The electrical tracking and erosion resistance evaluated using the inclined plane test: a critical task in the development of outdoor polymer insulating materials

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The Electrical Tracking and Erosion Resistance Evaluated Using the Inclined Plane Test: A Critical Task in the Development of Outdoor Polymer Insulating Materials

Key words: inclined-plane test, tracking, erosion, dry-band arcing, polymer insulators, silicone rubber, inorganic fillers, HVDC insulation.

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Understanding the reasons why the inclined plane test methods have been developed is becoming a significant task not only to enhance the test reliability and reproducibility but also to establish sound principles for tackling new tasks, such as the development of silicone rubber housing composites for outdoor DC insulators.

Introduction

Evaluating the electrical tracking and erosion resistance of polymeric housing materials is an essential task performed in the development of outdoor insulators. Tracking refers to the formation of a carbonaceous path on the surface of the insulation housing; whereas, erosion indicates weight loss of the housing material. An absolute realization of the electrical tracking and erosion resistance is not possible and therefore relative ranking of materials is the outcome that can be obtained in the standard electrical tracking and erosion tests. With the early utilization of organic insulating materials, failure due to tracking was a major concern, and therefore standard screening methods were proposed to mainly evaluate the tracking rather than the erosion resistance. Erosion is more important since the application of tracking-resistant composites compounded with high levels of inorganic fillers or possessing inorganic backbones such as silicones.

Several tests with different methods and apparatuses have been proposed to evaluate the tracking and erosion resistance, but with surface arcing induced as a result of the synergistic effect of voltage, moisture and pollution commonly identified as the aging mechanism. The wet-tracking index or the comparative tracking index (CTI) test method described in the IEC 60112 was considered as a superior replacement to the dry-arc resistance test as per ASTM D495, on which insulating materials were tested under dry conditions [1] . With a liquid-contaminant droplets applied between chisel-shaped electrodes that are separated by 4mm distance and energized under different voltage levels up to a maximum of 600 V, the CTI was found reproducible and suitable for low-voltage applications. A drawback, however, was raised about testing materials under higher voltages, thus the range of the materials that could be examined. Such a limitation probably contributed in obtaining a "no tracking" outcome for some of the materials that had actually failed in outdoor polluted environments [1]. When approaching an applied voltage of 750 V, the CTI test was shown to promote flashover rather than tracking, and therefore was not found severe enough to evaluate the best materials typically utilized for outdoor insulation applications. In 1956 Albright and Starr suggested the dust-fog test as a field-correlated method through which wider spectrum materials could be tested [1]. Sommerman showed strong correlation between the dust-fog test outcomes and field experience [2], and the dust-fog test was standardized in the

ASTM D2132 in 1962 [1].

In 1961, Mathes and McGowan proposed the inclined-plane liquid-contaminant test (IPT) [3], standardized in the ASTM D2303 [4] and IEC 60587 [5]. Evaluating materials with the IPT was shown possible in lesser time and variability as compared to the dust fog test [6]. The IPT provided flexible and firm parametric control of the liquid contaminant, thereby leading to reproducible tracking outcomes. In addition, the test configuration was found suitable for wide range of voltages, and the test outcomes could be correlated to an acceptable extent with the dust-fog test [3]. The correlation was determined despite maintaining continues scintillations throughout testing; a condition that does not simulate the intermittent nature of the scintillations reported for actual conditions. Most importantly, an erosion testing method separated from tracking could be implemented using the IPT apparatus, thereby promoting the IPT for evaluating housing compositions that are resistant to tracking and yet susceptible to erosion.

Although techniques such as the rotating-wheel dip test and the salt fog test have also gained popularity, the IPT is considered as a convenient and reliable technique at the material development stage. However, a parametric discrepancy in conducting the IPT is still evident, which imposes difficulty on tracing or utilizing the reported outcomes. In addition, lack of understanding on why the IPT procedures have been standardized can still be found. A critical review on the IPT methods and apparatus has been provided in [7] recommending amendments to the IEC 60587 which should result in more reliable and reproducible outcomes.

This article provides an in-depth understanding of the IPT methods and mechanisms. This is important not only to enhance the reproducibility and reliability of the IPT, but also to establish sound principles for tackling new challenges such as the development of the silicone rubber housing composites for DC insulation.

The Inclined-plane Test Methods and Measurements

The reproducibility of the IPT is highly dependent on the selection of the screening method and its controlling parameters. More straightforward selection is evident when evaluating tracking as compared to erosion, as the IPT has been fundamentally constructed to promote a tracking failure. For example, in addition to a wetting agent, different constituents were proposed for the liquid-contaminant of the IPT, but an aqueous solution of particularly ammonium chloride was standardized as no salt residue that can alter the tracking failure was obtained during testing [3], [6]. Gorur et al. clearly showed salt deposits of sodium chloride to promote a stable dry-band arcing leading silicone rubber failure in salt fog test [23]. In addition, the level of ammonium chloride was recommended to be 0.1% as such a concentration promotes tracking over erosion [3], [6].

Inorganic fillers are nowadays added to outdoor insulating materials in levels that practically suppress tracking and yet erosion remains to be evaluated. As such, for an IPT conducted with a standard liquid contaminant, careful selection of the erosion test method and the voltage levels used are essential tasks for reliable and reproducible evaluation of the erosion resistance.

