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A Study on the Reliability of Polyester Insulators Blended with Borax

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Abstract

Tracking is the main factor which limits the safe working electric stress of insulation in power system applications. Polymer samples have been tested in laboratory conditions according to ASTM D2303 on accelerated inclined plane tracking test. In this paper, a model based on improved Weibull statistics is proposed for estimating the breakdown time of polymeric insulating materials with borax. The confidence intervals of the Weibull shape parameter and the Weibull scale parameter are determined for the borax concentration values using the Weibull 7++ program.

Key Words: *Electrical materials, reliability, surface tracking.*

1. Introduction

The diverse conditions under which a high voltage apparatus is used necessitate careful design of its insulation and its effective lifetime. Insulation media can be gas, vacuum, solid and liquid, or a combination thereof. To achieve reliability and economy one must understand the causes of deterioration; thus optimum design calls for judicious selection of insulation in relation to such parameters as dielectric strength, corona discharges and other relevant factors.

Electrical aging of insulators is associated with a wide variety of phenomena; such as breakdown, discharges, treeing, electron interactions with charges, phonons, matters, etc. Several test methods have been developed to examine the performance of polymeric materials. However, polymeric materials often exhibit too many random factors associated with them, which reduce their reliability.

Tracking is one of the main factors which limit the safe working electric stress of insulation in power system applications. Tracking process involves surface breakdown initiated by surface discharges. Tracking degradation mechanisms are summarized in Figure 1 [1].

Polyesters are increasingly popular because of their low cost, ease of use, versatility. They have excellent dielectric properties and superior surface hardness and are highly resistant to most chemicals. They are widely used for making small electrical components in very large structures.

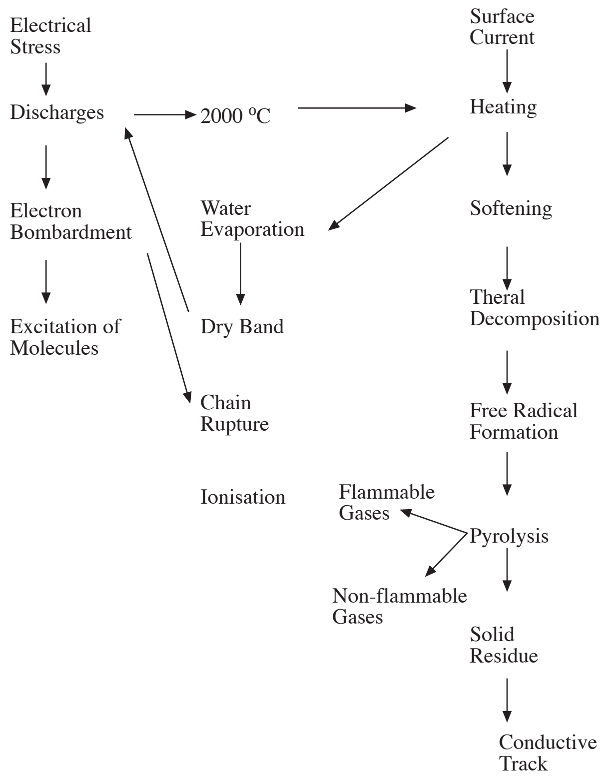

Figure 1. Tracking degradation mechanisms [1].

Flammability of each polymer is different. Some polymers, such as polyamide-imide, polyarylate, polyetheretherketone, polyetherimide, polyethersulfone and polyphenylene sulfide are inherently resistant to burning and require no further treatment. Other polymers, such as polyamides, polycarbonate and polysulfone are somewhat less resistant and several polymers burn readily. However, the flammability of these polymers may be significantly reduced by compounding with reactive and nonreactive halogenated compounds, phosphate esters, and antimony oxide [2, 3].

In our previous studies, we have investigated the use of borax minerals as filler in an unsaturated polyester resin, and found the addition reduces flammability and enhances the electrical properties of the composite compared to the polyester alone [4–6].

In this research, a model based on improved Weibull statistics has been proposed for estimating the breakdown time of polymeric insulation material. By using appropriate parameters this improved model can estimate the remaining lifetime within a reasonable accuracy in varying borax concentration. Model parameters were determined via several tests performed according to ASTM D2303 on accelerated inclined plane tracking test. With this study increasing borax concentration seemed to increase the useful lifetime of insulating materials.

