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‘DC Inclined-Plane Tracking and Erosion Test of Insulating Materials’

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DC Inclined-Plane Tracking and Erosion Test of Insulating Materials

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ABSTRACT

The paper reviews previous work on the DC inclined plane test and suggests equivalent DC voltage levels in parallel to AC voltage in the ASTM inclined plane tracking and erosion test. The aim of this work is to provide a basis for standardizing the inclined plane test for DC voltage. Round robin tests done in five laboratories on five specimens of a silicone rubber material were done with the purpose of establishing appropriate ratios by which the equivalent DC voltages can be determined with respect to the corresponding AC voltages. These levels were determined as 67% and 87%, for +DC and -DC respectively, of the AC initial tracking voltage.

Index Terms — DC Inclined plane test, tracking and erosion, ASTM D2303

1 INTRODUCTION

The ASTM D2303 liquid-contaminant inclined-plane tracking and erosion testing (IPT) of insulating materials [1], stems from the work reported in 1961 by Mathes and McGown [2]. The first edition of the corresponding IEC 60587 test, became available in 1977 [3], and currently is in its third edition [4]. These two standards are the most comprehensive tests for tracking and erosion of insulating materials for AC in that their scopes cover two tracking and one erosion procedure.

The inclined plane is the sample itself having the dimensions of a coupon, 125 x 50 x 6 mm thick, suspended at an angle of 45°, with a liquid contaminant that flows on the lower face of the sample from a filter paper reservoir under the high voltage electrode, down the sample face to the lower grounded electrode. The specified electrodes are separated by a distance of 50 mm and the rate of flow is tabulated for given applied voltage levels such that continuous scintillations occur on the sample face.

Prior to the application of voltage, a continuous liquid-contaminant rivulet has to be always maintained for a given flow rate, thereby minimizing the ability of hydrophobic surfaces to suppress continuous cycles of wetting and scintillations. For materials that track, rooting

of the scintillations occurs immediately above the lower grounded electrode, leading to progressive tracking towards the high voltage electrode. As for tracking-resistant materials, erosion can take place in defined areas or progressive paths towards the upper electrode.

Tracking is assessed in two ways, either by the initial tracking voltage, that is the lowest applied voltage at which progressive tracking takes place for a specified 12.5 mm, or by the time to track, which is the time taken for tracking to proceed over the specified distance at a given voltage. Commonly in both, the erosion depth is measured using a specified depth gage. A laser profilometer can be used to measure the erosion depth.

To date, the standard IPTs includes testing by AC voltage and although used by many researchers for DC voltage, the test method has not yet been standardized. The aim of this committee paper is to provide a basis for standardizing the IPT for DC voltage.

2 REVIEW OF PREVIOUS WORK

In this brief review, the relative ranking of the materials evaluated are not discussed as the conditions of test are not all the same. One of the first observations of the increased severity of DC over AC stress on polymeric materials was observed in 1988 in salt-fog chamber studies. In these tests it was clear that $-DC$ stress caused a marked reduction in the tracking and erosion resistance as compared to AC and $+DC$ which seemed to perform similarly [5]. In 1998, Guan used DC instead of AC voltage in the IPT and reported the damage level of samples tested by $+DC$ was greater than $-DC$ [6]. Moreno and Gorur [7] performed AC and DC IPTs on polymeric materials and noted that a substantial reduction in the tracking and erosion resistance of the polymeric materials tested was observed with DC stress, in comparison to AC. The poorer material performance stressed with DC voltage was attributed to higher magnitudes and longer duration times of the discharge current pulses.

In outdoor tests on polymeric materials at the Anneberg field station on the west coast of Sweden, DC stressed samples showed higher leakage current and exhibited larger surface degradation compared with samples exposed to AC voltage [8]. The constant voltage IPT method was employed to compare the resistance of various polymeric materials under the same AC, positive DC, and negative DC voltages. For all types of materials tested, it was observed that DC is more severe than AC and it was evident that there was a clear DC polarity effect [9].

In another IPT study, the performance of samples was evaluated under positive and negative DC [10]. At the same test voltage, it was observed that positive DC voltage showed the highest level of erosion which increased as the test voltage increased. However, positive DC showed more intermittent current discharges than negative DC and promoted higher average leakage current. In addition, erosion of the positive electrode from electrolysis and

oxidation of the bottom electrode due to high temperature arcing was also observed by Bruce et al [10] resulting in deeper erosion and greater mass loss under $+DC$ as compared to $-DC$. This is an indication that positive and negative test voltages cannot be at the same level in the IPT.

