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COMPARISON OF THE ARTIFICIAL CONTAMINATION ACCELERATED TEST METHODS USED IN THE ASSESMENT OF THE POLYMERIC INSULATORS

POLÝMERÝK YALITKANLARIN ÝZOLASYON PERFORMANSINI BELÝRLEYEN HIZLANDIRILMIÞ YAPAY KÝRLÝLÝK DENEYLERÝNÝN KIYASLANMASI

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ABSTRACT

Since the introduction of electricity in 19th century, there has been a growing demand for electrical energy. Higher voltages led the researchers to develop new types of insulator. Many natural insulators, which were widely used at the beginning of this century have been replaced by ceramic or porcelain materials. Many of these suffer low impact strength, brittleness, inflexibility, cracking during the manufacturing process, etc. New polymeric materials are advantages in such cases. Polyester resin mixed with other materials is becoming used throughout the electrical industry. However as with other polymeric insulating materials under abnormal long term stress conditions it suffers from several breakdown mechanisms such as treeing, surface tracking or erosion. Several test methods have been developed to examine the performance of polymeric materials, however usually they exhibit too many random factors associated with them, which reduce their reliability. This paper includes a knowledge of these factors and methods and tries to improve the accuracy and repeatibility of the results.

Keywords: Tracking, insulation, high voltage, test methods, contamination, polymeric material.

ÖZET

19. yüzyýlýn baþýndan beri elektrik enerjisine olan talep gün geçtikçe artmaktadýr. Yüksek gerilimlerde enerji iletiminin mümkün hale gelmesi araþtýrmacýlarý bu gerilim seviyelerine dayanabilecek yeni izolatör tiplerinin bulunmasýna sevketmiþtir. Bu yüzyýlýn baþýndan beri kullanýlmakta olan bir çok doðal izolatör yerini seramiklere býrakmýþtýr. Ancak bu malzemelerin çoðu düþük çarpma þiddeti dayanýmý, kýrýlganlýk, bükülmezlik ve üretim aþamasýndaki oluþan çatlak yapýlar gibi birçok olumsuz özelliklere sahiptir. Yeni polimerik malzemelerin bu yönden avantajlarý bulunmaktadýr. Günümüzde diðer malzemelerle karýþtýrýlmýþ olan polyester

reçine ve benzeri polimerik malzemelerin elektrik endüstrisinde gün geçtikçe daha geniþ bir kullanýml alaný bulmaya baþladýðý gözlenmektedir. Ancak olumlu özelliklerinin yanýnda, bu tip malzemelerde aðaç oluþumu ve yüzey aþýnýmý gibi bazý delinme mekanizmalarýnýn olduðu da bir gerçektir. Polimerik malzemelerin yalýtkanlýk etkisini inceleyen bazý test metotlarý geliþtirilmiþ olmakla birlikte, deneyler esnasýnda kontrolu güç yada imkansýz olan bazý rastlantýsal etkenlerin fazlalýðý bu metotlarýn güvenilirliðinin azalmasýna neden olmaktadýr. Bu çalýþmada, günümüzde özellikle yüksek gerilim izolatörleri olarak kullanýlan polimer yalýtlanlarýn niteliðini belirlemede oldukça baþarýlý sonuçlar veren bazý önemli standard test metodlarý ve bunlara etki eden çeþitli iç ve dýþetkenler incelenerek, daha doðru, kesin ve tekrar edilebilir sonuçlarýn elde edilebilmesi amaçlanmaktadýr.

Anahtar kelimeler: Ýz oluþumu, izolasyon, yüksek gerilim, test düzenekleri, kirlenme, polimerik malzemeler.

1. INTRODUCTION

Insulation materials are primarily used to isolate components electrically from each other or ground or to act as capacitive elements in devices, circuits and systems. None of the existing materials are perfect insulators, however for practical purposes an insulator can be regarded as a material which can limit the current flow to a certain low level[1].

