Comparison of AC and Impulse Breakdown of Model EPR and TR-XLPE Cables as a Function of Wet Electrical Aging

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Abstract: The effects of wet electrical aging during normal service conditions dominate the long term performance of medium high voltage shielded distribution cable. This paper presents the results of an extensive laboratory study of the effect of wet electrical aging using model cables aged at 6 kV/mm (150 V/mil) under wet conditions. The resulting data indicate that the AC strength of EPR formulations drops rapidly with initial aging and then levels off. The impulse strength for EPR formulations drops less than the AC strength, and also levels off to a constant value. The AC strength of two TR-XLPE formulations is relatively stable until shortly before failure, while the impulse strength of these TR-XLPE formulations drops steadily toward failure. The AC and impulse strength of a third TR-XLPE formulation both drop steadily with time. Toward the end of the aging study, the impulse strength of EPR and TR-XLPE formulations was indistinguishable, although the impulse strength of the EPR formulations had been stable for most of the test while the impulse strength of the TR-XLPE formulations continued to drop. The study suggests that AC breakdown strength can be a poor diagnostic for the condition of TR-XLPE cable and that impulse strength is a much better diagnostic. End of life came at about the same time for all formulations. End of life of the TR-XLPE cables was associated with the growth of large water trees which penetrated the insulation. The mechanism by which the EPR cables failed has not been established.

INTRODUCTION

The primary form of degradation experienced by shielded medium voltage distribution cable during normal service is the result of electrical aging under moist conditions, i.e., the result of electrochemical degradation. For this reason, we have undertaken an extensive study of wet electrical aging of model cables including three TR-XLPE dielectrics and five EPR dielectrics. The results of this study, as provided in detail below, indicate that the AC strength of EPR dielectrics drops to about 50% of its initial value and then remains very stable. The AC strength of two TR-XLPE dielectrics remains very stable until shortly before failure. Indeed half way through the test, at 26 weeks, the AC strength of these TR-XLPE cables had increased, even though the first TR-XLPE cable failed at 12 weeks and the impulse strength of these TR-XLPE cables at 26 weeks had dropped by 40% from its initial value. Both the impulse and AC strength of a third TR-XLPE formulation dropped with aging time. End of life in this test came at about the same time for all cable samples. End of life of the TR-XLPE samples was associated with the growth of very large water trees which penetrated the insulation wall. The cause of failure in the EPR cables has not been determined. Overall, the data suggest that retained AC strength can be a poor indicator of the condition of TR-XLPE cable, as water tree growth does not necessarily cause a substantial reduction in AC strength until shortly before failure. Impulse strength appears to be a much better indicator, as this drops steadily with wet electrical aging for all TR-XLPE formulations examined. This conclusion is consistent with previous experimental findings [1] and theoretical work [2].

CABLE SAMPLES

The cable samples consisted of 0.38 mm (15 mils) of semicon over #14-7 stranded wire with 0.76 mm (30 mils) of dielectric applied over the semicon. No ground shield semicon was applied. Approximately 1 km (3000 ft) of such cable was manufactured for each dielectric (three TR-XLPE compounds and 5 EPR compounds).

TEST PROTOCOL

Initial Quality and Conditioning

Approximately 100 AC breakdowns were carried out for each cable type as manufactured in order to establish manufacturing quality. The distribution of breakdowns for all cables was very narrow. Cables were then conditioned for 72 hours at 90 C under dry conditions to remove manufacturing byproducts. After this conditioning, approximately 100 AC breakdowns were again carried out on each cable type, the results of which are shown in Figure 1. The Weibull exponent ranges from 8 to 21, while r^2 ranges from 0.87 to 0.98. In this figure, cables D, E, and F are TR-XLPE while the remaining samples are EPR. The data tend to confirm good quality of manufacture.

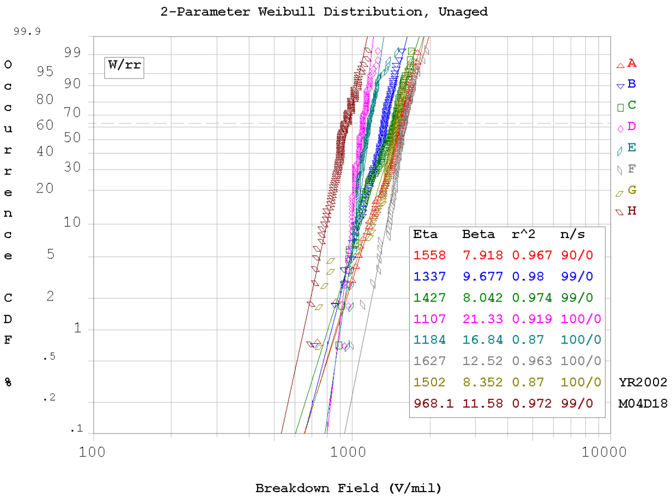

Figure 1. 2-parameter Weibull plot of breakdown field after conditioning at 90 C for 72 hours under dry conditions.

