that has been overdosed with silane, resulting in increased water absorption due to the availability of free hydroxyl groups.[15]

- Samples P and X are less annealed than the other samples, and this results in increased water absorption.[18]

- Samples P and X contain too much hardener and the water absorption is due to the hydrolysis of the hardener.[13, 16]

6.4 Artificial Pollution Tests

The first pollution test was developed in Britain in 1936 and was referred to as natural pollution testing.[19] In 1964, Ely produced a publication documenting the development of the salt fog test, and in 1987 Lambeth completed the final validation of the clean fog test for adoption as a standard test.[20]

There is a fair degree of controversy surrounding the applicability, repeatability and reproducibility of artificial pollution tests, especially when trying to equate an artificial pollution environment to actual environmental conditions. A justified question is: can the scientist equate an artificial pollution test environment to naturally occurring conditions? At best some form of correlation between the performance of insulation can be obtained when exposed to natural or artificial pollution environments of precisely identified conditions.

However, artificial pollution tests can provide helpful insight into the behavior of insulators in respect of polluted conditions – and if test conditions are reproducible, they can provide a relative ranking of insulation and insulation types. Additionally, they provide the researcher with rapid results as the tests tend to be measured in hours (typically 2-3 hours), rather than months or years if natural methods are utilized.

To quote Ely: "the performance of insulators can be assessed by natural pollution tests, which are imprecise but realistic, and by artificial tests, which are much more precise but less realistic".[21]

Artificial pollution tests, in general, are performed using conductive pollution layers, which necessitates the use of water to form the electrolyte. The use of water during the artificial pollution tests must therefore to some extent cause minor diffusion and therefore hydrolysis in the external and wettable polymer surfaces. This fact should be borne in mind when conducting multiple and consecutive artificial pollution tests on polymeric insulators, even if the effect of hydrolysis is found to be minimal.

Comparison between Porcelain and CE Insulators under Salt Fog Conditions – a hypothesis

Porcelain and CE insulators of identical dimensions and profile were compared in the salt fog chamber under identical fog and energization conditions – the porcelain insulator registered a significantly superior (lower magnitude) peak leakage current performance for the various salt fog salinities (Figures 5.3 and 6.20).
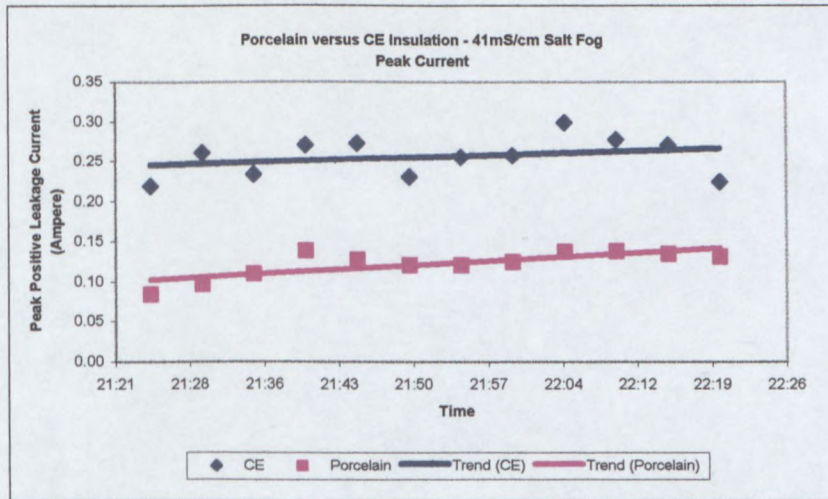

Figure 6.20: Leakage current on porcelain and CE insulators during 41 mS/cm salt fog

The power dissipated over the insulator surfaces indicates that the CE insulator moves from a condition of high power loss to condition of low power loss as the test progresses. This is due to the formation of substantial dry-bands, because of the initial high power loss (Figure 6.21) on the surface resulting in the drying of the conductive volume deposited during the salt fog test.

The formation of dry-bands leads to unstable peak leakage current conditions (Figure 6.20) that could result in the chance premature failure of the insulator to withstand the salt fog test – if the following sequence of events occur:

- A dry-band is established on the insulator surface due to the heating of the pollution layer (power loss in the conductive volume) resulting in the drop of the rms leakage current - as the dry-band is a high impedance zone.

- The drop in rms leakage current across the insulator surface results in the total wetting of the insulator surface external to the dry-band zone, resulting in a larger volume of conductive pollution and the resultant increase in insulator surface conductivity.

- Due to the increased wetting of the insulator (due to the established dry-band zone), a droplet of conductive contamination forms on a protruding feature above the dry-band zone and falls (gravity) into the dry-band zone and short-circuits the dry-band condition.

- Alternatively, the random stability and instability of the dry-band could result in the flashover and effective short-circuiting of the dry-band zone, possibly as the result of an electron or particle becoming available to initiate the collapse of the increased and concentrated electrical field separated by the high impedance dry-band.

- Since, prior to the short-circuiting the dry-band zone, the insulator was allowed to wet completely as a function of the dry-band, the short-circuiting of the dry-band results in the formation of very high peak leakage currents (with a possibility of flashover) of short duration until the insulator dries or the dry-band is re-established.

This phenomenon explains the reason for the reduction in the power dissipation over the insulator surface (Figure 6.21), but the increase in the peak leakage current for the same time period (Figure 6.20).
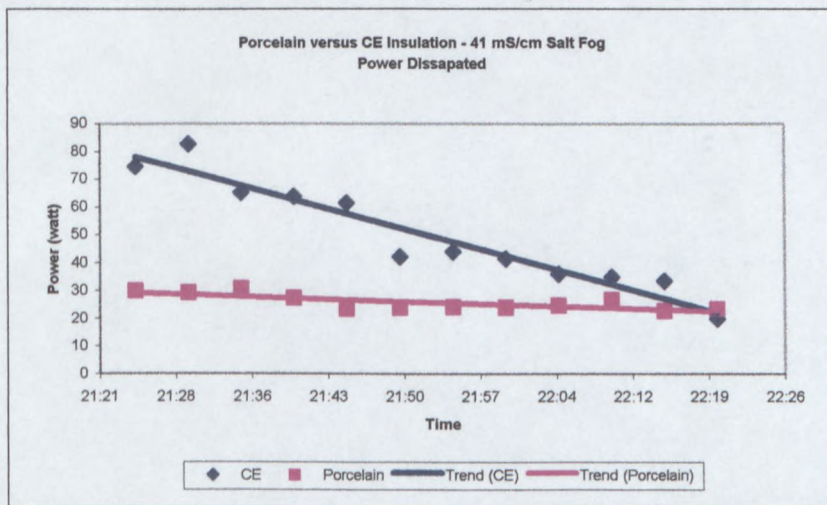
Figure 6.21: Power dissipated over CE and porcelain surfaces during 41 mS/cm salt fog

Fernando claims that material testing of insulators has provided sound evidence that the accumulated charge over the period of testing can be correlated to the degree of aging of polymeric insulators.[22]

Figure 6.22 unambiguously indicates that the CE insulator experiences the greatest amount of accumulated charge during the one-hour salt fog test. Since the other insulator evaluated is porcelain, one can assume that the only aging that took place in this specific salt fog test was the CE insulator surface, as porcelain does not indicate aging under low leakage current conditions.