Since the beginning of this century, major developments have been done in insulation technology. The main choices of solid materials were glass, porcelain, composite insulators with a glass fibre core, silicon rubber and EPDM. For high voltage (HV) transmission lines glass and porcelain insulators have been tried and tested for many years and accepted world wide. However with increasing transmission voltages and numbers of sub-conductors in bundles, the mechanical loads to be supported by overhead line types rose above the 40 tonne level. This number may increase up 100 tonne levels if the insulator is going to be used for mega volt services. This provided a logical entrée for the polymeric insulators, using the fibrous composite materials to give high ratious of tensile strength to both size and weight. During recent years polymeric materials have found wide applications in electric and electronic industry and several attempts have been made to investigate the molecular structure as well as the mechanical and electrical features of the polymeric materials [2-8].

There are many different materials on the market with various specifications about insulators. Generally there are three important factors which need to be considered before deciding how an insulator shall be made up and how it will perform in service. These factors can be summarised as ability to operate in adverse weather and contamination, the properties of materials within the insulator and its cost.

2. INSULATOR TYPES

Solid insulating materials may be classified in two basic categories; organic and inorganic. In addition to them, polymeric insulators gained some popularity over recent years.

2.1 Organic Insulators

Generally organic materials, which are vegetable or animal based, have similar characteristics. They are quite easy to apply to equipment and have good insulation characteristic. Their major disadvantage is that their mechanical and electrical properties deteriorate if the temperature exceeds 100 ^{o}C. Most of the organic insulators are absorbent (oil, varnish) solids [9].

2.2 Inorganic Insulators

Electrical porcelain and electrical glass belong to this category of insulator. They can keep their electrical and mechanical properties up to a working temperature of ~250°C. They are quite difficult produce, but generally have very good insulation properties. Their main disadvantage is that they can be cracked easily[10,11].

2.3 Polymeric Insulators

In early 1960's it was recognised that insulators manufactured from polymer composite materials could yield advantages in weight reduction and size with the added advantage of greater resistance to vandal attacks in problem urban areas[12]. As with porcelain insulators, composite insulators also require some acceptable criteria, such as insulation capability and resistance to tracking or erosion during surface electrical discharges and reliable long term mechanical performance[13]. The first composite insulators were produced from glass fibre reinforced epoxy resin. These insulators had some basic disadvantages[12], such as;

- deterioration of the composite surface due to weathering gives rise to the formation of conductive paths leading to electrical failure.
- mechanical failure of glass fibre reinforcements and end fittings.
- significantly higher cost of manufacture.

Polymeric insulators have a good pollution performance, high mechanical strength and have an approximately 90% weight reduction compared to porcelain counterparts. Their outer skin is made of hydrogen atoms, which enables them to resist wetting and contamination more than the ceramic insulators[13,14].

However over a 15 years period some problems, such as chalking and crazing of the sheds, which led to increased contaminant collection; bonding failures along the rod-shed interface, which led to flashover; hardware separation, which led to line drops; corona splitting of sheds and polymer voltage gradient control devices; which led to electrical failure and water penetration due to hot line water washing, which also resulted in electrical failure, forced the manufacturers into designing new and improved generations of non ceramic insulators.

3. FAILURE IN INSULATION SYSTEMS

In solid dielectric materials, the breakdown is not only dependent upon the molecular structure and morphology of the solid but also upon extraneous variables such as the geometry of the materials, the temperature and the ambient environment[1,15-17]. Several mechanisms associated with the breakdown of the polymeric high voltage insulators are summarized below.

3.1 Ageing

Environmental stresses such as humidity, temperature variation, ultraviole radiation, sunshine, mechanical stresses and space charges can accelerate the ageing of an insulator. Wind is also quite important factor especially in designing non ceramic insulators, because it can cause vibrations, which as a consequence can lead to mechanical fatigue in the insulating material[1,17]. Ageing observed in weather exposed polymeric materials has aroused great interest, because it can greatly reduce the lifetime of the polymeric insulators.

Generally ageing based on electrical degredation involves the mechanisms of treeing, partial discharges and dielectric heating.

3.2 Partial Discharge (Corona)

Corona was defined as a partial breakdown of insulation due to intensification of the electric stress at sharp edges or due to increased stress in one component of different insulating materials in series.

Later this definition was enlarged by describing the internal discharges as discharges occuring in conclusions or cavities, the surface discharges as discharges occuring at the surface of a dielectric and the corona discharges as discharges occuring around a sharp adge[18].