Test Methods and Voltage Selection

The IPT covers two screening methods: (1) the stepwise voltage method and (2) constant voltage method; both can be used to evaluate tracking but the constant voltage method is the approach preferred for erosion [4]. The flow chart in Figure 1 summarizes the procedures of the stepwise voltage method through which the material class can be determined. Selection of the initial voltage for the stepwise method has been generally performed based on experience. The selection does not seem to be a challenging task when testing for AC applications, because a broad experience exists in conducting the IPT under AC voltages. However, more effort is needed when it comes to the selection of the initial voltages for the DC IPT [7].

A critical voltage is applied while conducting the constant voltage method until failure occurs. The critical voltage could be identified as the severe voltage leading to filed-correlated failure, yet with no burning imposed [9]. From another perspective, a critical testing condition may refer to obtaining equilibrium between the rate of evaporation due to joule heating by the wetting current and the liquid-contaminant flow rate, thereby imposing continuous and effective scintillations in a reproducible fashion. Lesser voltage levels than the critical voltage may prolong the test or may not be severe enough to fail the insulating material [6]. In these conditions the advantages of conducting the IPT instead of the dust fog test or obtaining correlated outcomes with field experience may be lost. Similarly, if the voltage applied is higher than the critical voltage, the sample can burn or flashover rather than tracking and erosion failure may be imposed.

Mathes suggested coupling the selection of the critical voltage with the tracking voltage determined by the stepwise voltage method [6]. Initially, a rule of thumb was proposed identifying the critical voltage to be 0.5 kV less than the tracking voltage [3] and later on 0.75 kV less than the tracking voltage as per ASTM D2303 [4]. This approach was recently utilized to select the equivalent DC voltages of the constant voltage method [7]. Another systematic method, recommended by Jolly in [10] and promoted by Mathes in [6], was based on leakage current measurements. Jolly showed the critical voltage initiating distortion in the leakage current waveform or saturation in the leakage current magnitude, indicating equilibrium between the rate of evaporation and the flow rate. Recently, correlation was obtained between equivalent voltages determined for the DC IPT as per the ASTM D2303 and Jolly's method [11].

Another useful approach is based on experience; a critical voltage of 4.5 kV recommended at flow rate of 0.6 ml/min as per the IEC60587 has been identified suitable for commercial outdoor insulating composites such as silicones [7]. A voltage level of 6 kV at flow rate of 0.9 ml/min has also been found efficient to investigate silicones in severer conditions [12]. However, these experience-based critical voltages are beneficial in evaluating highly filled materials that are tracking-resistant and able to withstand a severe dry-band arcing, but not when evaluating weaker materials that may burn due to severe conditions. Mathes criticized the generic approach recommended in IEC 60587 to apply specific critical voltage level for each flow rate [6], [7], i.e 2.5 kV for 0.15 ml/ min, 3.5 kV for 0.3 ml/min and 4.5 kV for 0.6 ml/min. In other words, if burning is the purpose, a standard flammability test would be a more suitable fit. This issue becomes more critical when evaluating composites for new applications, such as HVDC insulation, in which field experience is not as widely available.

Seifert et al. reported the critical AC conditions to be too severe to be applied in the DC IPT, and therefore leading to uncorrelated outcomes with field experience [13]. Ghunem et al. proposed the selection of the +DC and –DC voltages in the IPT to be equivalent rather than equal to the corresponding standard AC voltages (respectively 70% and 85 %); otherwise the tested material may burn [7].

Tracking and Erosion Measurements and Failure Criteria

As per both ASTM D2303 and IEC 60587, obtaining a 2.54 cm carbonaceous path indicates a tracking failure of the material sample tested by the IPT. Some discrepancy, however, appears in identifying this failure for tracking-resistant materials such as filled silicone rubber. Mathes reported "tracking combined with erosion" as the failure pattern of silicones in the IPT. Kumagai et al. showed the concentration of carbonaceous residue in failure paths on silicone to be no more than 4wt% [14]. Reporting failure due to "erosion path" rather than "tracking" might therefore be more realistic for silicone rubber. Similarly, reporting a "failure" class or voltage rather than "tracking" class or voltage might be more meaningful for tracking-resistant materials. A "tracking" voltage/failure has been widely reported (with an implicit inference to erosion) for silicone rubber, for convenience or to avoid confusion [8].

The 2.54 cm path criterion which has been recommended by Mathes and McGowan [3] might not be enough to evaluate erosion. For example, silicone rubber filled with alumina tri-hydrate tend to form a layered char when thermally decomposed, thereby promoting underneath scintillations that often lead to deep erosion rather than paths [15]. Such an issue seems to be considered in the IEC 60587 as additional failure criteria have been listed, (1) ignition of the test sample, (2) obtaining deep erosion hole and (3) measurement of 60 mA or higher leakage current. Experience showed maintaining operation for the IPT despite observing these additional criteria does not serve reliable evaluation of the tracking and erosion resistance.

Ignition of the test sample is an indication of material premature failure, and dry-band arcs induced with high current levels (60 mA and above) promote a test for flashover rather than tracking and erosion. As for the deep erosion, a depth of half the sample thickness has been accepted in the industry as a useful failure criterion [7]. Reproducible outcomes for the IPT conducted under DC voltages were obtained when utilizing these additional criteria [11].