2. Experimental Procedure

All tests have been performed according to the ASTM D2303 test procedure under 4 kV AC voltage and 36 ml/h liquid-contaminant flow rate [7]. Polyester samples have been prepared with 0.25% MEKP (Methyl Ethyl Ketone Peroxide) and 0.25% cobalt as a chemical accelerator. All powder like borax minerals have diameter less than 35 μm and are added to unsaturated polyester resin at different percentages of total mass. To harden prepared products they are kept in 45 ^{o}C oven for 4 hours, and have the dimensions of 100 mm × 55 mm × 9 mm.

All specimens were tested in a cabinet without the upper cover for minimum air circulation. For each test, at least 10 samples were used. ASTM D2303 recommends continuing the test until the tracking pattern reaches 25 mm from the earth electrode up to the HV electrode. However to enable a complete structural pattern analysis, the experiment was continued until the gap between the electrodes has been short-circuited completely.

Tracking is a mixed process of discharge inception, carbon formation, carbon path propagation under the influence of an electrolyte, applied voltage, type of electrolyte, location of discharge, energy of discharge and molecular composition of the material.

3. Statistical Analysis

The reliability of a system is defined as the probability that it will perform its required function under stated condition, for a stated period of time. The Weibull statistical analysis is one method to define system reliability. The Weibull distribution depends mainly on two parameters: β denotes the *shape*, and α denotes the *scale* parameters. In order to determine these values a batch of identical samples were stressed at constant voltage and liquid-contaminant flow rate and the initiation time t for each batch has been observed.

Cumulative Weibull distribution function (cdf) $F(t)$ can be shown as

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]. \tag{1}$$

The Weibull shape parameter β is also known as the Weibull slope. This is because the value of β is equal to the slope of the line in a probability plot. Different values of the shape parameter corresponds to different distribution behaviors.

By taking the derivative of cumulative Weibull distribution function we have the probability density function (pdf) as

$$\frac{dF(t)}{dt} = f(t) = \left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]. \tag{2}$$

Reliability function $R(t)$ can be expressed as

$$R(t) = 1 - F(t) \tag{3}$$

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]. \tag{4}$$

Weibull distributions with $\beta < 1$ have a failure rate that decreases with time, also known as infantile or early-life failures. Weibull distributions with β close to or equal to 1 have a fairly constant failure rate, indicative of useful life or random failures. Weibull distributions with $\beta > 1$ have a failure rate that increases with time, also known as wear-out failures.

The mean life function, which provides a measure of the average time of operation to failure, is given by the relation

$$\mu = m = \int_{0}^{\infty} t \cdot f(t)dt. \tag{5}$$

It should be noted that this is the expected or average time-to-failure and is denoted as the MTBF (Mean-Time-Before Failure) and is also called MTTF (Mean-Time-To-Failure) by many authors. MTBF is used for repairable systems and MTTF is used non-repairable systems. If the failures are assumed to occur at a constant rate, the failure rate λ can be expressed as $\lambda = (\text{MTTF})^{-1}$.

One of the most confusing concepts to a novice reliability engineer is estimating the precision of an estimate. This is an important concept in the field of reliability engineering, leading to the use of confidence intervals (or bounds). A confidence interval (CI) is an interval estimate of a population parameter. Instead of estimating the parameter by a single value, an interval of likely estimates is given. How likely the estimates are determined by the confidence coefficient. The more likely it is for the interval to contain the parameter, the wider the interval will be [8].

Confidence intervals are used to indicate the reliability of an estimate. For example, a CI can be used to describe how reliable survey results are. All other things being equal, a survey result with a small CI is more reliable than a result with a large CI. In this study, 90% reliability is used to find the confidence intervals.

4. Results and Discussion

In this research, the effect of borax concentration on the useful life expectancy of composite polyester insulators has been investigated. Test results clearly reveal that specimens produced by different borax concentrations differ considerably from each other in tracking initiation times and in carbonized tracking patterns. An example of surface tracking patterns in polyester samples, obtained using ASTM D2303 inclined planed tracking test, is shown in Figure 2.

Figure 2. An example of surface tracking patterns of tested polyester samples.

We study the lifetime of plain polyester samples bearing concentrations up to 1.5% added borax using the Weibull++7 program. The reliability factors for 0.1, 0.2, 0.3, 0.4, 0.6, 0.7, 0.8, 1.0 and 1.5% borax added to polyester samples were obtained from 118 experimental results. For each borax-added sample, we take 12, and for pure polyester samples we take 10, samples for analyzing. The reliability functions and average lifetimes were derived for all of the borax concentrations. All the samples were grouped by borax concentration, then evaluated for compatibility to Weibull analyses.