In other tests reported by Rowland et al [11] it was indicated that the performance of materials in the DC IPT is not just about discharge resistance against erosion or carbonization, it is also about the way that moisture flows over the sample during the test.

Ghunem et al. [12] suggested the tracking/erosion class criterion in ASTM D2303 be used as a bench mark to set equivalent DC IPT voltage levels for the constant voltage (erosion and time-to-track) methods in the IPT. It was concluded that, for the tested composites, the equivalent $+DC$ and $-DC$ IPT voltages in the constant voltage methods have to be 67% and 84%, respectively, of the standard AC(rms).

In a subsequent paper, Ghunem et al. [13] showed correlation between the formation of surface residue and the inception of eroding dry-band arcing under DC with less correlation under AC and faster accumulation of residue under $-DC$ than under $+DC$.

In general, although polymeric materials have been evaluated using the DC IPT, the fundamental aspects of the test conditions has been less thoroughly researched than the AC case. Clearly, positive DC has been shown to be more damaging than negative DC or AC. For both polarities, the DC test voltage that evaluates material performance equivalent to AC, for the same conditions of test, is desirable for comparing AC to DC applications.

A critical test voltage range has been determined in the AC IPT according to specific flow rates of the liquid contaminant. Therefore, before a comparison between AC and DC IPTs can be made, there is a need for an equivalent critical DC test voltage, for both polarities, according to the specified contaminant flow rates in the AC IPT.

3 CONTROLLING PARAMETERS IN THE INCLINED PLANE TEST

Although the outcomes of the IPT may not be directly correlated to the tracking or erosion of outdoor insulating materials in field conditions, the equivalent AC and DC voltages must be selected with respect to the fundamental differences of the AC and DC dry-band arcs, with laboratory biasing conditions maintained to be insignificant. Such a dilemma can be solved through carefully modifying the applied DC as compared to the corresponding standard AC voltages, based on a thorough understanding of the controlling parameters of the IPT outcomes. The parameters that control the dry-band scintillations in the IPT namely, the conductivity of the contaminant, the flow rate of the contaminant, the series ballast resistor, the test voltage, and the surface tension of the contaminant as modified by a wetting agent, all will have an effect. Accordingly, for a specific contaminant

conductivity and flow rate, the test voltage has to be chosen to obtain continuous scintillations to be effective in creating tracking or erosion in the material surface [1]. Therefore, the chosen test voltage must lie within a critical range.

If the test voltage is well below the critical range, no scintillations will take place and the flowing contaminant acts simply as an aqueous resistor. Choosing the test voltage above the critical range will change the scintillation from steady to intermittent, and if the voltage is way beyond the critical range, the scintillations occur away from the surface and are ineffective to cause tracking and erosion and may cause flashover. Therefore, the selection of suitable combinations of the test voltage, ballast resistance value and flow rate, without biasing the degree of intermittency, is the essential task that has to be achieved.

3.1 EFFECTIVE AC TEST VOLTAGE

Early work reported by Jolly [15] using a salt-fog chamber to age polymeric materials indicated that for a specified contaminant conductivity, the critical range of test voltage for effective dry-band scintillations is such that the power dissipated to heat and evaporate the flowing contaminant layer balances the flow rate of the contaminant. What is meant by “effective” dry-band scintillations are scintillations that are as close as possible to the material surface and which are thus able to thermally ablate the material. Therefore it follows that the critical range of voltage in the IPT must be such that the same conditions are produced. It should be noted, on the other hand, that the term “critical testing voltage” has been also used in identifying the IPT voltage level leading to deep erosion or failure of insulating materials [16].

The contaminant in both standards is ammonium chloride and both specify a conductivity at 23 °C that is nearly the same; 2.5 to 2.7 mS/cm in ASTM whereas IEC specifies 2.5 to 2.6 mS/cm; the wetting agent added is nonionic with minimal influence on the conductivity. In both standards, the specified flow rate is the same, 0.075 to 0.90 ml/min, depending on the test voltage which ranges from 1.0 to 1.75 to 5.0 to 6.0 kV. However, ASTM specifies a higher value of current limiting resistance than in IEC for test voltages above 2.75 kV.

To examine the effective test voltage range in the AC IPT, room temperature vulcanized (RTV) silicone rubber samples having 30 wt % silica were exposed to a staircase voltage in steps of 0.25 kV over the range 0 to 5 kV, with each voltage step lasting one minute and the whole test lasting 20 minutes [12]. During the test, the RMS leakage current was sampled in one-second intervals. The test was done for 0.15, 0.3 and 0.6 ml/min flow rates, contaminant conductivity of 2.5 mS/cm and series resistance of 10 and 50 kΩ, respectively, as specified by ASTM D2303.