Consistency between the IPT method and the corresponding measurement reported to indicate the relative tracking and erosion resistance is an important issue that seems to be overlooked. Reproducible tracking classes can be determined as per the stepwise voltage method, given the class is indicated by the tracking voltage [6]. Time-to-track can be also indicating the tracking class, yet with the constant voltage method applied. It should be mentioned that voltage was preferred over time-to-track in evaluating the material class, since knowing the voltage at which tracking or erosion is initiated was somewhat found more realistic than reporting the time-to-track under accelerate aging conditions [3]. Erosion depth, mass and volume are reliable measurement of erosion as evaluated by the constant voltage method [6].

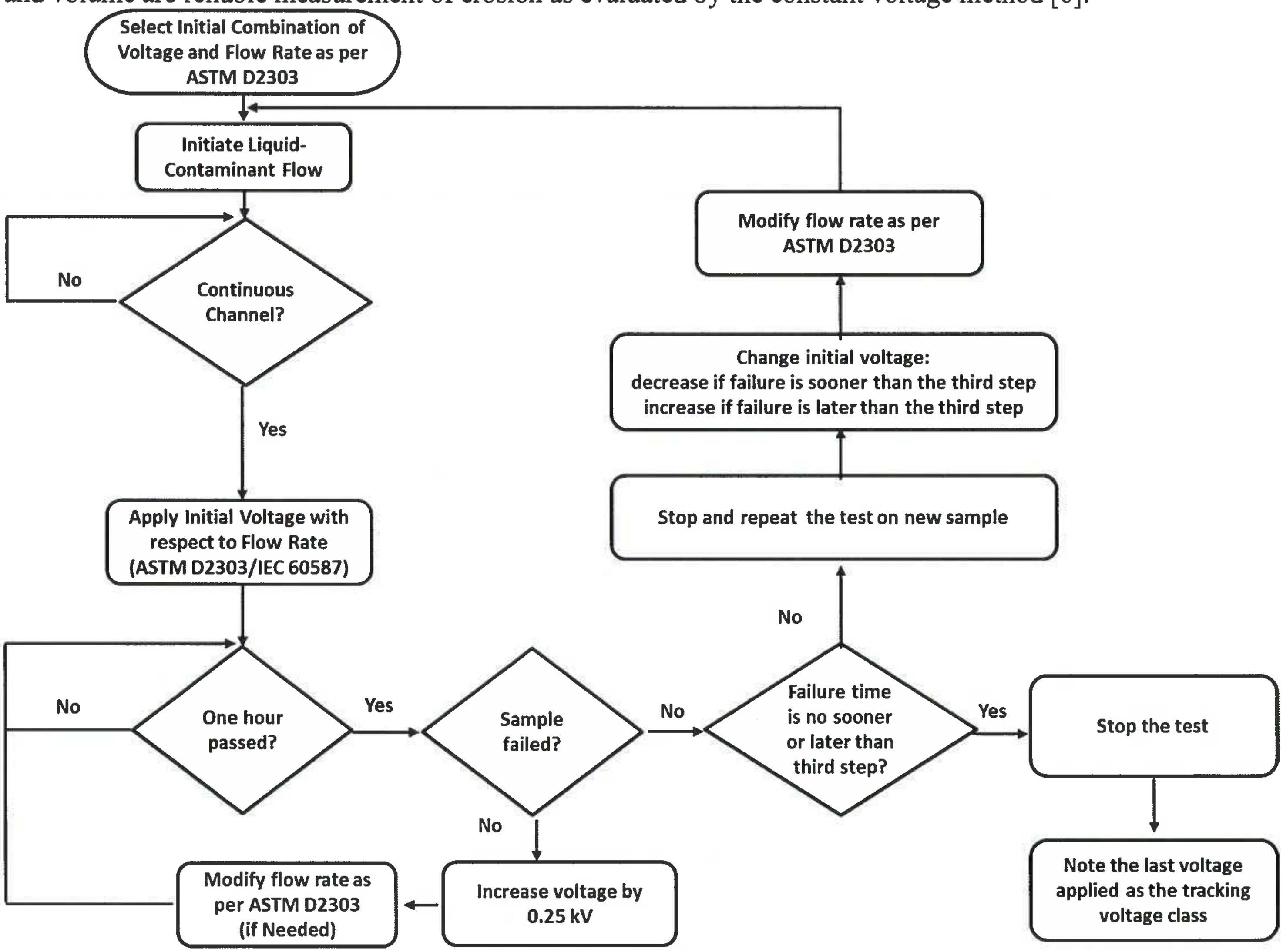

Figure 1. Flowchart of the stepwise Tracking Voltage Method conducted in the IPT as per ASTM D2303.

Leakage Current Measurements

Leakage current measurements and analysis have been extensively conducted for the IPT in order to understand the dry-band arcing mechanism leading to tracking and erosion. However, different techniques such as the salt fog test [16] and field measurements [17] are required to test for the hydrophobicity when seeking leakage current signatures for condition monitoring and diagnostics of outdoor insulators. The liquid contaminant of the IPT contains a wetting agent (Triton X100 [4]) that destroys the hydrophobicity of the tested material and thus maintains fair comparison of the tracking and erosion resistance for materials with different wetting properties.