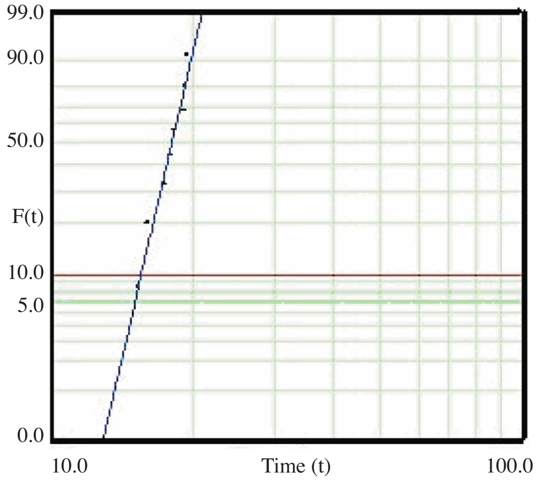

Figure 3. Probability-Weibull graphic of plain polyester samples.

The derived probability-Weibull graph for plain polyester samples is plotted in Figure 3. For these samples, average lifetime was found to be 17:23 minutes. Reliability as a function of time is given in Figure 4. The reliability function for plain polyester samples is thus

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] = \exp\left[-\left(\frac{t}{18.55}\right)^{12.92}\right]. \tag{6}$$

Table 1 shows the mean values of tracking time to the borax concentration, N. The second column shows the arithmetic mean values and the third column shows the mean values derived from Weibull 7++, for plain and borax-added polyester samples.

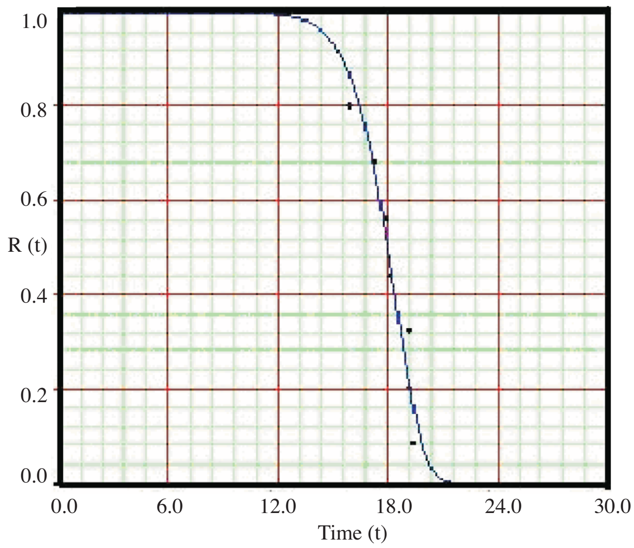

Figure 4. Reliability of plain polyester samples.

In Figure 5, probability density of the polyester samples is given as a function of time. As seen, the optimum tracking initiation time is between 17 min and 19 min.

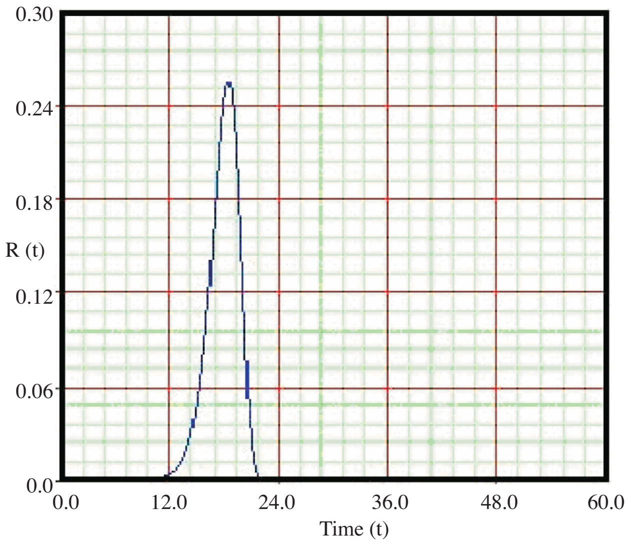

Figure 5. Probability density function of plain polyester samples.

Table 1. The effect of borax concentration to tracking initiation time.