It is not easy to produce perfect insulators without any voids. In most cases the gaps (voids) within the dielectric are filled with gas which have a lower permittivity than the polymer. As a consequnce excess field intensification occurs at the ends of the voids. Depending on the gas pressure and other factors, the enhanced field may cause the gas to become ionised and cause breakdown or discharges within the void. Discharges within the dielectric which do not cause the whole polymer insulator to breakdown immediately, are usually called partial discharging.

3.3 Treing

Treeing in solid insulators can be described as an electrical pre-breakdown phenomenon. Treeing is divided into two categories; water treeing and electrical treeing. Electrical treeing occurs after water treeing in this phenomenon. The electrical treeing process can be splitt into different parts[19]:

1- a formative stage in which energy is deposited in a preferred site in the dielectric.

2- a tree initiation stage in which concentrations of ions in the gaseous phase are formed at places of high field concentration and deposition of energy.

3- A tree growth stage in which energy is supplied from the field to the gases which then further erode the solid.

Several mechanisms such as localised overheating, thermal decomposition, fatigue cracking from repeated polarity changes, the presence of small voids, the development of hot electrons, electron injection, mechanical damage from compression due to electrical stress, etc. have been proposed to explain the tree initiation phenomena in solid dielectric materials.

3.4 Thermal Breakdown

Internal heating is usually caused by discharges in voids. In most cases the rate of heating increases with increasing electrical conductivity and temperature. The heat generated is partly lost by conduction to the surface and partly absorbed. If breakdown does not occur, then the temperature will continue to increase until the cooling of the insulator is equal to the electrical power dissipation and a steady-state heat flow is set up[20].

Breakdown can occur if the physical characteristic of insulating materials change, such as breakdown strength is lowered below the applied voltage or the conductivity of the insulation and hence its electrical power dissipation is increased causing a further incrase in temperature. The first phenomenon can be called “destructive breakdown” and the second one can be described as “thermal instability”.

3.5 Electromechanical Breakdown

A rapid decrease in electrical strength of many polymers occurs at temperatures above their softening points. This fact reveals a speculation about a connection between electrical strength and mechanical properties of the material. Experiments show that a repeated electromechanical stress induced around the needle point by an AC voltage application works as a compression force on the polymer. Then the induced mechanical stress perpendicular to the direction of the electric field appears in an elastic material such as a polymer by which the crazing might be caused starting from a micro defect such as a micro void in the polymer when the stress exceeds a critical value[20,21].

3.6 Erosion

Surface discharges in polymeric materials cause thermal and electronic changes in the molecular and atomic structure of the insulating materials. In some cases during these changes carbon volatiles are formed as a part of the backbone structure, which means no residual carbon is left[22]. Such materials do have little or no tendency to track, instead, due to extensive surface discharges, their surface erodes. By using the Thermogravimetric Analysis technique, it is possible to classify a polymer as having a tendency in tracking or eroding.

3.7 Surface Tracking

Surface tracking is a severe degradation process observed on polymeric insulators working in hostile environments. It can be described as a mixed process *(Figure 1)* of discharge inception, carbon formation, carbon path propagation under the influence of an electrolyte, applied voltage, type of electrode, location of discharge, energy of discharge and molecular composition of material[22].

Leakage along the surface of a solid insulating material, which often occurs a result of surface contamination and moisture, may result in dry-band arcing and carbonisation of organic materials and hence conduction along the carbonised path. This process is called “surface tracking”. It is usually progressive, eventually linking one electrode to another and causing complete breakdown along the carbonised track.

The tracking process begins with the creation of low intensity discharge activity. The discharge arises from formation of dry bands and subsequent interruption of leakage current flowing in the layer of ionised water flowing over the surface of the insulator.

The form of the current flow across the surface changes in terms of its magnitude and frequency content according to the discharge activity on the surface. Thus the information contained in the current waveform could also be used to monitor the degradation on the surface on a real time basis.