Generally, both tracking and erosion in the IPT were strongly correlated with the dry-band arcing energy. Mathes showed a correlation between the dry-band arcing energy and the tracking voltage as well as the eroded volume [6], [18]. With the extensive application of silicone rubber insulators, a particular interest has been given to leakage current signatures of tracking and erosion on silicone rubber tested by the IPT. Dry-band arcing power as determined by the third harmonic component of the leakage current was correlated with hotspots causing erosion [19]. Rate of energy absorption was proposed as an indicator of material failure during the IPT [20]. Dry-band arcing energy determined during the DC IPT using wavelet transform was correlated to the tracking and erosion performance of silicone rubber [21]. These findings which seem to agree with field experience [22] and standard salt-fog testing [23] show tracking and erosion to be dominantly a thermal degradation mechanism.

Another important perspective is understanding the nature of the heat source leading to tracking and erosion. In addition to the dry-band arcing plasma, Kumagai et al. identified oligomers released in the gas phase due to silicone rubber decomposition as sources of feedback heat when combusted (Figure 2). In addition, two stages were reported for the dry-band arcing while impinging silicone rubber in the IPT, using simultaneous leakage current and temperature measurements. In the first stage, the dry-band arcing is intermittent raising surface temperature to levels approaching 200^{o}C and thus leading to surface decomposition; whereas, a stable dry-band arcing inducing hot spot temperatures exceeding 400^{o}C was reported for the second stage [9]. Similarly, Ghunem et al. identified an intermittent and stable dry-band arcing stages during the DC IPT, using the wavelet-based multiresolution analysis of the leakage current and simultaneous temperature measurements. Thermo-oxidation (Andrinov mechanism [24]) of silicone rubber was reported during the intermittent dry-band arcing stage, thereby leading to residue formation. The residue was shown to promote a stable and intense dry-band arcing, with more degree of stability and intensity shown under DC as compared to AC [25]. Degree of intensity of the dry-band arcing as increased by reduction in its length was shown by Zhang et al. to highly accelerate surface degradation of silicone rubber [26]. In addition, the dry-band arcing length was shown by Ghunem et al. to be dependent on the type of voltage, with the dry-band arcing induced to possess lesser lengths under DC as compared to AC voltages [27]. In summary Figure 3 shows the dry-band arcing cycle during the AC and DC IPTs.

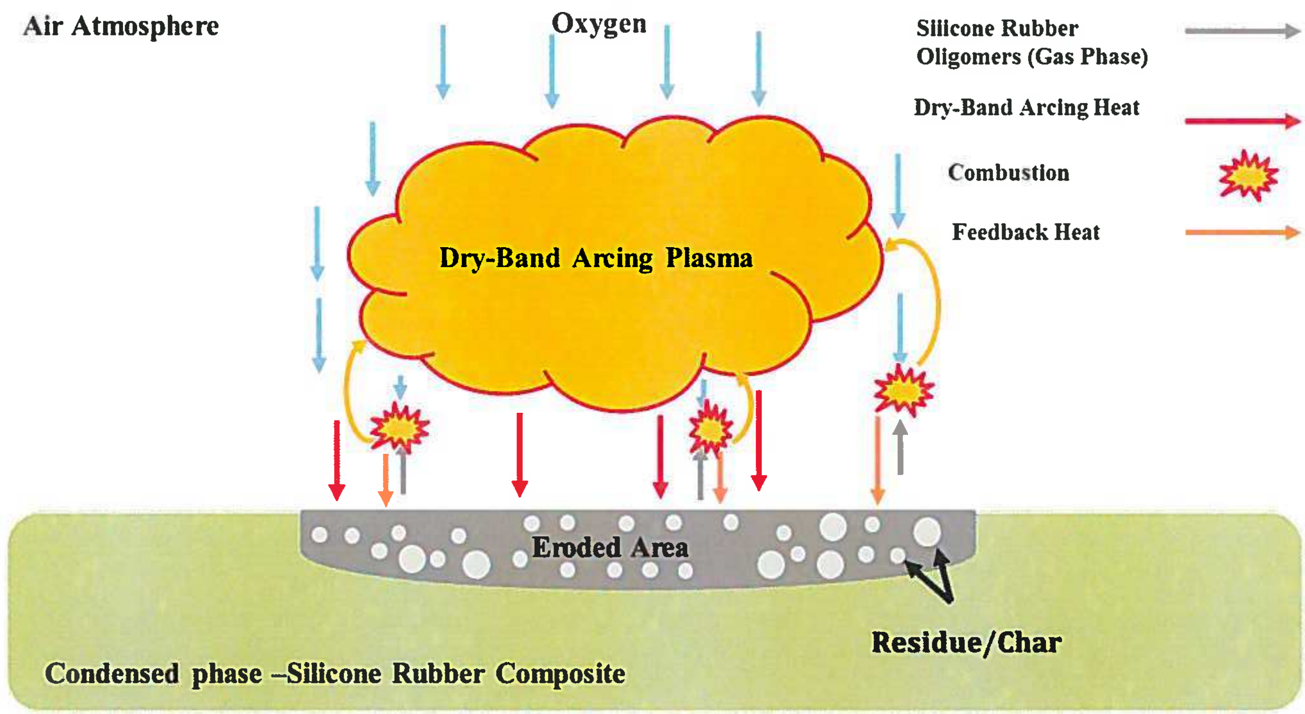

Figure 2. Sources of heat ablation due to dry-band arcing on silicone rubber during the IPT.