The leakage current, accumulated charge and power dissipated over the insulator surface has further impact on the utility network:

- The power lost over insulator surfaces in respect of polluted conditions is represented as an additional load on the generation, transmission, distribution and reticulation equipment

- Dry-band activity is characterized by non-linear impedances over the insulators surfaces, and as such, heavy dry-band activity would result in the injection of current harmonics (and voltage harmonics, depending on the complex impedance of the supply network) into the utility supply networks.
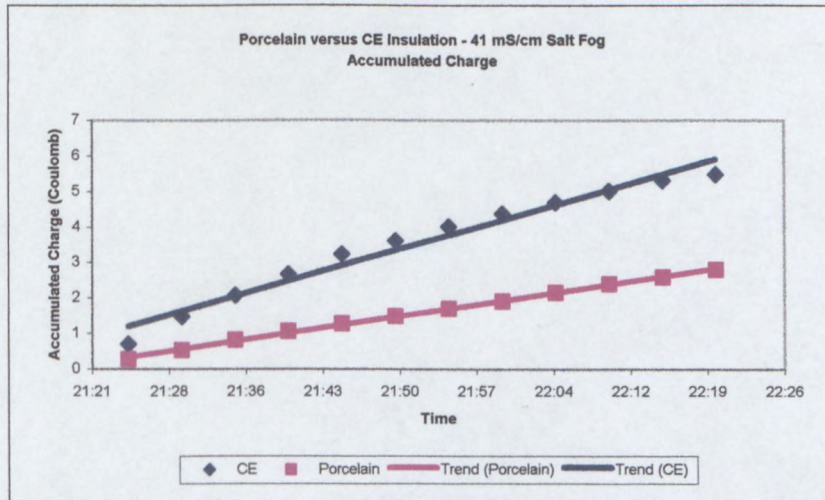
Figure 6.22: Accumulated charge on CE and porcelain insulators during 41 mS/cm salt fog

Gorur claims that when testing CE, Silicone Rubber and Ethylene-propylene Rubber insulator samples under salt fog - the leakage current pulses bear some relation to the degree of aging of the materials.[23]

Figure 6.23 indicates the distribution of leakage current pulses for the identical porcelain and CE insulators:

- The CE insulator demonstrates a significant majority over the porcelain unit when it comes to the number of leakage current pulses over the one-hour test period - at all current levels.

- The CE insulator is the only unit to experience current pulses of the magnitude $200 < I\ mA < 299$
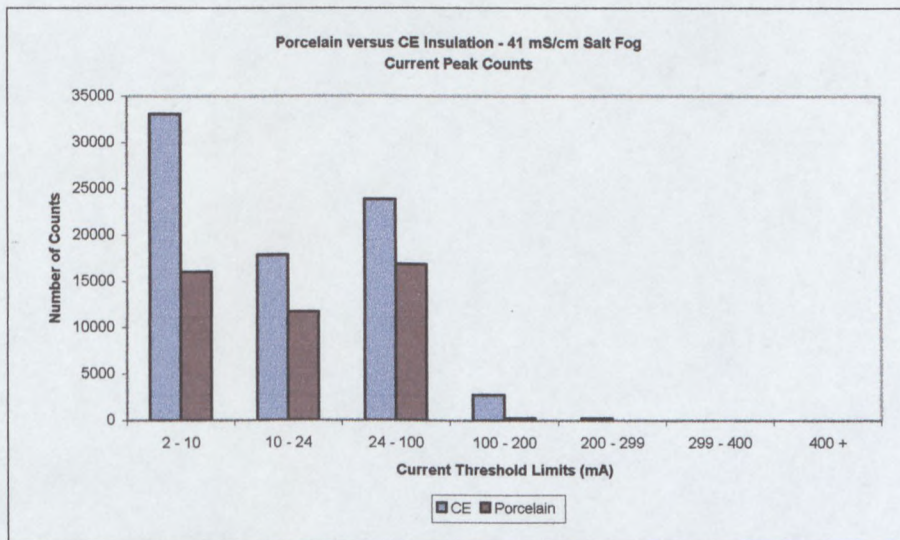
Figure 6.23: Current peak counts on CE and porcelain insulators during 41 mS/cm salt fog

Clean Fog Tests

Clean fog tests were performed on field-aged CE insulators and the peak leakage currents were recorded. Additional SDD measurements were made of the pollution contamination, to assist with providing some form of correlation between the artificial test and naturally occurring conditions.

Samples	Pre-contamination Conductivity mS/cm	Recorded Leakage Current Range mA	Projected SDD (Figure 6.15) mg/cm^2
A27S-1 to 5	97	93 < I < 316.5	0.167
	139	225 < I < 450	0.239
B19H-1 to 5	42	95.2 < I < 138.6	0.256
	60	225 < I < 299.8	0.365
	139	385.6 < I < 907.8	0.846
B19H-6 to 13	42	135.7 < I < 344	0.259
	60	203 < I < 392	0.370
	139	659.8 < I < 834.2	0.858
B21H-1 to 4	139	454.4 < I < 595	0.664
C21H-1 to 4	139	231 < I < 375	0.931
D21H-1 to 4	139	560.3 < I < 703.4	0.832
D27S-1 to 4	139	170.5 < I < 214.4	0.321
D27S-5 to 8	139	43.2 < I < 169	0.251

Table 6.9: Summary of clean fog data referenced to SDD data

By evaluating the clean fog data in Table 6.9, the following can be deduced:

- There is no correspondence between pre-contamination conductivity and the pollution layer SDD ultimately deposited onto the insulator surface

- There is no correspondence between the expected performance of the CE insulators (using the pollution classification in IEC 815 and 507) and the SDD values.

- Insulators C21H and D21H were exposed to identical pre-contaminations and clean fog conditions yet registered different peak current readings and SDD levels. This is due to the complex CE insulator surface aging due to the effects of UV. Only the parts of the insulator exposed to the sun's solar radiation present rough and therefore pollution friendly surfaces to the pre-contamination solution to bind to (Figure 6.24).

Figure 6.24 serves as evidence to the effect of UV aging, as by logical extension: if the surface degradation evident on the insulator was caused by leakage current activity (in isolation) - the under-shed regions should demonstrate similar aging characteristics to the shed tops. This is because the leakage current supposedly causing the aging on the shed tops would have to flow over the under-shed regions in order to complete the leakage current electrical circuit from conductor to earth, through the pollution layer and one would then expect similar aging.
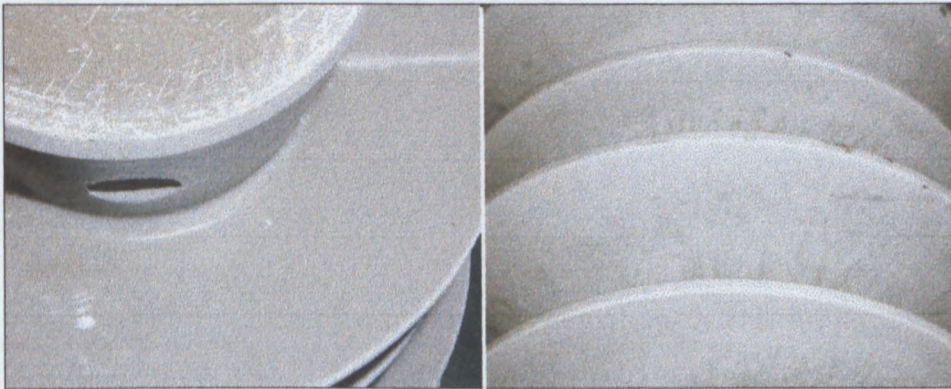

Figure 6.24: Complex CE insulator surface aging due to natural solar radiation (UV) exposure showing smooth shiny under-shed zones in contrast to chalky rough shed tops.