Surface tracking consists of three phases[13]. When non ceramic insulator are new, their surface are particularly hydrophobic. Surface leakage current are restricted and the insulators have an excellent pollution performance exhibiting high surface resistance *(Leakage current domain 1).* Slow build-up of pollution and cyclic wetting allows the surface leakage current to increase, which in turn may produce a temporary or more permanent low of hydrophocity *(Leakage current domain 2).* Dry band arcing in domain 2 may be responsible for surface erosion since relatively stable arc roots are able to inject significant energy into the NCI material . As leakage current increases, the roots become increasingly mobile and because flash-over is then more likely, the ability to inject significant energy into localised regions is lost *(Leakage current 3).*

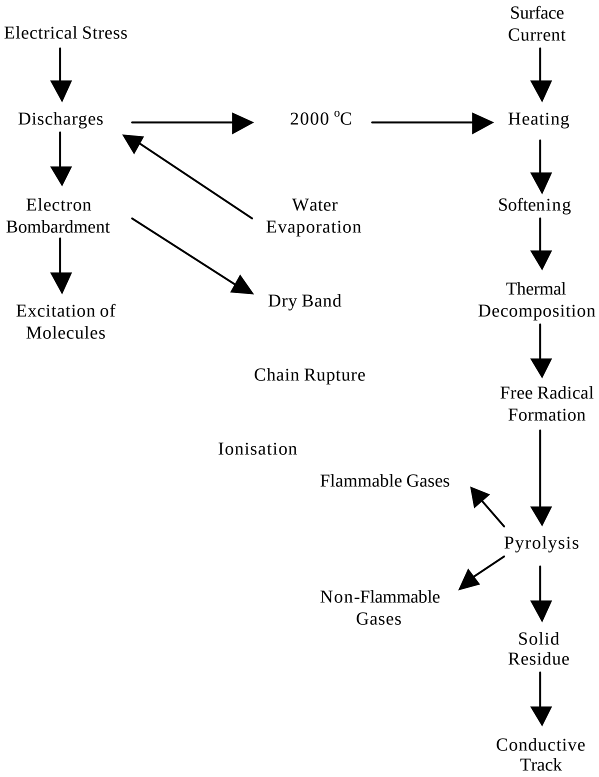


***Figure 1**. Tracking degradation mechanisms[27]*

4. COMPARISON OF THE ACCELERATED TRACKING TEST METHODS

Polymeric insulating materials are exposed to several ageing mechanisms during their service life. These factors can severely damage their dielectric properties and cause a total breakdown of the insulator. However in most cases this process takes quite a long time, which makes it difficult to draw conclusions about the quality of the insulating material. To solve this problem various tests have been developed for assessing the relative tracking and erosion resistance of polymeric insulating materials in a relatively short time under laboratory conditions. Several of tracking methods such as Inclined Plane Test, Comparative Tracking Index Test, Dust Fog Test, Salt Fog Test, Dry Arc Test, Differential Wet Tracking Test and Tracking Endurance Wheel Test have been developed, however in this review only the most common methods are investigated in detail.

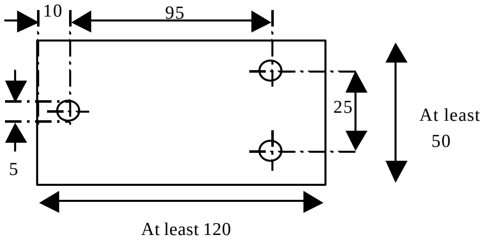
4.1 Inclined Plane Test

The Inclined Plane Tracking and Erosion Test was established in 1961 and was standardized in 1964 with the reference ASTM D2303 [23]. The British version of this standard is BS 5604, which has been adopted by IEC as IEC 587 standard. This test was mainly developed to assess materials required for outdoor use. A sample *(Figure 2)* with the dimensions of *50 mm ´ 120 mm ´ 6.25* mm is mounted at 45^o to the horizontal with a contaminant solution, ammonium chloride *(NH_4Cl)* flowing down the underside of the sample at specified rates between the electrodes. The gap between the HV and earth electrodes is defined as 50 mm and tests are performed at 23 ± 2°C.