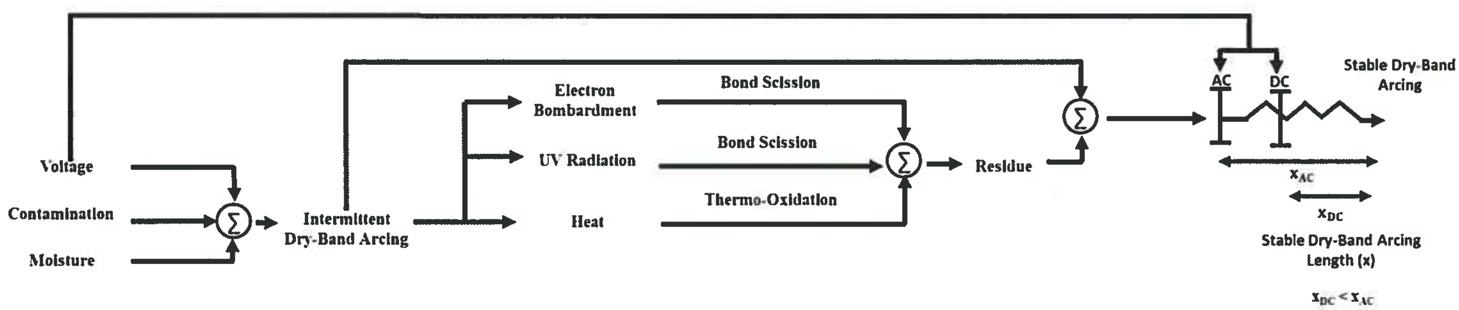

Figure 3. Development of the Stable dry-band arcing during the IPT.

The Electrical Tracking and Erosion Resistance Improved by Inorganic Fillers.

Effect of Fillers

A strong correlation has been reported between the carbon content and the susceptibility of insulating materials to tracking. In the absence of effective oxidation, carbon residue can form on the surface of housing material as result of dry-band arcing impinging and thus decomposing the surface. Traditionally, the use of inorganic fillers was proposed to inhibit the track formation, as an analogy was made to the volume effect (dilution effect) of flame retardant fillers replacing the polymer and thus reducing its content of fuel (carbon).

Norman et al. postulated a chemical effect for the hydrated fillers to promote an internal oxidation mechanism that suppresses tracking. For butyl rubber that was highly filled with hydrated alumina, gas pocket due to an internal oxidation rather than internal tracking or breakdown took place in an internal dielectric test. Spectrometric analysis showed the internal oxidation to take place as result of the dehydrated water (vapor) attacking the decomposed organic groups from the polymer, yielding carbon oxides and hydrocarbon gases [28].

Parr and Scarisbrick described a physical cleaning effect for the water of hydration when released to scatter the carbon residue and thus suppress a formation of conductive paths. In addition, a thermal effect was identified for the fillers in raising the thermal conductivity of the composite and thus dissipating the heat away from the local spots impinged by the dry-band arcing [29].

Mathes questioned the involvement of an internal oxidation mechanism, as an increase in the tracking voltage was determined for materials tested by the IPT in an inert atmosphere [6]. The role of the internal oxidation was not found significant by Grour et al., utilizing salt-fog testing of high temperature vulcanized silicone rubber, EPDM and cycloaliphatic epoxy [30], but emphasis was placed on the thermal conductivity of the filler and the cleaning effect of the water of hydration [23]. The induced dry-band arcing in the salt-fog test was not found severe enough to initiate the second decomposition stage of alumina tri-hydrate at hot spot temperatures approaching 540°C [30]. Meyer et al. showed the thermal conductivity to be the dominant factor governing the erosion resistance. Such a finding was supported by determining insignificant difference in both thermal conductivity and the erosion resistance of silicone rubber composites filled with alumina tri-hydrate and silica to 50wt% [31]. Shmidt et al. proposed novel ATH-free silicone rubber composites for outdoor insulation applications, as insignificant effect could be shown for alumina tri-hydrate to raise thermal conductivity as compared to silica [32].

Kumagai et al. confirmed the internal oxidation to take place during the second dehydration stage of alumina tri-hydrate at temperatures approaching 540°C; however, were able to measure elevated temperature under critical voltages applied in the IPT. A critical alumina tri-hydrate level (45wt%) in silicone rubber beyond which internal oxidation takes place was accordingly determined [9]. Krivda et al. detected mullite ($Al_6Si_2O_{13}$) in erosion paths formed due to dry-band discharges rising surface temperature of silicone rubber filled with alumina tri-hydrate to more than 1200°C [33].