Salt Fog Tests

Serial	Salt Fog Severity mS/cm	Recorded Leakage Current mA	Salt Fog IEC 815 Pollution Classification
A27S-1 to 5	52	286.7 < I < 693.2	Medium
B19H-1 to 5	8	251 < I < 316	Light
	20	347.6 < I < 594.4	Light
	28	656.3 < I < 841.3	Medium
B19H-6 to 13	8	361.2 < I < 544	Light
	20	380.6 < I < 941.3	Light
	28	629.6 < I < 807	Medium
B21H-1 to 4	17	316.5 < I < 502.6	Light
	22	425.4 < I < 1012	Light
	28	586.6 < I < 611.1	Medium
C21H-1 to 4	14	340.5 < I < 584	Light
	22	412.7 < I < 715	Light
	28	638 < I < 639	Medium
D21H-1 to 4	14	244 < I < 542	Light
	22	562 < I < 795	Light
	28	I = 601	Medium
D27S-1 to 4	54	391 < I < 878	Medium
	67	277 < I < 605.7	Heavy
	80	I = 875	Heavy
D27S-5 to 8	54	288 < I < 572	Medium
	67	431 < I < 519	Heavy
	80	441 < I < 792	Heavy
	94	414.9 < I < 735	Heavy

Table 6.10: Summary of salt fog data referenced to IEC 815

The salt fog test was developed to provide an indication of the performance of insulation in respect of marine pollution conditions. As an artificial pollution method, the salt fog demonstrates the following characteristics:

- Lambeth found that an insulator exposed to the IEC 507 salt fog test reaches a state of equilibrium within the environment after 15 to 20 minutes. This condition is demonstrated by the stabilization of leakage current activity during this period.[24] By observing the salt fog data for the porcelain insulator (Figure 6.20) it can be seen that the University of Stellenbosch salt fog chamber is operating according to the original design principles as documented by Lambeth.

- Ely found good correlation between the artificial salt fog and both marine and industrial pollution conditions.[19]

- Gorur found that salt fog tests at reduced conductivities shows improved correlation with natural pollution conditions and their associated aging mechanisms.[9] Table 6.10 indicates that salt fog tests were performed at low salinity levels, and that the salinity levels were increased until the insulators could not withstand the salt spray conductivity/salinity. The purpose of the salt fog tests was not to demonstrate aging patterns, but to provide an accurate estimate of the ability of the field-aged insulators to withstand salt fog salinities. Ely found that the salt fog test determining the withstand salinity of the insulation provides superior correlation with naturally occurring marine pollution, in contrast to the flashover voltage salt fog method – where the variable is the system or test voltage.[21]

- Gorur found that leakage currents due to salt fog testing is determined by the ability of the insulation to reduce the volume of the pollution film occurring on the insulation surfaces.[23] This pertinent point indicates that the surface condition of the insulator plays a significant role in the ability of the insulator to withstand salt fog tests.

Since the clean and salt fog tests are artificial representatives of different naturally occurring pollution conditions, it is vital to understand the reasons for the differences. The most significant difference between the clean fog and salt fog artificial pollution tests is the fact that the clean fog test is an evaluation of one pollution layer applied once to the insulator surface and wetted by steam – where the salt fog test is a continuously applied pollution layer (for the duration of the test).

The dynamics of the clean fog layer during the test are such that the layer becomes less and less conducting with the application of steam, due to the washing effect of the applied steam actually leaching the salt (NaCl) from the kaolin binding agent contained in the pre-contamination solution. The leaching of the salt from the pre-contamination pollution layer results in the reduction of the peak leakage currents in time, as the test progresses. The clean fog pollution layer is to a degree, dynamic, as the 'drips' associated with the test can promote the bridging of non-conductive zones or dry-bands.

The salt fog pollution layer is entirely dynamic in its application to the insulation surfaces and is a constantly re-generating layer. The conductivity of the salt fog layer is much less dependant on the relative temperatures (dew point) between the insulation surface and surrounding atmosphere – the pollutant is fundamentally a traveling mass of atomized solution simply requiring a surface to collect on.

By evaluating the salt fog data in Table 6.9, the following can be deduced:

- A27S-1 to 5 do not meet the IEC 815 artificial pollution severity criteria

- B19H-1 to 5 do not meet the IEC 815 criteria

- B19H-6 to 13 do not meet the IEC 815 criteria

- B21H do not meet the IEC 815 criteria

- C21H do not meet the IEC 815 criteria

- D27S-1 to 4 begins fail at 54 mS/cm and total batch failure occurs at 67 mS/cm – therefore a borderline condition.

- D27S-5 to 8 begin failing at 80 mS/cm, therefore marginally meets the IEC 815 criteria.

However, in all cases of salt fog testing (specifically the horizontal shed insulators), the peak leakage currents flowing over the insulator surfaces at reduced salt fog severities are far too high in magnitude (Table 6.10). This results in rapidly accelerating aging of the insulator surfaces – therefore indicating that CE insulation is best suited to pollution types where complete pollution contamination and continuous wetting of the insulator surface does not occur.

6.5 The Industry Questionnaire

The function of the industry questionnaire was to obtain a 'customer' based viewpoint on the performance of the insulation medium in respect of field conditions. The following can be interpreted from the three replies:

- Utilities operating near or in marine environments have not had satisfactory performance from CE insulation

- Utilities operating in medium industrial or agricultural pollution environments have had satisfactory performance from CE insulation

- Existing Class B (pin-type) CE insulation is prone to puncturing and not a recommended form of insulation

- The frequency of lightning occurrence does not seem to have an effect on the performance of the Class B insulation.

Class B insulation with respect to areas of lightning incidence

Several studies have been conducted into the susceptibility of Class B (pin-type) CE insulation to lightning, and to date no South African laboratory testing has successfully caused the destruction of such insulation under artificial lightning impulse conditions.[25, 26]

All tests causing the destruction of the insulators are preceded by the necessity for unrealistic physical damage to the insulator, and the requirement for the testing to be performed under oil in order to force the lightning impulse to discharge through the superior CE dielectric rather than the dielectrically inferior surrounding air. The total susceptibility of Class B CE insulation to lightning is therefore debatable – when considered in isolation to the effects of the prolonged system AC voltage.

There is undoubtable evidence that naturally occurring lightning impulses cause the destruction of Class B CE insulators. However, there is also substantial evidence that many Class B failures are caused by the effects of partial discharges.

CE insulation is most susceptible to the effects of partial discharge activity. Alexeyev states that: "there is no doubt that partial discharges in insulation are one of the main aging factors".[27] Diessner claims that measurable partial discharges significantly affect the lifespan of CE insulators.[28] Mähönen states that the advanced primary discharge channels are caused by high stress levels (partial discharges, high peak voltages) within the material and that the field tailoring of all structures connected to the medium is indispensable.[29]

By examining Class B insulator field failures (Figure 6.25), the following failure modes appear:

1. Failure of a Class B CE insulator due to the effects of partial discharge activity.
2. Failure of a Class B CE insulator due to the effects of partial discharge activity – but total failure is triggered by a lightning impulse
3. Total failure of a Class B CE insulator due to the effects of naturally occurring lightning impulses

It appears that the variable that separates Items 2 and 3 is exposure to pollution:
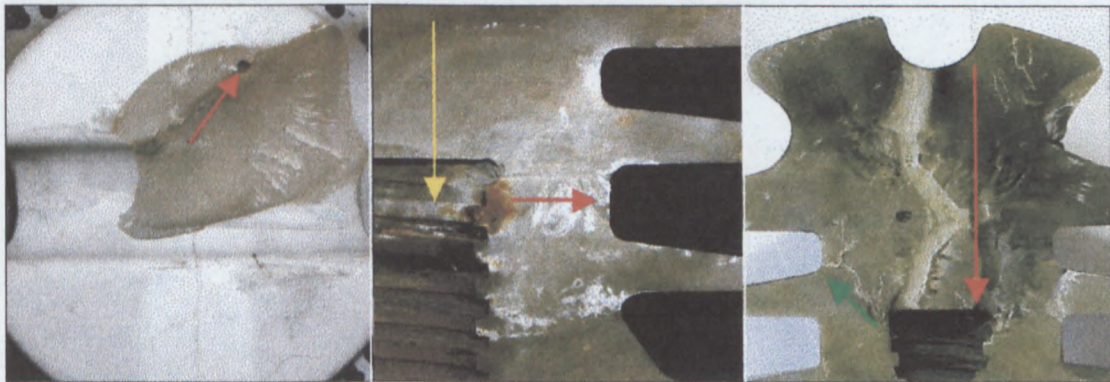
Figure 6.25: Items 1-3 (left to right) – failure mechanisms for Class B CE insulation.