As soon as a delta shaped liquid layer is obtained on the surface, a standard voltage is applied between the electrodes. As described in ASTM 2303, the initial tracking voltage test method is used to determine the voltage at which progressive tracking starts. In this method [24] the applied voltage is increased by 250V every hour until a track progresses 13mm from the bottom electrode. The starting test voltage is determined so that tracking failure does not occur sooner than the third step. In order to maintain effective scintillation, the rate of contaminant flow is adjusted for every fourth voltage increment *(Table 1)*. This method is quite useful in evaluating materials to be used at high voltages or outdoors and unprotected.

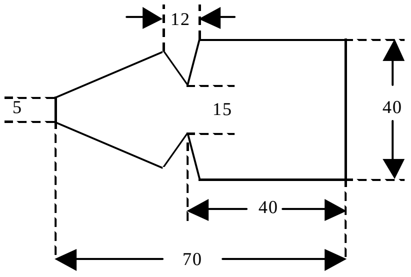
Table 1. Recommended series resistors and flow rates for various voltage levels

	ASTM D2303		IEC 587& BS 5604	
Transformer Voltage (Kv)	Ser. res. (kÙ)	Flw. Rate (ml/min)	Ser. res. (kÙ)	Flw. rate (ml/min)
1.0 - 1.75	1	0.075	-	-
2.0 – 2.75	10	0.150	10	0.15
3.0 – 3.	50	0.300	22	0.30
4.0 – 4.50	50	0.600	33	0.60



(All diamensions are in millimetres)

***Figure 2**. Test specimen*



(All diamensions are in millimeters)

***Figure 3**. Filter Paper*

The other slightly modified method *(IEC 587),* time to track, classifies materials according to withstand 2.5, 3.5 or 4.5kV rms. for a maximum of 15 hours without tracking or erosion. Also if the test lasts less than 10min, the material is assumed to be out of the voltage class. The failure criteria is defined as having a current more than 60mA for a minimum of 2s or if the track is longer than 25mm from the lower electrode. Severe erosion is also accepted as a complete failure. This method is useful for categorising materials for indoor and protected outdoor applications.

The test rig

All electrodes used in Inclined Plane Test apparatus are made of stainless steel, which is more resistant to corrosion from the contaminant than the copper based non ferrous alloys. Both electrode arrangements are presented in *Figure 4.*

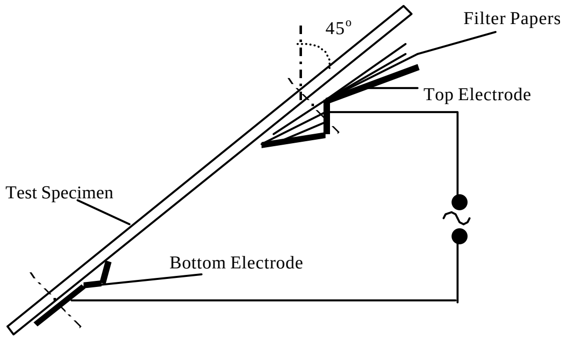
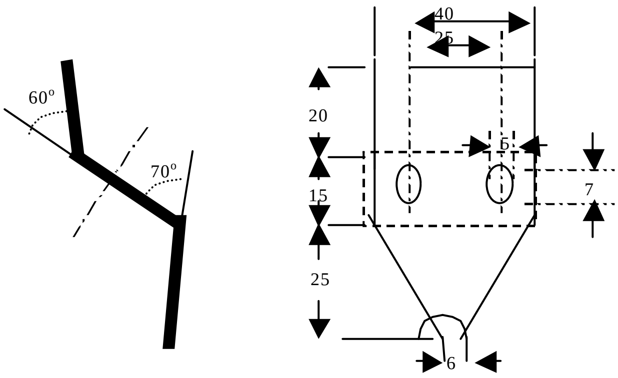


***Figure 4**. Electrode assembly*

Eight layers of filter paper *(Whatman, qualitative),* of dimensions as presented in *Figure 3,* were clamped between the top electrode and the specimen to smooth out the flow of contamination solution. The end of the high voltage electrode *(top)* is provided with a quill tip as shown in *Figure 5(a),* which is in contact with the sample surface. The filter paper was located behind the electrode *(Figure 4)* and outside to extend on to the test surface. The earth electrode *(bottom)* shown in *Figure 5(b),* has a serrated edge angled slightly to make good contact across the whole width of the sample.