Following the above protocol, three stages in the development of leakage current is observed as shown in Figure 1. In the first stage (A in Figure 1), below 1.75 kV,

the contaminant acts as an aqueous resistance while above this level the leakage current shows the beginnings of distortion (third harmonic) indicating the early stage of dry band arcing (B in Figure 1). At 2 kV, the dry band arcing is sustained (C in figure 1) and this level can be considered as the ideal test voltage for the conditions outlined and as recommended by Mathes and McGown [2]. When the above protocol is followed for the three flow rates and series resistances, the experimentally determined optimum test voltage matches the ASTM recommended test voltages for contaminant flow rates of 0.15 and 0.30 ml/min, but is lower by 0.5 kV than recommended for the 0.6 ml/min flow rate. Note that a tolerance of 0.25 kV has been already recommended to be taken in consideration when looking into the IPT outcomes [1].

When the above experimental method is applied to –DC and +DC, the measured optimum test voltages are shown in Table 1. The experimentally derived optimum test voltage is between 75 and 88 % and 67 and 88% of the recommended ASTM AC test voltage, respectively for –DC and +DC. The relative difference in the dry-band inception voltage with respect to the voltage type, indicates a corresponding difference in the surface resistance prior to scintillations [16], which modifies the leakage current magnitude.

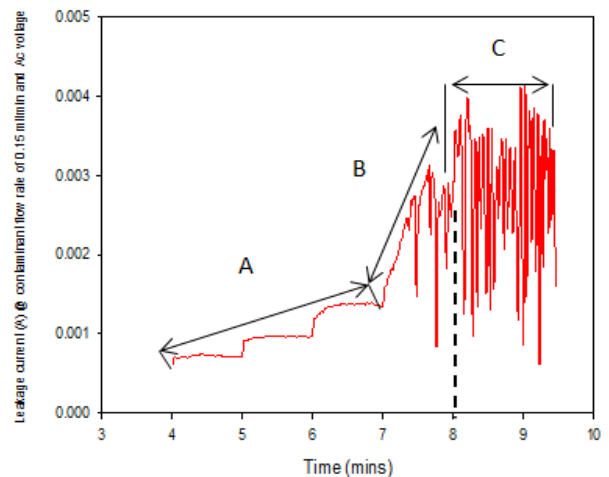


Figure 1. Stages in the development of leakage current, sampled in one second intervals in the IPT with contaminant conductivity of 2.5 mS/cm, 0.15 ml/min flow rate, and ballast resistance of 10 kΩ while increasing voltage from 0 in 0.25 kV steps in one-minute intervals on a RTV silicone rubber sample filled with 30 wt% silica. In A to 1.75 kV, the contaminant acts as an aqueous resistor; B to 2 kV, initial stage of dry band arcing as evidenced by distortion (third harmonic) of the leakage current; C sustained dry band arcing or the optimum test voltage.

Table 1. Optimum IPT voltages determined by staircase application of voltage obtaining stage “C” in Figure 1.

Voltage Type	Contaminant flow rate ml/min	Series Resistance kΩ	Optimum Test Voltage kV	ASTM Test Voltage kV
AC	0.15	10	2.0	2.0
	0.30	50	3.0	3.0
	0.60	50	3.5	4.0
-DC	0.15	10	1.75	0.88ASTM
	0.30	50	2.25	0.75ASTM
	0.60	50	3.25	0.81ASTM

+DC	0.15	10	1.5	0.75ASTM
	0.30	50	2.0	0.67ASTM
	0.60	50	3.5	0.88ASTM

3.2 BEHAVIOUR OF LIQUID CONTAMINANT UNDER +DC, -DC AND AC

Surface tension is an inherently dominant force in the wettability of the surface by liquid contaminant in the IPT. Contact angle arises from the capillary energy at the triple interface formed by the contaminant, the surface of the sample, and air, as reduced by electrostatic energy from the electric field. This phenomenon is referred to as electrowetting. Electrowetting is dominant at DC through the minimization of interfacial energy by charge, either injected or induced, but it also applicable to AC, to a lesser extent at power frequency. In a diverging electric field, the expulsion of small droplets of contaminant in the IPT will occur which increases with increasing applied voltage and is an indicator of instability at the triple point that comes about when the electrostatic force overcomes the capillary force. Ghumen et al. clearly observed the expulsion of small droplets from the contaminant rivulet under AC, +DC and -DC as reproduced in Figure 2 [13]. With increasing test voltage, the volume of ejected contaminant increases, reducing the rivulet and therefore the conductance and the dry band arcing current also diminishes. Similar images of water droplets surrounding a continuous conductive channel during testing under AC have been reported earlier [18].