Item 1: there is no evidence to any other failure mechanism, other than a pin-hole puncture on the top of the insulator in the general conductor area, and a pin-hole puncture in the mounting spindle area (not visible in Figure 6.25). This is due to the prolonged effects of partial discharge activity resulting in the localized aging of the CE dielectric and creating a discharge channel.

Item 2: Partial discharge activity took place for a lengthy period before the insulator was catastrophically destroyed by a lightning impulse – evidence to this fact (extended time) is the amount of iron oxide visible on the CE dielectric in the discharge channel, and the amount of metal corrosion on the mounting spindle. If failure was due to a lightning impulse there would not have been an appropriate

amount of time to cause the mounting spindle oxidation and the penetration of the oxidation into the PD channel.

The partial discharge activity was initiated by the potential transfer mechanism of the conductive pollution layer deposited on the insulator. The effects of pollution build-up and the resultant potential transfer mechanisms that take place because of conductive pollution accretion on insulator surfaces can combine to form enhanced stress zones within the CE bulk dielectric – ultimately resulting in the failure of the insulator units in manners not quite expected.

The red arrow indicates the actual failure path while the yellow arrow indicates the actual shortest distance between the earth electrode and the energized electrode – through the dielectric. The actual path-lengths and electrical stresses are (excluding the field enhancement in air-gaps between the spindle and dielectric):

- Yellow arrow – 65 mm (304 V_{pk}/mm)
- Red arrow – 12 mm (1.64 kV_{pk}/mm)

Reynders states that the highest field strength on Class B CE insulators is in the zone above the mounting spindle.[25] This is possibly a simplification of the mechanism because the study did not include the dynamic nature of the pollution layer and the resultant redistribution of the system potential. Item 1 indicates that the possibility exists that PD activity is possible along the yellow route. Therefore, because of the redistribution of potential due to conductive pollution, PD activity should be more likely along the red route since the electrical stresses are higher.

Item 3: The overriding discharge channel is the channel formed by the lightning impulse, denoted by the red arrow. There are minor discharge channels that are in their beginning stages (green arrow) – that have probably been formed by light pollution layers on the external surfaces of the insulator in conjunction with the applied system potential. However, the actual pollution is not very conductive and does not allow for the re-distribution of the applied AC potential to areas that would favor high field stress and PD failure.

The apparent preference for the lightning discharge path through the CE insulator bulk dielectric and not through the surrounding air is possibly due to the following phenomena:

- The rise time of the applied lightning impulse was very steep – in the sub-1 µs time range, or the magnitude of the applied wave shape was extremely high.

- The time taken to set up the discharge channel through the CE dielectric was shorter than the time required to set up the discharge channel through the air surrounding the insulator.[30]

Electrical breakdown processes in gases is not an instantaneous event – there is a time lag between the application of the voltage and the actual disruptive discharge process.

The breakdown period consists of two time events: the waiting period and the formative period. The waiting or statistical lag period is characterized by the unknown

time required for the availability of an initiating electron, while the formative period is characterized by the time taken to form the critical avalanche condition ultimately resulting in streamer formation that bridges the space between the electrodes containing the dielectric. The waiting and formative periods are dependant on the applied voltage wave shape and magnitude. The higher the applied voltage, the less the time required for breakdown of the gaseous medium. The formative period ranges from 10^{-4} to 10^{-9} seconds, depending on the magnitude of the applied voltage.[31]

Conclusion

Chapter 6 discussed the results of Chapter 5 and provided the following characteristics for CE insulation:

- The difference in dry and wet AC flashover voltage for reference insulators is due to the geometry of the insulators. The slanted shed design accomplishes the goal of permitting less pollution to adhere to its surfaces than for the horizontal design.
- The difference between the wet AC flashover voltages for reference and field-aged insulators is due to the changes to the insulator surfaces because of aging.
- The mould release agent provides CE insulators with their hydrophobicity and initially superior performance in respect of polluted conditions and artificial pollution tests. Once the mould release layer has been degenerated (by aging), no recovery of hydrophobicity is possible – the changes are permanent.
- Laboratory UV (QUV) aging of CE samples results in smoother sample surfaces, where field aging results in the roughening of CE surfaces.
- The SAI is shown to correlate with the SDD tests on aged CE insulator surfaces, and succeeds to correlate where surface roughness measurements become erroneous.
- The IEC 1109 voltage test is shown to provide valuable information as to the relative stability of CE samples.
- The water immersion test data is shown to provide valuable insight into the constitution of CE samples, and in this case indicated differences in manufacturing conditions.
- The artificial pollution tests indicate that CE insulation is better suited to clean fog type pollution, as the salt fog type pollution causes severe stress in the form of high leakage currents at significantly reduced pollution conductivities.
- The comparison between the porcelain and CE insulators of identical profile and dimensions indicates that the CE insulation material performs significantly worse than porcelain – by registering much higher leakage currents during salt fog testing.
- The industry questionnaire highlights the fact that CE insulation is contra-indicated for use in marine type climates.
- It is shown that Class B insulation has not performed in the RSA because of pollution induced potential redistribution, partial discharge activity and lightning.

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HYPOTHESIS FOR AGING OF CYCLOALIPHATIC EPOXIDE INSULATION

The aging of CE insulation is a diverse phenomenon, and is not restricted to the role of the insulator within the utility networks. Aging of the insulator begins immediately that it is created, but for the purposes of this hypothesis the aging mechanisms discussed will be those directly responsible for a tangible effect on the properties of the insulator.

The aging processes can be placed in three categories:

1. Damage to the insulator at the point of manufacture
2. Insulator damage as a result of transportation and storage
3. Exposure to the environment during typical insulator duties

Damage to the insulator at the point of manufacture

CE insulators are cast objects and are cast in moulds consisting of two halves. The zone where the two halves of the mould meet is known as the mould-line zone and is usually visible as a raised surface on CE insulators. In most cases, since the CE resin system is injected into the mould under pressure, some of the resin system seeps into the zone between the 2 halves and upon reaching gelation point results in a raised polymer formation known as the flash (Figure 7.1).

Figure 7.1: Illustration of the flash on an EPDM insulator (left), and the damage due to the removal of the flash on CE insulation (right).

The manufacturers remove the flash by cutting or abrasion. The action of cutting or abrading may modify or cause damage to the surface of the insulator. In the case of the CE insulators reviewed and evaluated, mechanical damage was caused to the surface of the insulator.

The mechanical damage is in line with the run-off path for condensation, represents roughening of the surface and thus traps more pollution than the surrounding insulator surfaces. This results in the weakening of the insulator before it leaves the manufacturing plant, in the following ways:

- The mould-line zone contains less filler than the CE insulator bulk (Figure 5.29). CE materials that contain less filler show high sorption rates and degrees of diffusion when evaluated in the water immersion tests (Chapter 6).

- Most conductive pollution layers contain soluble salts that could diffuse into the CE insulator mould-line – because of its weakness as a result of its reduced filler content and damage done at the point of manufacture – and thus provide additional charge carriers to the mould-line zone with a resultant increase in conduction within and over the material.

- The conduction of electrical current within and over the material of the mould-line zone could result in the accelerated aging due to the formation of heat, erosion and tracking.

- The aging of the mould-line zone could result in the further roughening of the mould-line, thus increasing its ability to trap moisture and pollutants. This further roughening of the mould-line (as a result of the initial roughening at the point of manufacture) could be represented as a 'run-away' condition – as the initial roughening traps pollution, that causes further roughening that causes the trapping of yet more pollution (a self-perpetuating mechanism).

If the flash were to remain as a continuous entity on the insulator surface, the following phenomena are likely (Figure 7.2):

- The flash represents a sharp and non-uniform electrode profile and could, with the assistance of potential redistribution due to the effects of a dynamic pollution layer, result in the intensification of the electric field on its surfaces. The intensification on the flash could result in the formation of ozone (due to the ionization of the surrounding air). Ozone is a powerful oxidant and this mechanism could result in the localized weakening and aging of the insulator surfaces.