Borax concentration, N (weight %)	Tracking initiation time, t (min) (Average value)	Tracking initiation time, t (min) (Mean value)
0	18:24	18:13
0.1	52:27	52:25
0.2	54:34	54:08
0.3	59:41	54:08
0.4	59:29	59:68
0.6	45:12	45:07
0.7	48:01	47:97
0.8	46:51	47:46
1.0	62:17	62:17
1.5	52:43	55:72

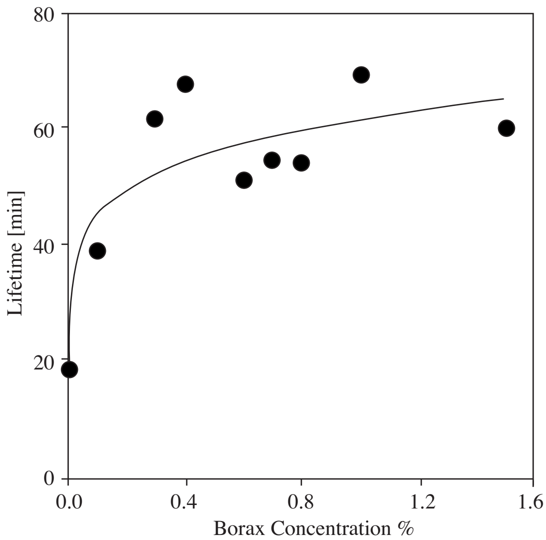

Figure 6. The effect of borax concentration on the tracking initiation time.

Estimation of lifetime as a function of borax concentration N is shown in Figure 6. According to the experimental results, we propose the following equation for polyester samples lifetime versus borax concentration:

$$\ln t = 0.175996 \ln N + 4.02897. \tag{7}$$

The confidence intervals of the Weibull shape parameter and the Weibull scale parameter are determined for the borax concentration values using the Weibull 7++ program.

Table 2 shows the effect of borax concentration on Weibull scale parameter α. Here the lower, mean and upper values of α are also given. As seen, scale parameter rises with borax concentration.

Table 2. The effect of borax concentration on Weibull scale parameter α.

Borax concentration, N (weight %)	α, scale parameter		
	Lower limit	Mean value	Upper limit
0	17.874	18.55	19.252
0.1	49.263	58.35	70.376
0.2	50.027	61.01	74.391
0.3	50.054	61.01	74.376
0.4	57.384	67.24	78.740
0.6	40.966	50.89	63.218
0.7	42.350	54.16	69.273
0.8	43.529	53.05	65.900
1.0	59.963	67.17	78.942
1.5	39.666	59.60	89.565

The confidence interval values of parameter α are shown in Figure 7, for different borax concentration values. The following two equations are derived from the variation values in the shape parameter, α:

$$\ln \alpha = 0.156195 \ln N + 4.11597 \tag{8}$$

$$\alpha = 61.31 N^{0.16}. \tag{9}$$

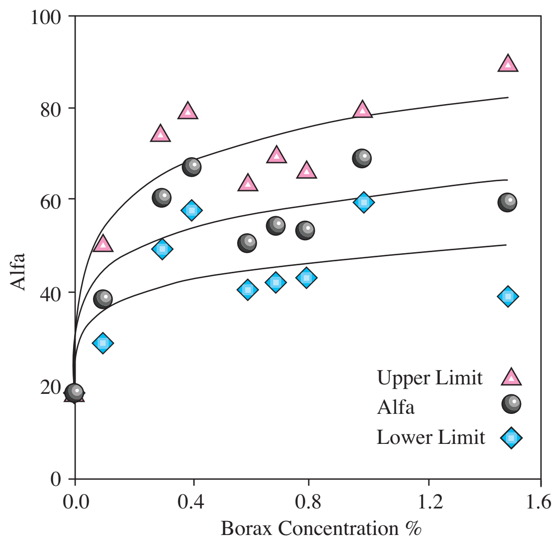

Figure 7. The effect of borax concentration on Weibull parameter α.

In Table 3 gives values of β obtained from Weibull 7++. From the experimental results, it was observed that the shape parameter decreases with increasing borax concentrations. The condition $\beta > 1$ denotes the degradation caused by aging. The decrease in β caused by increased borax concentration shows that the reliability also increases. Increasing the concentration of borax improves the dissipation of surface energy and also tracking resistance. The results of scale parameter are also plotted, in Figure 8. From the data in this graph the following two functions are derived for β:

Table 3. The effect of borax concentration to Weibull shape parameter β.