Although several studies were conducted on identifying correlations between the filler effect and the erosion resistance, less effort has been spent to understand the in-situ effects of the fillers during the IPT. Such a strategy becomes very important if further optimization is required for the existing composites or if new composites are needed to be developed for new applications such as the HVDC insulation. With an analogy made to the fire cycle approach proposed by Hornsby in [34], a mechanistic frame work to understand the effect of inorganic fillers (summarized in Table 1) can be accordingly constructed as shown in Figure 4.

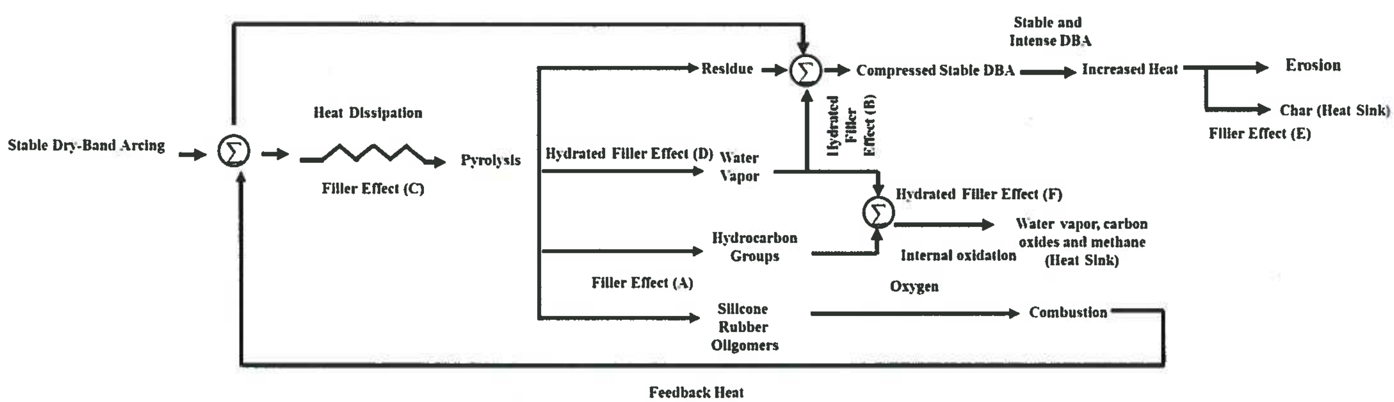

Figure 4. Erosion mechanisms and filler effects due to stable and intense dry-band arcing during the IPT.

Table 1. Effects of inorganic fillers on suppressing erosion due to stable and intense dry-band arcing during the IPT.

Filler Effect			Mechanism of Tracking Suppression		Mechanism of Erosion Suppression	
Identification	Tag	Description	Phase	Description	Phase	Description
Volume/ dilution	A	Inorganic filler particles replacing the polymer	Solid	lesser amounts of carbonaceous residue	Gas	Reduction in volatile oligomers that combust
Physical	B	Scattering residue formed on the surface	Solid	Impeding continuous tracks formation	Solid	delaying the development of the stable and intense dry-band arcing
Thermal	C	Increasing thermal conductivity of the composite	Solid	Higher resistance to pyrolysis	Solid	Higher resistance to pyrolysis
	D	Enthalpy of dehydration	Solid/ Gas	raising the heat capacity of the polymer during dehydration	Solid/ Gas	raising the heat capacity of the polymer during dehydration
	E	Inert Char formation	Solid	Heat sink	Solid	Heat Sink
Chemical	F	Internal oxidation	Gas	Producing carbon oxides and methane gases instead of carbonaceous residue	Gas	Produced gases possess high heat capacities

Development of Silicone Rubber Housing Composites for HVDC insulation: Conventional Versus Mechanistic Frameworks

Due to their hydrophobicity, silicone rubber housing composites have been dominantly applied for outdoor insulation applications. Typically, alumina tri-hydrate is the inorganic filler added in a level around 58wt%. Such an approach can be justified as the water of hydration can be released as approaching the decomposition temperature of silicone rubber at around 200°C. In addition, it has been generally accepted that high levels of alumina tri-hydrate up to 58wt% are required to achieve an acceptable limit oxygen index determined as per flammability standards (UL94 test procedures) [34]. It should be also mentioned that material cost is reduced as the alumina tri-hydrate is replacing the specialty polymer. Challenges may arise in applying this traditional practice to develop new composites for new applications such as DC insulators. Utilization of AC insulators in HVDC applications has been the approach adopted, with consideration given to the difference in withstand voltages under AC and DC by modifying the creepage distance. Field experience has shown such an approach useful when selecting silicone rubber insulators for HVDC lines that are located in areas with light, medium and sometimes locally heavy pollution conditions [13]. However, recent reports showed significant erosion on silicone rubber insulators energized under DC in heavily polluted locations, [35] and more severe erosion has been consistently found in the IPTs under the equivalent DC as compared to the standard AC voltages [7], [36].

With the lack of field experience on the nature of the dry-band arcing induced under HVDC, utilization of a mechanistic approach might be a useful initial step in the development of silicone rubber housing composites for outdoor DC insulation. Addition of inorganic filler can be still performed based on the concept of flame retardancy, but with a mechanistic understanding to the erosion during the DC IPT. Another important task is to develop in-situ indicators for the effect of fillers in response to the DC dry-band arcing. In other words, it is important to obtain a relative measure for the effect of inorganic fillers during the IPT itself rather than speculate or utilize other analytical techniques with different conditions than the IPT. The analytical techniques can be used to identify rather than evaluate or determine the effect of the filler. Hull et al. proposed quantifying the relative effect of mineral fillers for further improvement in the burning behavior of flame retardant materials [37]. Wavelet-based multiresolution analysis of leakage current was found useful to extract in-situ leakage current signatures for the effect of fillers in both the condensed and the gas phase of silicone rubber during the DC IPT [25], [27], [38].