- The exposed profile of the flash (relative to the general insulator surface) could result in the flash-line being more exposed to environmental aging factors (solar UV, condensation, physical impact with organic material etc.) and this could result in the localized aging of the flash and mould-line zone.
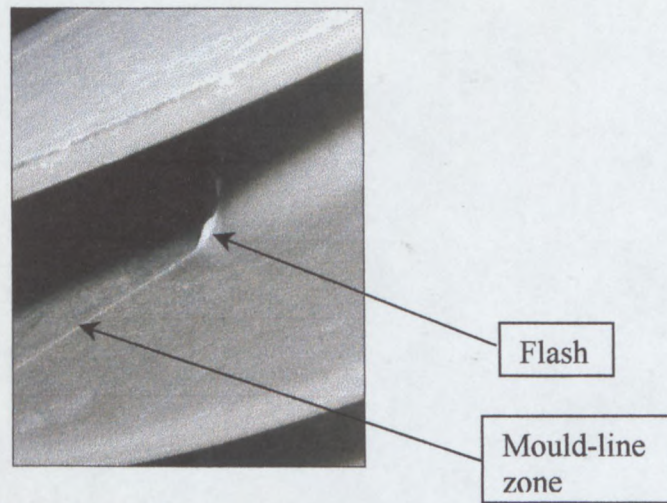
Figure 7.2: Flash protruding from the insulator surface

- The raised profile of the flash could result in the 'catch' of airborne pollution. The 'catch' of pollution could result in the increased electrical activity local to the flash and mould-line zone – resulting in localized aging on the insulator surface.

Insulator damage as a result of transportation and storage

A study was conducted by a local utility into the failure of CE products once delivered by the manufacturers, and it was found that at least 80% of CE transformer bushings were damaged by the utility personnel during transit or storage.[1]

Most of the damage occurs while loading and unloading the complete transformers – the CE bushings already being mounted on the transformer tank – in preparation for the connection of customers to the utility network. It is not clear whether the 80% failure figure includes a detailed examination of all CE transformer bushings, as due to the nature of the product hairline cracks could remain undetected until failure of the bushing occurs in the field due to the application of system voltage and/or moisture ingress.

Exposure to the environment during typical insulator duties

New CE insulator surfaces are hydrophobic because of the use of mould release agents as required by the APG process. The mould release layer and its hydrophobic properties can be depleted by various means:

- The physical handling of CE insulators by utility personnel can redistribute or remove sections/areas of the mould release layer
- The physical impact of sand (sand and dust storms), rain, hail and pollution particles
- The application of system voltage to the insulator resulting in the electrical aging of the layer
- Solar radiation and the resultant UV energy that is absorbed by the layer

A detailed explanation for the electrical, condensation and solar radiation aging mechanisms occurring on the insulator surface is as follows:

1. New CE insulator surfaces are hydrophobic (Figures 5.15 and 5.27), and when energized with AC voltage capacitive current flow through the bulk insulator dielectric. The insulator does not exhibit pollution-driven resistive leakage current behavior.

2. Physical impact due to sand, dust, condensation and solar UV radiation results in the lowering of the hydrophobic qualities of the CE insulator surface, allowing for more condensation and pollution to collect onto or attach to the surface.

3. The condensation that attaches to the surface of the CE insulator absorbs/traps pollution and forms areas of conductive moisture. The electric field present due to the AC energization of the insulator elongates/distorts the water droplets, thus covering larger areas of the insulator surface and resulting in the further reduction of its hydrophobic qualities.[2] Additionally, the entrapment of pollution in the moisture on the insulator surface has further ramifications. SO_2 (sulphur dioxide), a by-product of the internal combustion engine – particularly diesel - when dissolved in water, forms a weak and unstable acid known as sulfurous acid (H_2SO_3).[3] Furthermore, petroleum internal combustion engines release noxious gases into the atmosphere – and the addition of the noxious gases to water results in nitric acid – one of the strongest acids known. The action of acids on the surfaces of polymeric insulators, especially CE materials, appears to weaken and deteriorate the mechanical qualities of the material.[4]

4. The conductive moisture, in the form of droplets located in the electric field encapsulating the insulator results in the formation of high field stresses on the droplet geometry, and results in UV radiation and the formation of ozone due to the ionization of the air surrounding the droplet.[2,5] Ozone reacts with the insulator surface more quickly and energetically than oxygen, because it has a greater energy content (ozone is second only to fluorine when it comes to oxidizing ability).[3,6] This results in the oxidation and aging of the surface layer. Ozone has been found to age an insulator to the same degree as stressing the insulator with 'simulated indoor conditions'.[7]

5. Ultimately the condensation present on the insulator surfaces merges to form an electrolyte (as a result of the trapping of conductive pollution) that encapsulates the entire insulator surface and results in a resistive leakage current. Additionally, the electrolysis of moist conductive (because of the resistive leakage current) pollution containing sodium chloride results in the formation of sodium hydroxide. Silica-filled CE insulators are particularly prone to the action of sodium hydroxide, which enhances the diffusion of moisture into the CE epoxy interior and results in hydrolysis and weakening of the material.[8]

6. As the resistive currents increase in magnitude due to the further accretion of pollution onto the moist insulator surface, the predominant insulator current moves from being the capacitive current to a fully-fledged pollution initiated resistive leakage current. The heat liberated in the resistive pollution layer assists in the formation of dry-bands on the insulator surface.

7. Due to the instability of the dry-band and the fact that a dry-band is characterized by local discharges, ozone and UV radiation is liberated that assists with the aging of the dry-band zone.

8. The aging mechanisms continue in time and result in the modification of the insulator surface characteristics: erosion, tracking and de-polymerization (polymer chain scission). The aging of the insulator surfaces results in roughening and the further accretion of conductive pollution. If the surface conductivity reaches a significant and critical level, flashover of the insulator might occur.

Running in parallel with the pollution (surface) driven aging mechanism for CE insulators is the susceptibility of the insulator bulk dielectric to the effects of the system potential, transient over-voltage conditions and lightning surges. An explanation for the aging of the insulator bulk dielectric – specifically targeted towards the Class B CE insulators (however, the mechanism described is applicable to all insulation types and classes):

1. The insulator is placed in position within the utility network and is exposed to the power frequency system voltage, temporary over-voltages and lightning surges. The insulator bulk dielectric is composed of the resin and filler components. The 'quality' of the dielectric is determined by the lack of voids between the filler and the resin components.

2. The action of casting CE insulators involves the use of heat to anneal and cure the insulator. The incorrect cooling of the unit after casting can cause micro-cracks and voids resulting in areas of weakness that are prone to partial discharges occurring at low inception voltages.[9] (Similar to the previously mentioned rough handling of CE transformer bushings resulting in micro-voids and cracks).

3. The sustained operating condition is the power frequency system voltage (50 Hz in the RSA) that is permitted to deviate within close tolerances of up to 110% of the nominal system voltage. High electric stresses occurring in CE insulation due to incorrect designs, dynamic pollution layers (and the resultant potential transfer) or sharp profiles can cause treeing (Figure 6.20), and partial discharges due to voids in the CE dielectric aggravate the condition.[10]

4. Repetitive over-voltage conditions cause the aging of the CE dielectric. The higher the magnitude of the over-voltage condition, the shorter the life-span of the CE dielectric due to the weakening of the resin system.[11]

5. The partial discharge activity results in the oxidation of the CE insulator dielectric and forms by-products consisting of nitric, glycolic, formic and glyoxilic acids that could result in the ultimate failure of the dielectric.[12]

6. Any deviation in voltage above operating voltage levels aggravates the aging mechanisms. Lightning impulses can cause the violent failure of the units, depending on the degree of aging already experienced by the dielectric (Chapter 6.5).