(All dimensions are in millimetres)

***Figure 5a.** High voltage electrode*

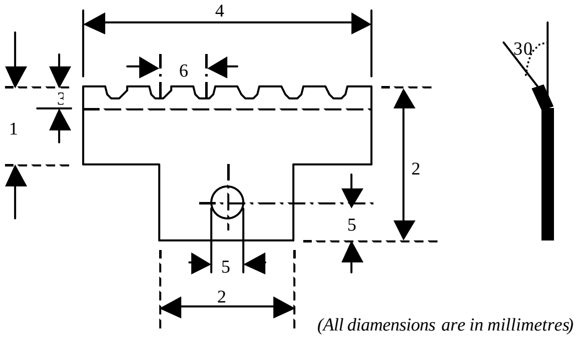


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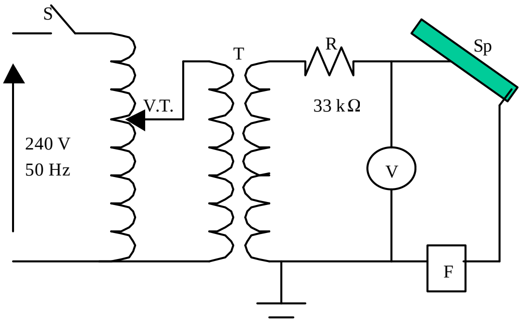
***Figure 5b.** Earth electrode*

The electrode assembly is supplied via a 33kÙ resistor. The applied voltage level is adjusted by using a variable power supply having an output of 25kV stabilised to ±5% with a current rating of no less than 0.1A. The schematic circuit diagram of the system is shown in *Figure 6.* The liquid contaminant used was 0.1±0.002% by mass of analytical quality Ammonium Chloride *(NH_4Cl)* and 0.02±0.002% of the ionic wetting agent Triton X-100 in distilled water. The flow rate of contaminant was 0.6ml/min and the applied voltage was 4kV.

This voltage value provides the best test conditions, because it accelerates the test while maintaining its basic features.



R: Series resistor
S: Power supply switch
Sp: Specimen
T: H.V. Transformer (240 V:25 kV)
V.T: Variable ratio transformer
V : High voltage side voltmeter
F: 60 mA fuse

Figure 6. *Schematic diagram*

4.2 Comparative Tracking Index Test

This test has been developed in Norway and accepted as a standard by the International electrotechnical Commission in 1959 and has been modified in 1979 under designation IEC 112. It has been accepted by ASTM[25] under designation D3638-77, which has been adopted to British standards under designation BS 5901[26,27]. The test consists of two chisel shaped platinum electrodes *(Figure 7)* having a cross section of *5mm´2mm* and are placed *4±1mm* apart on the surface of the sample with a total angle of 60° between them.

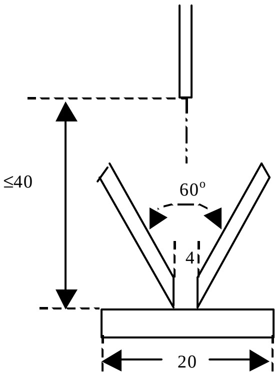


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Figure 7a. *CTI electrode arrangment*

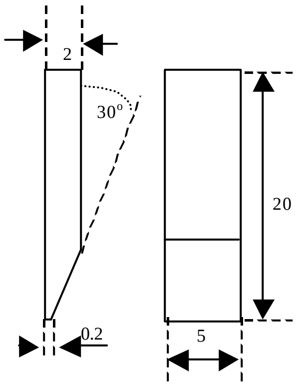
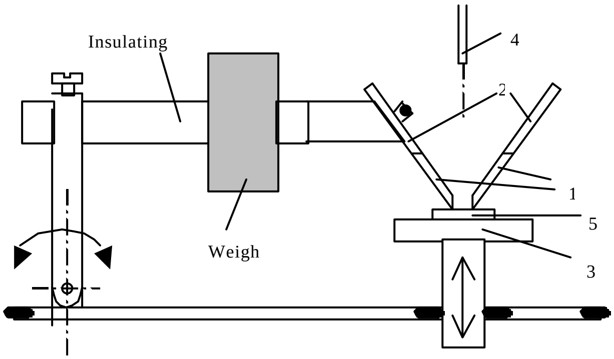