Conclusions

A critical review on the IPT methods and its parametric selection in evaluating the electrical tracking and erosion resistance of outdoor insulating materials was performed. For a standard liquid-contaminant utilized for the IPT, it is an important task to apply the suitable testing method, voltage level and even the failure criteria for reproducible outcomes. The merits behind conducting the IPT in its existing standard state are reviewed and it seems that amendments can be proposed to enhance the reliability of the test. For example, applying the critical test voltages or increasing the content of ammonium chloride to raise conductivity of the liquid-contaminant may be useful when evaluating erosion for tracking-resistant composites. The effects of inorganic fillers in suppressing both tracking and erosion based on a flame retardancy approach were described, and a mechanistic framework was proposed as an essential step towards developing silicone rubber housing composites for outdoor DC insulation applications.

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References

[1] M. W. Albright and W.T. Starr, "Tracking Resistance Test Methods," *Trans. Amer. Instit. Electr. Engineers, Part III (Power Apparatus and Systems),* vol. 75, pp. 441-448, December 1960.

[2] G. M. L. Sommerman, "Electrical Tracking Resistance of Polymers," *Trans. Amer. Instit. Electr. Engineers, Part III (Power Apparatus and Systems),* vol. 79, pp. 969-974, June 1956.

[3] K. Mathes and E. McGowan, "Surface electrical failure in the presence of contaminants: the inclined-plane liquid-contaminant test," *Trans. Amer. Instit. Electr. Engineers, Part I (Communications and Electronics),* vol. 80, pp. 281-289, July 1961.

[4] Standard Test Methods for Liquid-Contaminant, Inclined-Plane Tracking and Erosion of Insulating Materials, ASTM D2303-97.

[5] Electrical insulating materials used under severe ambient conditions – Test methods for evaluating resistance to tracking and erosion, IEC 60587 2007-05.

[6] K. N. Mathes, "Surface Failure Measurements", in Engineering Dielectrics, Electrical Properties of Solid Insulating Materials: Measurements Techniques, Vol. 2B. R. Bartnikas, Ed. Philadelphia: STP 926, pp. 289-293, 1983.

[7] A. Krivda, L. E. Schmidt, X. Kornmann, H. Ghorbani, A. Ghorbandaeipour, and M. Eriksson, "Inclined-Plane Tracking and Erosion Test According to the IEC 60587 Standard," *IEEE Electr. Insul. Mag.*, vol. 25, pp. 14-22, 2009.

[8] R. A. Ghunem, S. H. Jayaram and E. Cherney, "Erosion of silicone rubber composites in the AC and DC inclined-plane tests," *IEEE Trans. Dielectr. Electr. Insul.,* vol. 20, pp. 229-236, Feb. 2013.

[9] S. Kumagai and N. Yoshimura, "Tracking and erosion of HTV silicone rubber and suppression mechanism of ATH," *IEEE Trans. Dielectr. Electr. Insul.,* vol. 8, pp. 203-211, Apr. 2001.

[10] D.C. Jolly, "A quantitative method for determining the resistance of polymers to surface discharges", *IEEE Trans. Electr. Insul.*, vol. ET-17, no. 4, pp. 293-299, 1982.

[11] E.A. Cherney, R.S. Gorur, A. Krivda, S. H. Jayaram, S. M. Rowland, S. Li, M. Marzinotto, R. A. Ghunem, and I. Ramirez, "DC Inclined-Plane Tracking and Erosion Test of Insulating Materials," *prepared by the IEEE DEIS Outdoor Insulation Technical Committee, IEEE Trans. Electr. Insul.*, accepted, Nov. 2014.

[12] S. Ansorge, F. Schmuck, and K. O. Papailiou, " Improved Silicone Rubbers for the Use as Housing Material in Composite Insulators," *IEEE Trans. Dielectr. Electr. Insul.,* vol. 19, pp. 209-217, Feb. 2012.

[13] J. M. Seifert, D. Stefanini, and H. Janssen, " HTV Silicone Composite Insulators for HVDC Applications – Long-term Experiences with material and Design for 500kv and Above" *Proceedings of the 16th International Symposium on High Voltage Engineering*, pp. 1-6, 2009.

[14] S. Kumagai, X. Wang, and N. Yoshimura, "Solid Residue Formation of RTV Silicone Rubber due to Dry-Band Arcing and Thermal Decomposition", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 281-289, 1998.

[15] R. A. Ghunem, S. H. Jayaram and E. A. Cherney, "Comparative inclined plane tests on silicone and EPDM elastomers under DC," IEEE Electrical Insulation Conference (EIC), 2013, pp. 356-359.

[16] H. El-Hag, S. H. Jayaram, and E. A. Cherney, "Fundamental and low frequency harmonic components as a diagnostic tool to study aging of RTV and HTV silicone rubber in salt-fog", IEEE Trans. Dielectr. Electr. Insul., Vol. 10, pp. 128-136, 2003.