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Conclusions and Recommendations

This chapter reviews the investigation into the use of CE insulation within the RSA with reference to the aims as stated in Chapter 1: Introduction.

Conclusions

1. CE insulation of equivalent dimensions and profile performs worse than an equivalent porcelain unit under salt fog test conditions.

2. CE insulation that has been exposed to field aging mechanisms experiences a degree of surface roughening that results in the reduction in wet AC flashover voltage, and increased leakage current performance under both salt and clean fog conditions.

3. CE insulation experiences severe stress in the form of high leakage currents when exposed to salt fog testing, yet seems stable under clean fog conditions.

4. A significant performance boost results from the mould release agent that forms a layer of silicone based oil on all new CE insulators. The silicone layer provides the CE insulators with superior hydrophobicity; reduced leakage current levels under clean and salt fog tests and acts as a UV buffer in the event of field application. The mould release layer presents no recovery characteristics, and once degraded and leakage current flows, exhibits no recovery mechanisms.

5. CE insulation appears to possess no intrinsic hydrophobicity mechanism and presents no hydrophobicity recovery mechanism once aged (the latest hydrophobic CE systems have not been evaluated).

6. CE insulation is easily aged by leakage current activity, hydrolysis, partial discharge activity, thermally and by UV radiation.

7. Class B insulation is not contra-indicated as a CE insulation type, but special care must be taken to avoid any chance for partial discharge activity in the mounting-spindle-CE-material-zone around the mounting spindle screw-thread.

8. The final qualities of the CE product are determined by both the resin system employed, and the manufacturing tolerances. Variations in quality were found that could only be attributed to manufacturer error.

9. The horizontal design CE insulator evaluated in this work presents a highly attractive surface to pollution and consistently results in salt deposit densities

two orders greater than the reference glass disc specification in IEC 507. The slanted shed design performs marginally better than the reference glass disc specification in IEC 507.

10. A new method for the quantitative evaluation of surface aging was investigated: the Surface Area Index (SAI). The method utilizes advanced Atomic Force Microscopy methods and correlates with existing practice and the SDD results.

11. The clean fog pre-contamination method was adjusted to evaluate the effect of surface roughness on the accretion of pollution to CE surfaces. The method proved successful, but due to the complex aging patterns on CE insulators, requires careful analysis of the results for meaningful interpretation.

12. It was found that the specific laboratory aging method used in this work resulted in the smoothening of CE insulator surfaces when exposed to UV radiation and condensation, yet field-aged samples indicated increased roughness of the surfaces. Similar results have been obtained by few other researchers.

13. The utility questionnaire, in combination with the salt fog test results indicates that CE insulation should not be used in areas of heavy marine or industrial pollution, possibly avoiding marine environments completely.

Recommendations (including further work)

1. Due to the differences in performances obtained during material testing of identically manufactured CE samples, manufacturer quality control should be assessed.

2. The use of artificial UV radiation and condensation to age CE samples should be investigated, since the laboratory and field aging of CE provides dissimilar results.

3. The use of the Surface Area Index method for quantitatively evaluating the surface aging of CE samples should be further evaluated. Initial results seem promising.

4. The use of clean fog tests for evaluating CE insulators should be evaluated. The fact that only the surfaces exposed to UV radiation appear rough and allow pollution to adhere results in the unexposed under-shed surfaces skewing the clean fog test results, as there is reduced pollution on these regions and results in reduced leakage currents.

APPENDIX A

RECENT EXPERIENCE WITH CE INSULATORS

Historic Background: Polymers in General

The electrical insulating qualities inherent in most polymers have long been harnessed to isolate conducting materials from earth potential, to sustain high electric fields and adverse environmental conditions without electrical breakdown of the dielectric surrounding such conducting materials.

Polymeric insulating materials were originally manufactured from naturally occurring products or sources. The first Trans-Atlantic telephone cables laid in the 1860s were insulated with a naturally occurring polymer, gutta-percha, extracted from rubber trees.[1]

As synthetic high polymers became available in the 1940s there was a movement to using such polymers as insulating materials on high voltage indoor equipment. Initially, the advantage of using these polymers was their ease of manufacture by molding and inherent electrical insulating properties.

CE insulators were introduced as outdoor insulation in England in 1963, after having been introduced to the engineering public in 1957.[2] They were characterized as being of superior quality to the original Bisphenol based indoor units, due to their increased resistance to carbon formation when exposed to electrical tracking.

However, the first units to be applied in the United States of America (1960's) failed shortly after installation in outdoor environments. These units were marketed under the name GEPOL, and failed due to surface discharges and punctures. [2]

CE insulators were used in experimental 500 kV station breaker bushings, 115 kV bushings in the 1970s and for suspension insulators by Transmission Development Limited (TDL) of England. The TDL insulators used slanted shed designs to attempt to facilitate natural washing of the insulator surfaces.[2]

The first CE insulation to be used in the RSA were experimental 275 kV units, manufactured by Permali, England, in July 1975. The suspension units failed after 22 months due to internal flashover. Cracks in the housing permitted the ingress of moisture into the core area and resulted in tracking.

CE insulation has since seen widespread use in the RSA as reticulation (11 – 33 kV) class insulation: post and pin type insulators, cut-out fuses and transformer bushings. The use of CE insulation in the RSA has been characterized by uncertainty as to the merits of using this type of insulation in outdoor applications, specifically in coastal areas.

Recent global experience with CE insulators

USA – Georgia Power Company [3,4]

Georgia Power Company has employed CE bushings in their system since 1986. Twelve 115 kV bushings were installed in a substation, as part of circuit breaker assemblies. The substation supplies a paper mill and is located near the mouth of a coastal river.

The substation is prone to salt spray from the ocean and airborne pollution from the paper mill. According to the engineer, Mr. Peter Vagle: "Heavy coatings of pulp fibers and some salt collect on all surfaces".

Georgia Power Company practice annual preventative maintenance and silicone greasing on all substation bushings, except for the CE units, which have not needed such attention since installation. During the period of operation, one flashover of a CE bushing has occurred. This is contrast to the four flashovers on the remaining porcelain substation bushings.

Europe

a) Finland [5,6]

CE outdoor insulators have been in commercial use in Finland since 1967. No official statistics are available for the performance of these insulators in the time period of 1967 – 1981. However in the winter of 1981, an initiative was made to begin keeping a report of failures:

- Period up to 1981 – two electrical breakdowns in disconnect switch insulators. Cause postulated as being internal voids and subsequent partial discharge damage.

- 1983 – insulators of a disconnect switch failed due to surface damage. Failure was attributed to seagull nesting.

- 1985 – failure of 20 kV insulator due to electrical breakdown. Failure attributed to internal voids.

- 1985 to 1990 – failure of 5 line post insulators due to voids and inconsistent mould quality.

- No failures due to mechanical defects have ever been noted.

The projected failure rate for the application of outdoor CE insulators in Finland is one failure per million insulator years.

b) Switzerland [5]

The Swiss railways (SBB) have had experience with 15 kV post type outdoor CE insulators since 1980. They stated the following requirements:

- Electrical ratings and dimensions similar to equivalent porcelain units

- Cantilever strength of 10 kN at -30^0C

They commented on the significant weight reduction over equivalent porcelain units and the subsequent ease of installation. There have been no reports of failure to date.

Japan [5,7]

The Tokyo Electric Company awarded 'The Presidents Prize' at the 1986 JECA Exhibition of Electrical construction Equipment and Materials Fair for a unique design of distribution-class transformer that utilized the versatility of Ciba Araldite casting resins in its construction.

The award was made in recognition of:

- Suitability of use for outdoor application without housing (all electrical components are contained within the resin system).

- Low maintenance requirements

- Enhanced safety due to the fact that the winding is not oil immersed

- Compact dimensions and low weight: single-phase transformer of 50 kVA / 6.6 kV mass is 390 kg and measures 485x500x840 mm.

- Integration of all live components into the resin system

The long-term electrical performance of the transformers could not be established.