Figure 7b. *CTI electrode arrangment*

The sample has the dimensions of minimum *15mm´15mm´3mm* and the force on its surface should be *1±0.05N*. Drops of 0.*1±0.002%* ammonium chloride in distilled water falls on the surface of the test specimen between the electrodes at intervals of *30±5* seconds *(Figure 8).* The volume of each drop is $20mm^3$



1. Platinum electrode
2. Brass extension
3. Support
4. Tip of dropping device

Figure 8. *CTI test set-up*

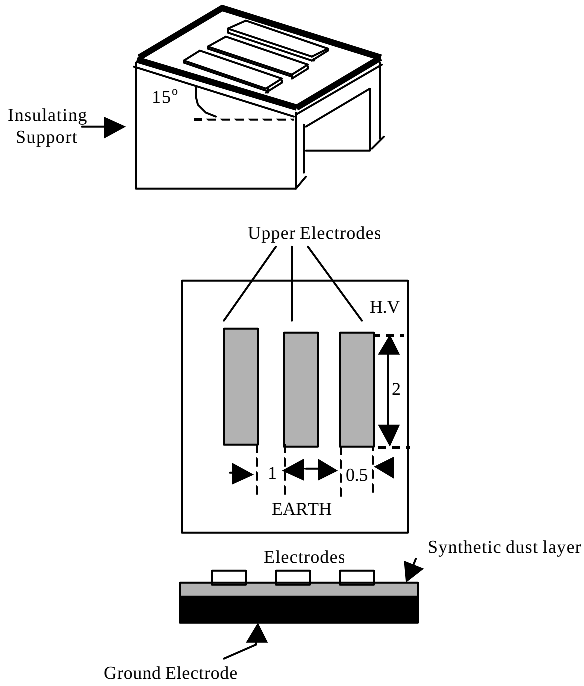
A voltage between 150V to 750V is selected before the test and the circuit resistance is adjusted to limit the short circuit current *to 1±0.1A*. Test continues until the sample tracks or 50 drops fall. Failure occurs if a current more than 0.5A flows between the electrodes for more than 2s.

4.3 Dust fog test

The dust-fog test was first introduced in 1956, modified slightly in 1979 and accepted as ASTM D2132-68 standard[22,27]. In this test the surface of the polymer is coated with a solid contaminant containing 3% NaCl and is exposed to an artificial fog. Test specimens *(Figure 9)* consist of material sheets, 0.0625inch thick and having an area of 5 to 6inch². After positioning the electrodes, samples are coated with a dust layer to a uniform depth of 0.02 to 0.025inch. The dust has a solid contaminant and the recommended composition by weight is 85% Fling *(SiO_2 floated,240-mesh),* 9% Clay *(325-mesh),* 3% Salt *(NaCl, technical grade),* 3% Paper *(filter pulp).* In this mixture salt produces an ionic surface contamination and the rest act as bulk and adhesive properties

A water spray or fog wets the dust coating on the specimen and the drainage of the sample surface is achieved by an inclination of the sample 15° to the horizontal. After the wetting operation, an initial voltage of 500V is applied to the surface via copper electrodes spaced 1inch apart. Due to the surface conduction the boils off and scintillation occur across the dry band region.

To maintain this process, the surface of the sample is wetted continuously within the rate of evaporation caused due to the discharges and surface current in the contaminant film. During the test the contaminant resistance increases due to the loss of the salt caused by continuous water spraying, hence the voltage is increased gradually up to 1.5kV. The criterion for failure by tracking is accepted as the time taken for the electrodes to be bridged by a track across the surface. If the tested material is non tracking, then it will fail by erosion through the thickness of the sample to a grounded plate underneath. This test can classify materials as tracking resistant, tracking effected and tracking susceptible. A typical test time is around 500 hours, although in some cases it may take up to 2000 hours for a compete failure