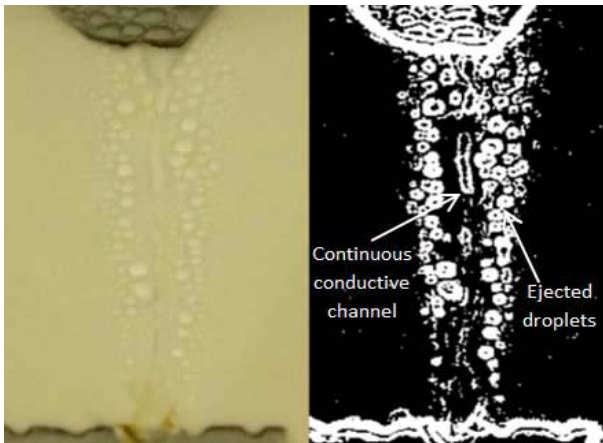


Figure 2. Expulsion of droplets of liquid contaminant in the IPT under DC as reported by Ghunem et al. [12].

Foam in the contaminant rivulet under -DC has been observed which appears to be generated at the upper electrode [10, 12] and the production of hydrogen during electrolysis was suggested as the reason for the foam [10].

3.3 DC POLARITY EFFECT

The effect of DC polarity on electrode and material erosion has been reported by several researchers [6, 10, 12]. In both AC and DC tests, the electrodes can become severely eroded and they need to be replaced for

subsequent tests. In DC tests, the positive electrode erodes considerably more than the negative electrode due to electrolysis [10]. Normally, the top electrode is made positive or negative, but when made positive, the electrolysis process of liberating metallic ions may contribute to increased electrical conductivity. Another possibility is the effect of the electrolysis on increasing the conductivity of the burning arc [19]. In DC tests, there is evidence of erosion of the positive electrode (anode) from electrolysis and oxidation of the bottom electrode due to high temperature arcing [10]. In DC IPT on silicone rubber, Wang et al. [17] observed white electrocorrosion deposits near the ground electrode which affected the arc duration.

In all three voltage modes, the eroded path is initiated from the bottom electrode. Positive DC tests have higher average leakage current, are more intermittent and produce deeper erosion and greater sample mass loss as compared to their equivalent negative test while the time-to-track is shorter with -DC than +DC [13-14]. The observed surface degradation pattern is also considerably different in each case. The likely contributing factors to the above are: shape and volume of conductive filaments on the surface, the electro-hydrodynamic behaviour of the contaminant, existing surface damage patterns and the effects of electrolysis [10].

3.3 THE EFFECT OF SURFACE CONDITION

Longer channels of deposits under +DC as compared to -DC were reported by Bruce et al. [10, 11] and a correlation between these deposits and hot spots leading to erosion was reported by Ghunem et al. [14]. Vas et al. [20] showed energy dispersive X-ray analysis (EDAX) images of these deposits indicating their formation due to decomposition of silicone rubber and the corrosion byproducts of the upper electrode with a distinction between these deposits and char which is formed as a byproduct of erosion [2]. The char sometimes shields the virgin surface of the silicone rubber from the heat of the dry-band arcing when arcing takes place above the char but it has been reported that when liquid contaminant flows between the char and the surface, dry-band arcing promotes burning of the rubber [21-22]. Gorur et al showed conductive deposits to influence the tracking and erosion performance of silicone rubber and EPDM composites in salt fog [5].

The effects of the deposits on the tracking and erosion resistance was first recognized by Mathes and McGowan [23] who selected ammonium chloride as the liquid contaminant as opposed to salts in an attempt to reduce the accumulation of deposits on the sample during testing, thereby reducing their influential effect.

4 SELECTION OF THE EQUIVALENT TESTING CONDITIONS

Equivalent erosion testing conditions has been mostly understood in the context of applying equivalent voltages

under AC and DC [10, 13], leading to similar dry-band arcing power under AC and DC. Voltage selection with respect to the withstand voltages have been also proposed, as the insulator stress level is selected with respect to the withstand voltages/creepage distance [24]. Similar approaches can be used when testing for tracking resistance in the time-to-track method, but not in the initial tracking voltage method in which voltage itself is the outcome. The contaminant flow rate and conductivity will also have an effect on the result.

5 ROUND ROBIN TESTS

The IPT samples supplied for these tests were in the form of coupons, 127 mm long × 50 mm wide and a thickness of 5 mm which were prepared from RTV 615 liquid silicone rubber, a two-part vinyl-polydimethylsiloxane without fillers. The two parts, A and B, were mixed using a high shear mixer maintaining a weight ratio of 10:1 between the two parts and then adding 30 wt % silica filler to the mix. The silica filler has a median particle size of 1.4 μm and a density of 2.65 g/cm³.