Aging Samples and Test Protocol

After conditioning at 90 C for 72 hours, model cables were soaked for 24 hours and then aged at 6 kV/mm (150 V/mil) in tap water at room temperature. No effort was made to fill the strands with water. The test samples consisted of 3, 150 m (500 ft) coils of each insulation type and 12, 15 m (50 ft) coils of each insulation type. The 15 m samples were removed periodically to monitor the progress of aging by measuring both the AC and impulse breakdown strength (5 breakdowns each). Once aging appeared to reach steady state, at least for the EPR samples, the 500 ft coils were removed and approximately 100 AC breakdowns were carried out for each cable type.

RESULTS

Impulse Breakdown vs Time

Figure 2 shows the retained impulse strength and impulse breakdown field vs time as measured when the 15 m coils were removed and tested. Again, cables D, E, and F are TR-XLPE while the remainder are EPR. A number of the EPR cables show a rapid decrease in impulse strength to a minimum, followed by some recovery of impulse strength. The reason for this behavior is not known; however, the minimum in impulse strength may be caused by partial diffusion of moisture into the cable, which results in the insulation being radially inhomogeneous until full penetration of moisture occurs. After the initial drop and partial recovery, the impulse strength is very stable for the remainder of the aging time.

The impulse strength of the TR-XLPE cables has an obvious downward trend with time. Given the substantial standard deviation of the data based on only 5 breakdowns per point (typically in the range of 5 to 10 kV), conclusions related to trends cannot be drawn on the basis of a single point. However, TR-XLPE dielectrics D and E appear to be on a monotonic downward trend. These data are consistent with those published for two years of field aging at normal operating voltage (Figure 3, [1]).

AC Breakdown vs Time

The AC breakdown strength vs aging time is shown in Figure 4. Again, these data are based on 5 breakdowns, and the mean breakdown voltage is plotted. However a number of features are striking. The performance of the EPR samples is as expected, i.e., the AC strength drops substantially from its initial value and levels off well above operating field. The breakdown field of TR-XLPE dielectrics D and E increases with aging time, probably as a result of evolution of manufacturing byproducts. Yet while the AC strength increases, the impulse strength drops by 50% over the same period (Figure 2). In addition, the first failure during testing of all insulation systems was very similar, in the range of 12 to 16 weeks. This suggests that while the average AC strength of dielectrics D and E remained very high, discrete defects (i.e., water trees) were developing which reduced the impulse strength. A few of these water trees grew to a size which caused early failure during AC aging. This conclusion is consistent with