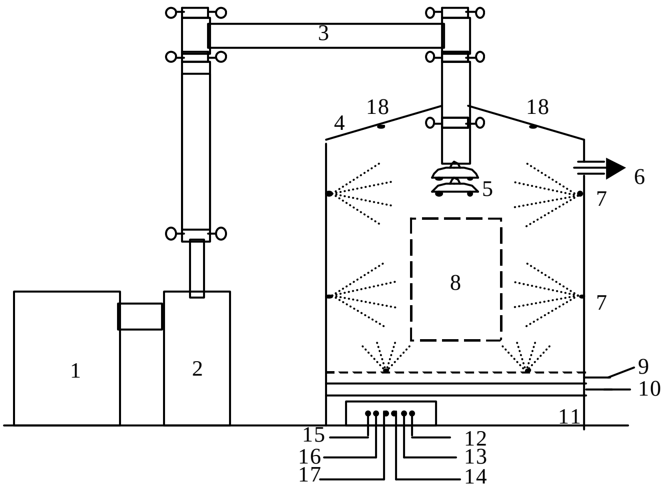
(all dimensions are in inch)

Figure 9. *Dust-fog electrode assembly*

4.4 Salt fog test

This test has been accepted by IEC under designation 1109 and used as an effective method to assess the tracking and erosion resistance of polymeric insulators. It uses a moderate test voltage of around 10kV, which is connected to a 1 inch in diameter, 6-8inch long tungsten rod electrode. The test chamber *(Figure 10)* is filled with fog which is produced by a turbo sprayer, humidifier or IEC 60 atomising spray system.

The size of droplets should be smaller than 50ìm. The test aims to gradually raise the current level and monitor the region where tracking occurs *(0.5-5mA).* However rather than giving an estimate about the service life of an insulator, the test is basically designed to classify materials as having a tendency to tracking or erosion.



1. Test Transformer
2. Potential divider
3. H.V. connection
4. Chamber shell
5. Test object
6. Pressure outlet
7. Spray outlet
8. Chamber door
9. Earthing surface
10.Metallic ring
11.Sump
12.Water supply to corner nozzles
13.Water supply to corner nozzles
14.Water supply to base nozzles
15.Electrical supply to pump in sump container
16.Air supply to corner nozzles
17.Air supply to base nozzles
18.Water purge nozzles

Figure 10 *Salt-fog test facility*

In order to improve the reliability and accuracy of the results, several modifications have been done to the test procedure, such as stopping the water spraying for a fixed time to allow the recovery of the hydrophobic surface character of the test material, which is quite common under real environmental conditions[15,27,28].

5. CONCLUSION

The long term insulation performance of the polymeric high voltage insulators can be determined in laboratory conditions by using some accelerated tests. Such test are quite useful to observe the degradation and tracking process on the surface of the polymeric insulators. In this review several accelerated test methods have been investigated and compared. The Inclined Plane Tracking test is quite useful in representing the 'wet tracking' phenomenon and the results usually correlate quite well with the performance of the materials used outdoor. The test is easy to set-up and perform, however in most cases it is quite difficult to achieve reproducible result. Environmental factors such as temperature, air circulation, flow rate, etc. need to be monitored and controlled continuously during the test period[29]. To overcome the problems associated with the Inclined Plane Tracking Test, 'Dust-Fog' and 'Salt-Fog' tests with longer test durations have been developed, which should simulate the real service conditions more closely. However Dust-Fog is difficult to perform and needs continuous attention. If the current during scintillation can be maintained at 15mA, then the variability in the results can be reduced. Otherwise results become random and cannot be reproduced from sample to sample.

The CTI test monitors the performance of insulating materials at low test voltages under wet conditions. Its main disadvantage is that the voltage source is limited to 600V, hence it does not allow to test insulators with high surface resistance.

Some researchers suggested that the variability in the test result can be reduced and experiments can be accelerated by monitoring the loss of weight caused due to erosion in a certain time. Also by considering a standard mass of material as the critical parameter before the test, materials can be classified according to their rate of erosion. However this method has the disadvantage that some materials, especially filled polymers can erode slowly, but in most cases they puncture prematurely. Many materials show this tendency in the Dust-fog test and outdoor tests have confirmed this high strees local erosion. According to this erosion test it is possible to determine a material to be acceptable for a prolonged outdoor service.

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