The material weights were measured using an electronic balance, Sartorius model AC 211S-00MS, having an accuracy of 0.1 g. The prepared composites were degassed and then cured at room temperature. The cross-linked composites were heated in an oven at 85 °C for three hours, and then the samples were cleaned using ethanol and deionized water.

Fifteen samples with type 302 stainless steel electrodes for each sample were supplied to five laboratories for the round robin tests. The main purpose of the round robin tests is to establish the appropriate ratios by which the equivalent DC voltages can be determined with respect to the corresponding AC.

The initial tracking voltage (ITV) method as per ASTM D2303 was implemented as outlined in the following steps where the test begins once a continuous channel of the liquid contaminant on the surface is observed [1]. The flow rate of the liquid contaminant was chosen to be 0.3 ml/min, and accordingly a ballast resistance of 50 kΩ was used. The failure criteria for stopping the test are (1) obtaining a 2.54 cm (1 inch) erosion path, and (2), a hole due to intensive erosion or ignition of the sample surface.

1. Voltage is applied in one hour steps with a level increment of 250 V in each proceeding step.
2. If a failure criterion is met within the first two voltage steps, the test is terminated and repeated with a lower starting voltage.
3. The ITV is the voltage at which a failure criterion is met, given that the failure has occurred in no sooner than the third voltage step.

The starting voltage is normally chosen based on experience and for the round robin tests, the starting rms AC, +DC and -DC voltages were 3.25 kV, 2 kV and 2.5 kV, respectively.

All five laboratories completed the tests in accordance with the above protocol. These results are shown in Table 2.

Table 2. Results of the round robin initial tracking voltage (ITV) tests. Each row corresponds to the results from the individual laboratories.

Starting Voltage kV	Initial Tracking Voltage kV				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
AC 3.25	4.25	4.0	4.0	4.25	4.25
	3.75	4.0	4.0	3.75	4.0
	3.25	3.5	3.5	3.75	3.5
	3.5	3.75	3.75	4.0	3.75
+DC 2.0	4.0	4.25	4.0	3.75	3.75
	2.25	2.0	2.25	2.25	2.25
	2.5	2.75	2.5	2.75	2.75
	2.75	2.75	2.5	2.5	2.5
-DC 2.5	2.5	2.5	2.25	2.5	2.5
	2.0	2.25	2.25	2.25	2.25
	3.0	3.0	3.0	3.0	2.75
	2.75	3.25	3.25	3.25	3.25
	2.75	3.75	3.5	3.75	3.75
	3.0	3.25	3.0	3.25	3.0
	2.75	2.5	2.75	2.75	2.75

Table 3 shows the average and one standard deviation of the results from the five samples and the five test laboratories. The standard deviation is in the range of 7 to 11 percent of the average which is remarkably good for the IPT. The table also shows the average test results rounded to the nearest voltage step as per test guidelines and also shows the number of voltage steps from the initial starting voltage. The results clearly show the +DC and -DC initial tracking voltages are respectively, 67 % and 87 % of the AC initial tracking voltage.

Table 3. Summary of round robin initial tracking voltage tests.

Voltage	$\bar{x} \pm \sigma$	Nearest voltage step range	Steps from starting voltage
AC	3.85 ± 0.27	3.75 - 4.0	2 - 3
+DC	2.42 ± 0.22	2.25 - 2.5	1 - 2
-DC	3.08 ± 0.34	2.75 - 3.25	1 - 3

6 CONCLUSIONS

The accepted tracking and erosion tests of materials for use in outdoor AC insulation applications is the ASTM D2303 and the corresponding IEC 60587 tests. While there are no standard tests for outdoor DC insulation applications, DC voltage has replaced the AC voltage in inclined-plane tracking and erosion tests. Equivalence in tracking and erosion testing has been mostly understood in the context of applying equivalent voltages under AC and DC leading to similar dry-band arcing power under AC and DC. Voltage selection with respect to the withstand voltages have been also proposed, as the insulator stress level is selected with respect to the withstand

voltages/creepage distance.

The aim of this committee paper is to provide a basis for standardizing the inclined-plane tracking and erosion test for DC voltage. Round robin tests done in five laboratories on five specimens of a silicone rubber material were done with the purpose of establishing appropriate ratios by which the equivalent DC voltages can be determined with respect to the corresponding AC voltages. These levels were determined as 67% and 87%, for +DC and -DC respectively, of the AC initial tracking voltage.

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