[17] I. Ramirez, R. Hernández, and G. Montoya" Measurement of Leakage Current for Monitoring the Performance of Outdoor Insulators in Polluted Environments", IEEE Electr. Insul. Mag., Vol. 28, pp. 29-34, 2012.

[18] K. N. Mathes and E. J. McGowan, "Electrical insulation tracking A design engineering problem," Electro-technology, vol. 69, no. 4, pp. 146-151, April 1962.

[19] L. H. Meyer, S. H. Jayaram, and E. A. Cherney, "Correlation of damage, dry band arcing, and temperature in inclined plane testing of silicone rubber for outdoor insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 11, pp. 424-431, 2004.

[20] J. Crespo-Sandoval, A. Haddad, H. Griffiths, and P. F. Coventry, "Rate of energy absorption as indicator for the tracking/erosion test of silicone rubber", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, pp. 1772-1780, 2010.

[21] R. Sarathi, S. Chandrasekar, and N. Yoshimura, "Investigation of Tracking Phenomena in Outdoor Polymeric Insulation Material Under DC Voltages Using Wavelets", IEEE Trans. Power Delivery, Vol. 21, pp. 515-517, 2006.

[22] T.G. Gustabsson, S. M. Gubanski, H. Hillborg, S. Karlsson, and U. W. Gedde, " Aging of Silicone Rubber under ac or dc Voltages in a Coastal Environments", IEEE Trans. Dielectr. Electr. Insul., Vol. 8, pp. 1029-1039, 2001.

[23] R.S. Gorur, E.A. Cherney, R. Hackam, "The AC and DC Performance of Polymeric Insulating Materials under Accelerated Aging in a Fog Chamber", IEEE Trans. Power Delivery, Vol. 3, pp. 1892-1902, 1988.

[24] D. Timpe, "Silicone Rubber Flame Resistance," *Rubber and Plastics News,* 2007.

[25] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Investigation into the Eroding Dry-band Arcing under DC Using Wavelet Based Multiresolution Analysis," *IEEE Trans. Dielectr. Electr. Insul.,* vol. 21, pp. 713-720, Apr. 2014.

[26] X. Zhang, S. M. Rowland, and V. Terzija, "Increased Energy in Stable Dry-band Arcs Due to Length Compression", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, pp. 521-532, 2010.

[27] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney" The DC Inclined-Plane Tracking and Erosion Test and the Role of Inorganic Fillers in Silicone Rubber for DC Insulation", IEEE Electr. Insul. Mag., Vol. 31, pp. 13-22, 2015.

[28] R. Norman and A. Kessel, "Internal Oxydation Mechanismen for Nontracking Organic Insolations," Trans. Am. Inst. Electr. Eng., Part III. Power App. Syst., vol. 77, pp. 632–636, Apr. 1958.

[29] D. Parr and R. Scarisbrick, "Performance of synthetic insulating materials under polluted conditions," Proc. Inst. Electr. Eng., pp. 1625–1632, 1965.

[30] R.S. Gorur, E.A. Cherney, R. Hackam, "Performance of Polymeric Insulating Materials in Salt-Fog", IEEE Trans. Power Delivery, Vol. 2, pp. 486-492, 1987.
[31] L. H. Meyer, E. A Cherney, and S. H Jayaram "The Role of Inorganic fillers in Silicone Rubber for Outdoor Insulaion Alumina Tri-Hydrate or Silica ", IEEE Electr. Insul. Mag., Vol. 20, pp. 13-21, 2004.
[32] L. E. Schmidt, X. Kornmann, A. Krivda, and H. Hillborg "Tracking and Erosion Resistance of High Temperature Vulcanizing ATH-free Silicone Rubber", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, pp. 533-540, 2010.
[33] A. Krivda, F. Greuter, J. Rocks, X. Kornmann and P. Meier, "Chemical analysis of outdoor silicone materials after electrical and environmental testing", *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 389-392, 2006.
[34] P. R. Hornsby "Fire retardant fillers for polymers", International Materials Reviews, Vol. 46, pp. 199-210, 2001.
[35] A. I. Elombo, J. P. Holtzhausen, H. J. Vermeulen and P.J. Pieterse, " Comparative Evaluation of the Leakage Current and Aging Performance of HTV SR Insulators of Different Creepage Lengths when Energized by AC, DC+ or DC in a Severe Marine Environment", IEEE Trans. Dielectr. Electr. Insul., Vol. 20, pp. 421-428, 2013.
[36] G. heger, H. J. Vermeulen, J. P. Holtzhausen, and W.L. Vosloo, "A comparative study of insulator materials exposed to high voltage AC and DC surface discharges", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, pp. 513-520, 2010.
[37] T. R. Hull, A. Witkowski, and L. Hollingbery, "Fire retardant action of mineral fillers", Polymer Degredation and Stbaility, Vol. 96, pp. 1462-1469, 201.
[38] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Suppression of Silicone Rubber Erosion by Alumina Tri-Hydrate and Silica Fillers from Dry-Band Arcing under DC," *IEEE Trans. Dielectr. Electr. Insul.*, accepted.

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