Borax concentration, N (weight %)	β, shape parameter		
	Lower limit	Mean Value	Upper limit
0	8.745	12.92	19.089
0.1	1.908	2.49	3.331
0.2	1.474	1.97	2.627
0.3	1.479	1.97	2.634
0.4	1.878	2.57	3.507
0.6	1.479	2.07	2.909
0.7	1.503	2.24	3.354
0.8	1.622	2.36	3.455
1.0	2.647	3.79	5.439
1.5	0.828	1.23	1.826

$$\ln \beta = -0.174525 \ln N + 0.342462 \tag{10}$$

$$\beta = 1.4N^{-0.17}. \tag{11}$$

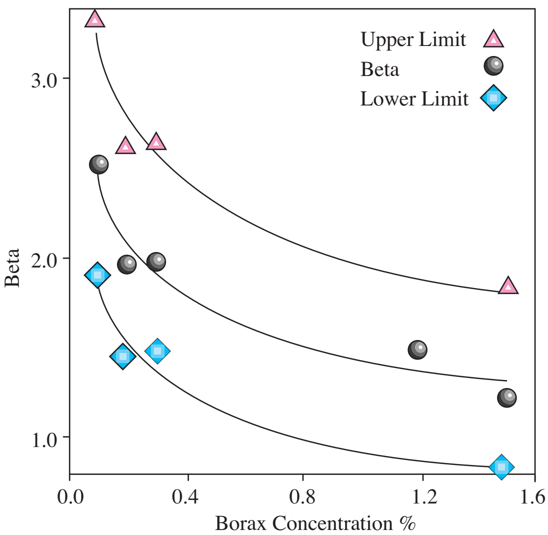

Figure 8. The effect of borax concentration on Weibull parameter β.

Substituting the shape and scale parameter relations equations (9) and (11) into equation (4), the following empirical relation is obtained for the dependence of the reliability function on borax concentration:

$$R(N,t) = \exp\left[-\left(\frac{t}{61.31N^{0.16}}\right)^{1.4N^{-0.17}}\right]. \tag{12}$$

The reliability function $R(N, t)$, for concentrations between 0.1% and 1.5%, is plotted in Figure 9. As can be observed in Figure 9, polyester samples with borax have longer lifetimes; and lifetimes that increase with borax concentration. For example, for $t = 80$ min, the reliability of samples with 1% borax is observed as zero; while the reliability level is 0.27 for samples with 1.5% borax.

Figure 10 shows the variation of the probability density as a function of time and borax concentration from 0.1% to 1.5%. Again, it can be observed that the peak value of failure occurs at low borax concentration.

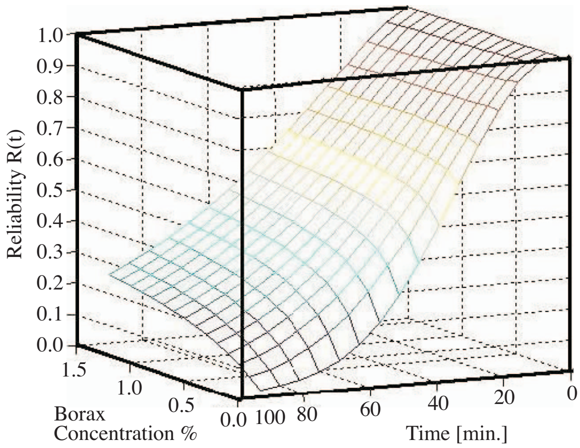

Figure 9. Reliability function $R(t)$ versus time and borax concentration using with confidence interval of Weibull parameters.

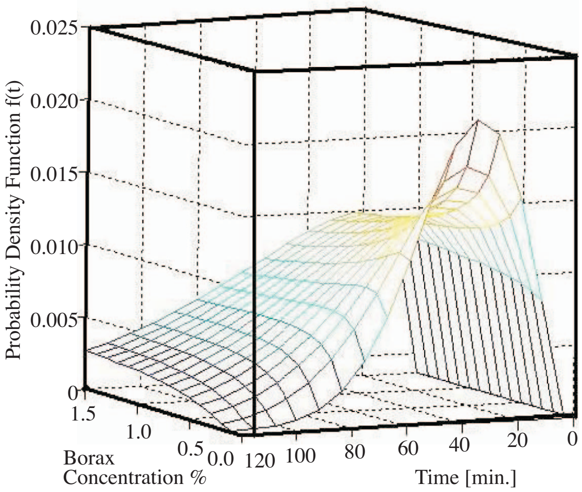

Figure 10. Probability density function $f(t)$ as a function of time and borax concentration, using confidence interval of Weibull parameters.

5. Conclusion

In this study the breakdown in polyester resin was observed experimentally using IPT method for different borax concentrations. Using the Weibull distribution, a new approach was proposed to representing and estimating the breakdown time of polyester insulator. Initially, the graphical plotting technique was used to estimate the basic Weibull parameters. At later stages additional parameters were calculated using a commercially available mathematical program. Finally, a statistical model was developed and proposed which can estimate the mean breakdown time of polyester insulators for different borax concentrations.

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