The Republic of South Africa

There have been five independent manufacturers of CE insulation products in the RSA:

a) General Electric Company [8,9]

GEC manufactured the first wall bushings in 1976. These units were rated at 11 kV and were installed at Witfield Substation in Boksburg, Gauteng. The units are still performing reliably.

b) Electrical Moulded Components [8,9,10]

EMC manufactured CE bushings to be used in Merlin-Gerin kiosks in 1981. These were the first units that the company produced and were a copy of existing porcelain units. The external weather shed was of the type that was glued to the support stem, and are still installed.

In 1986 EMC supplied the first batch of 22 kV line post insulators to Nelspruit. These insulators were characterized by a 135 kV basic insulation level (BIL) and a 19 mm/kV creepage distance. These insulators are still installed.

In later years EMC has supplied transformer bushings, line post and pin type insulators to electrical utilities throughout the RSA. It is estimated that there are 3.4 million EMC insulators installed and in use on the ESKOM network.

c) Insulator Industries [8,9,11]

Insulator Industries started producing CE transformer bushings in 1988. It subsequently ceased to exist in 1990.

d) Hardware Assemblies (HA)[8,9,10]

HA started producing drop-out-fuses in 1987 and line post insulators in 1988. There are approximately 261 000 drop-out fuses and 24 000 line-post insulators installed in utility networks in the RSA.

e) Linegear 2000 [8,9,10,12]

Linegear 2000 have been supplying pole-mounted switchgear and fuses utilizing CE bushings to the RSA market for the past 11 years. There are approximately 100 000 CE units installed in the country.

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APPENDIX B

INSULATOR DIMENSIONS

Appendix B discusses the actual shape or profiles of the insulators evaluated under all the tests specified in Chapter 4 – with reference to IEC 815. IEC 815 was specifically draughted for ceramic insulation, but many of the principles upheld by the standard are relevant on non-ceramic insulators.

The shape/profile and dimensioning of the profile of insulators has an effect on the performance of the insulator in respect of polluted conditions. IEC 815 can be used as a guide for the selection of insulators in respect of polluted conditions – and uses the concept of creepage distance to do so.

IEC 815 – Insulator Dimensioning (Ceramic and Glass) [1]

"The performance of insulators in polluted conditions (Table B1) has been the subject of many studies that permit the specification of the required insulation when the site pollution is known, or by experience of insulator performance in the same region which has been operating at the same or different system voltage. The approach based on the laboratory simulation of natural pollution consists consequently of the following steps:

- evaluation of type and severity of the pollution at the site;
- specification of a laboratory test as representative of the site as possible;
- selection of insulators which would show a good behavior under this test

This method of selection and specification of the required insulation should be adopted whenever circumstances permit."

Influence of the diameter

Tests performed in laboratories indicate that the pollution performance of post insulators decreases with the increase in average diameter for that insulator. In order to determine the nature of the insulator pollution application level, one needs to determine the factor k_D which is representative of the average insulator diameter.

For the insulator under test (all the insulators are identical with regard to profile), the approximated formula is:

$$D_m = [D_{e1} + D_{e2} + 2D_i] / 2$$

Minimum distance 'c' between sheds

'c' is the minimum distance between sheds of similar diameter. This distance is measured by drawing a perpendicular from the lowest point of the outer rib of the upper shed to the shed below of the same diameter".

'c' has influence on insulator performance under rain conditions - by indicating the probability of bridging of insulation between two (2) successive sheds. A practical value for 'c' should be in the vicinity of 30mm.

For insulators of length l ≤ 550mm, or insulators with relative smaller shed overhang 'p' (p ≤ 40mm) a value of 'c' in the vicinity of 20mm is acceptable.

Ratio s/p between spacing and shed overhang

This ratio is of importance to the self-cleaning capabilities of the insulator. It provides a guide to the limitation of leakage distance with regard to shed overhang 'p'.

The ratio s/p ≥ 0.8. This value can be reduced (empirically determined) to 0.65 when plain sheds are employed.

Ratio I_d / d between creepage distance and clearance

The ratio I_d / d describes the use of the creepage distance in order to avoid local short-circuiting.

I_d / d < 5 (applied to the worst case condition on the insulator).

In simple terms - the potential difference produced along distance 'I_d' should not be of such a magnitude so that 'bridging' of the air dielectric should occur between the successive sheds including the distance 'I_d'.

Alternating Sheds

The difference (p_1 - p_2) between consecutive shed overhangs is an important factor in the ability of the insulator to withstand rain conditions and avoid bridging between these consecutive sheds. This is linked to the ratio I_d / d.

Practical values for (p_1 - p_2):   (p_1 - p_2) ≥ 15mm

Creepage Factor

Creepage Factor: $C.F. = l_t / S_t$

The creepage factor can be used to characterize the profiles of all insulators, and it is advisable to keep the creepage factor within certain limits - according to prevailing pollution conditions where the insulator is to be employed:

$C.F. \leq 3.5$ for pollution levels I and II,
$C.F. \leq 4$ for pollution levels III and IV.

This limit for creepage factor can be extended, provided experience of the insulator in operation or laboratory tests simulating conditions indicate that the insulator performance under these conditions indicates compliance.

The Profile Factor

The profile factor is defined as the ratio of the simplified leakage distance to the actual insulating creepage distance measured between the two points which define the spacing 's'.

Profile Factor: $P.F. = [2p_1 + 2p_2 + s] / l$

It is advisable to maintain a profile factor above 0.8 for pollution levels I and II, and 0.7 for pollution levels III and IV.

The insulator dimensioning is performed with the pollution severity levels in mind (Table A1). The IEC is a rough guide to the pollution severity levels and is quite explanatory in its simplicity.

Unfortunately Table A1 does not adequately define all locations and their expected pollution severities – and relies on the common sense of the interpreter to arrive at the approximate site severity level where insulators are to be applied.

Pollution Severity Levels

Pollution Level	Examples of typical environments
1 - Light	- areas without industries and with low density of houses equipped with heating plants
	- areas with low density of industries or houses but subjected to frequent winds and/or rainfall
	- agricultural areas
	- mountainous areas
	* all these areas shall be situated at least 10-20km from the sea and not exposed to winds directly from the sea
2 - Medium	- areas with industry not producing particularly polluting smoke and/or average density of houses equipped with heating plants
	- areas with high density of houses and/or industries but subjected to frequent wind and/or rainfall
	- areas exposed to winds from the sea but not too close to the coast (at least several kilometers distant)
3 - Heavy	- areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution
	- areas close to the sea in any case exposed to relatively strong winds from the sea
4 - Very Heavy	- areas generally of moderate extent, subject to conductive dusts and to industrial smoke producing thick conductive deposits
	- areas generally of moderate extent, very close to the coast and exposed to sea spray or to very strong and polluting winds from the sea
	- desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation (fog or mist).

Table B1: IEC 815 guide to the pollution severity levels [1]

Insulator Measurements

R19H

Criteria	IEC 815 requirement	Test Insulator
D_m		< 300 mm
Specific Creepage 'd'		19 mm/kV
Pollution Level	20 < s.c. < 25mm	Pollution Level I
Imax		1.538A
'c'	$c \cong 20mm$	23 mm
s / p	$s / p \geq 0.6$	1.64
I_d / d	$I_d / d < 5$	3.17
$(p_1 - p_2)$	$(p_1 - p_2) \geq 15mm$	**5 mm**
P.F.	P.F. > 0.8	3.286
C.F.	$C.F. \leq 3.5$	2.195

Table B2: R19H Dimensioning according to IEC 815 [1]
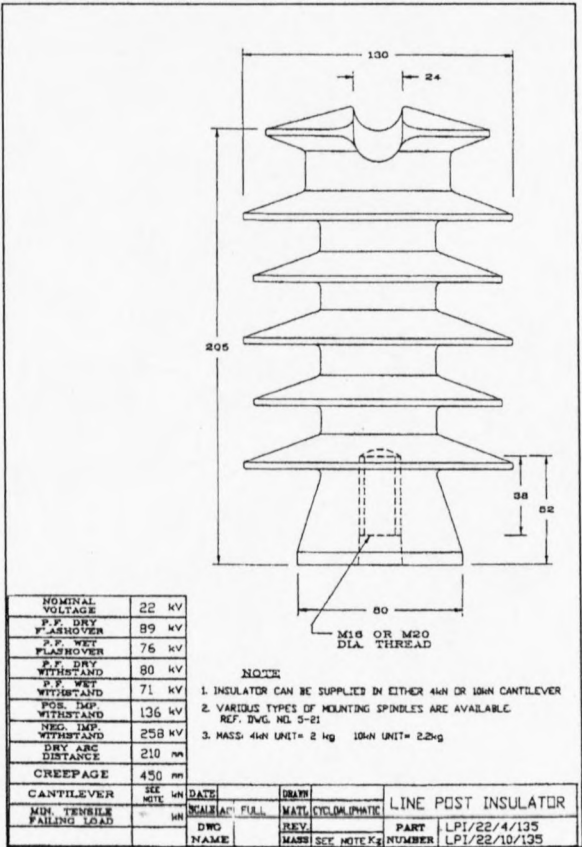
Figure B1: Manufacturers drawing for R19H [2]

R21H

Criteria	IEC 815 requirement	Test Insulator
D_m		< 300 mm
Specific Creepage 'd'		21 mm/kV
Pollution Level	20 < s.c. < 25mm	Pollution Level II
Imax		1.78A
'c'	$c \cong 20mm$	23 mm
s / p	$s / p \geq 0.6$	1.64
I_d / d	$I_d / d < 5$	3.17
$(p_1 - p_2)$	$(p_1 - p_2) \geq 15mm$	5 mm
P.F.	P.F. > 0.8	3.206
C.F.	$C.F. \leq 3.5$	2.202

Table B3: R21H Dimensioning according to IEC 815 [1]

NOMINAL VOLTAGE	22	kV
P.F. DRY FLASHOVER	97	kV
P.F. WET FLASHOVER	80	kV
P.F. DRY WITHSTAND	93	kV
P.F. WET WITHSTAND	65	kV
POS. IMP. WITHSTAND	157	kV
NEG. IMP. WITHSTAND	332	kV
DRY ARC DISTANCE	243	mm
CREEPAGE	535	mm
CANTILEVER	4	kN
MIN. TENSILE FAILING LOAD		kN

LINE POST INSULATOR

PART NUMBER LPI/22/4/135/M3
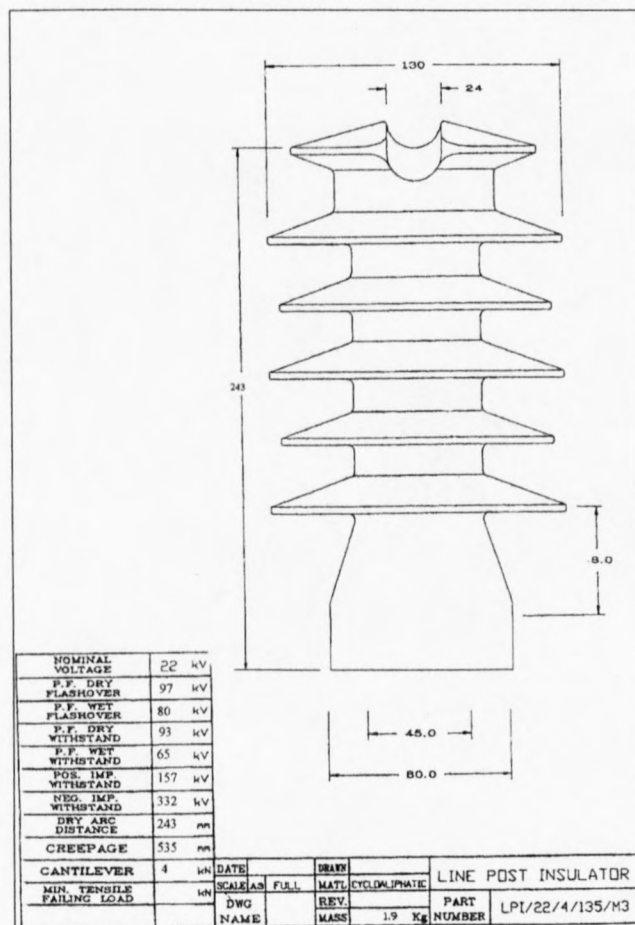
Figure B2: Manufacturers drawing for R21H [2]

R27H

Criteria	IEC 815 requirement	Test Insulator
D_m		< 300 mm
Specific Creepage 'd'		27 mm/kV
Pollution Level	20 < s.c. < 25mm	Pollution Level III
Imax		3.11 A
'c'	$c \cong 20mm$	26 mm
s / p	$s/p \geq 0.8$	**0.433** < s/p < 0.812
I_d / d	$I_d / d < 5$	4.85
$(p_1 - p_2)$	$(p_1 - p_2) \geq 15mm$	23 mm
P.F.	P.F. > 0.7	1.667
C.F.	C.F. ≤ 4	2.33

Table B4: R27S Dimensioning according to IEC 815 [1]

NOMINAL VOLTAGE	22 kV
P.F. DRY FLASHOVER	90 kV
P.F. WET FLASHOVER	70 kV
P.F. DRY WITHSTAND	85 kV
P.F. WET WITHSTAND	62 kV
POS. IMP. WITHSTAND	166 kV
NEG. IMP. WITHSTAND	310 kV
DRY ARC DISTANCE	278 mm
CREEPAGE	690 mm
CANTILEVER	4 kN
MIN. TENSILE FAILING LOAD	kN

INSULATORS ARE SUPPLIED WITH STEEL INSERTS TO SUIT M 20 SPINDLES
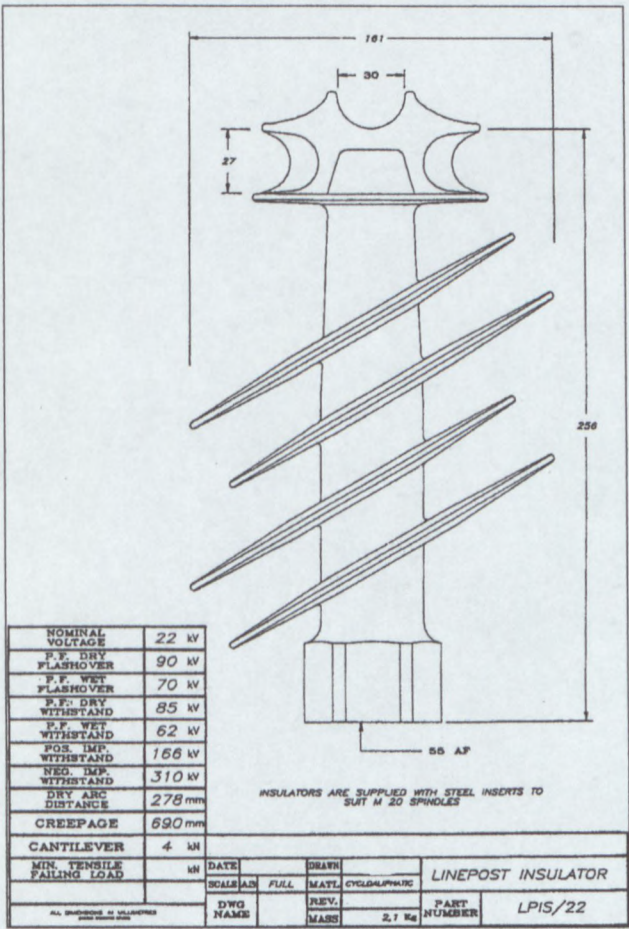
LINEPOST INSULATOR
LPIS/22

Figure B3: Manufacturers drawing for R27S [2]

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