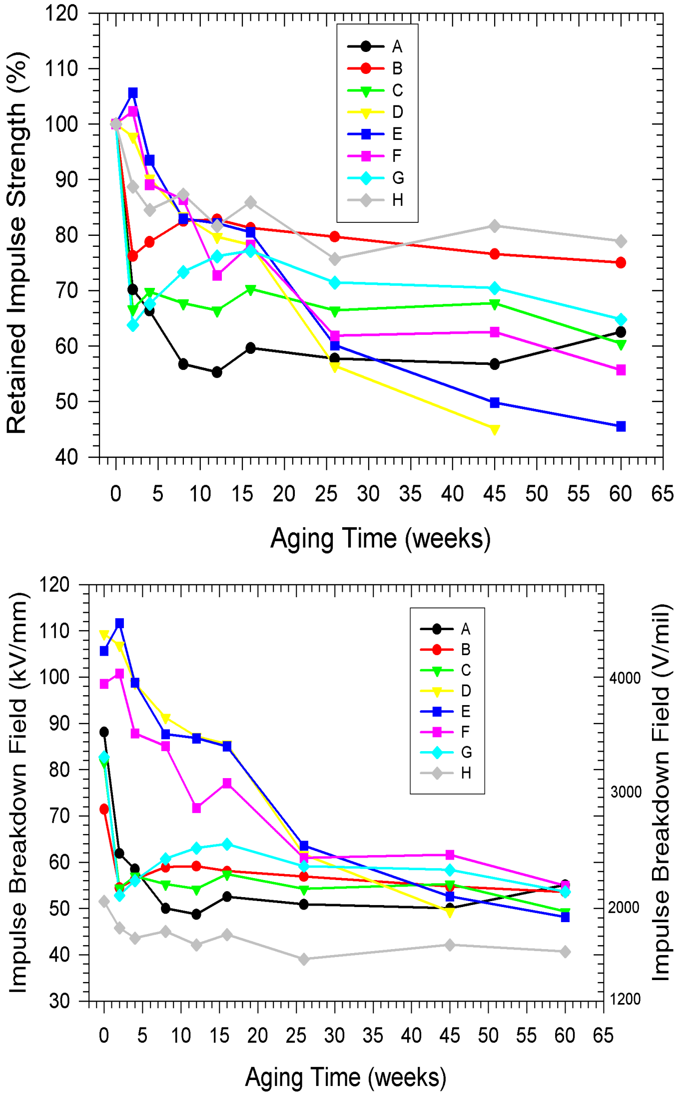

Figure 2. Retained impulse strength and impulse breakdown strength vs wet electrical aging time based on 5 impulse breakdown at each time. The data points plot the average impulse breakdown voltage. Standard deviations are typically in the range of 5 to 10 kV.

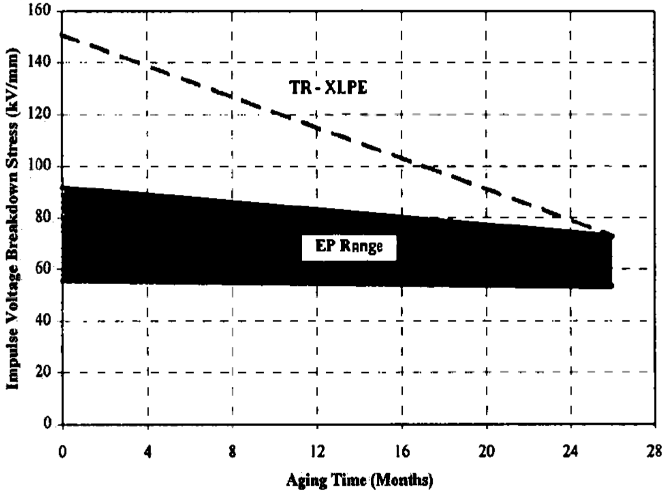

Figure 3. Data published by Katz et al. [1] for the impulse strength of EPR and TR-XLPE cables during two years of field aging.

the data presented in [1] and with the aging mechanism proposed in [2].

The trend in AC breakdown of TR-XLPE F differed from that of TR-XLPE D and E. The AC breakdown strength of F dropped steadily with aging time without any clear trend toward leveling off. On the other hand, the impulse strength for this dielectric (Figure 2) may be leveling off at a withstand similar to that of the EPR insulations .

AC Breakdown Strength at 26 Weeks

The 150 m coils were removed at 26 weeks, and about 100 AC breakdowns were measured for each cable type. The 2-parameter Weibull analysis of these data is presented in Figure 5 and confirms the data of Figure 4 in showing that TR-XLPE dielectrics D and E retain very high breakdown strength even though their impulse strength has dropped by 40% at this time (Figure 2). TR-XLPE F has a slightly greater AC breakdown strength than the EPR's but is on a downward trend, as can be seen from Figure 4, so that by 45 weeks, the AC breakdown strength of TR-XLPE F is similar to that of the EPR dielectrics which show essentially no change in AC breakdown strength from 16 to 45 weeks.

Insulation Resistance

Several 15 m samples had regions of very low insulation resistance after aging for 60 weeks. In the case of sample D, the low resistance region was located to the point at which a large water tree had grown all the way through the insulation (Figure 6). A similar low resistance location has been found in sample F but has yet to be analyzed. Figure 7 shows other water trees found near the water tree of Figure 6. Once this one large water tree was removed, the insulation resistance of the remaining sections of the 15 m sample became infinite as measured with a General Radio "Megger". The insulation resistance measurements and discovery of large water trees in combination with the AC and impulse breakdown data, suggest that discrete "defects", i.e., water trees, develop in the TR-XLPE insulation and are responsible for the degradation of impulse withstand over time. However, in the case of TR-XLPE D and E, the formation of water trees apparently does not impact the AC withstand while having a substantial effect on the impulse withstand, possibly for the reasons described in [2].

The insulation resistance of EPR cables varied from a few GΩ to infinite. The implications of low insulation resistance have yet to be explored fully; however, given that failure was frequent during wet electrical aging of all samples at 6 kV/mm (150 V/mil) after 60 weeks, anomalously low insulation resistance probably is indicative of imminent failure. In the case of TR-XLPE cables, such failure is clearly associated with water trees; however, the cause of sample failure for the EPR cables has yet to be determined. Table 1 shows the insulation resistance measured for the various 15 m cable samples after 60 weeks of wet electrical aging at 6 kV/mm (150 V/mil). As always, samples D, E, and F are TR-XLPE and the remainder are EPR. Based on the data shown in Table 1, isolated regions of low insulation resistance were located for samples C2 and F1 in addition to that which had

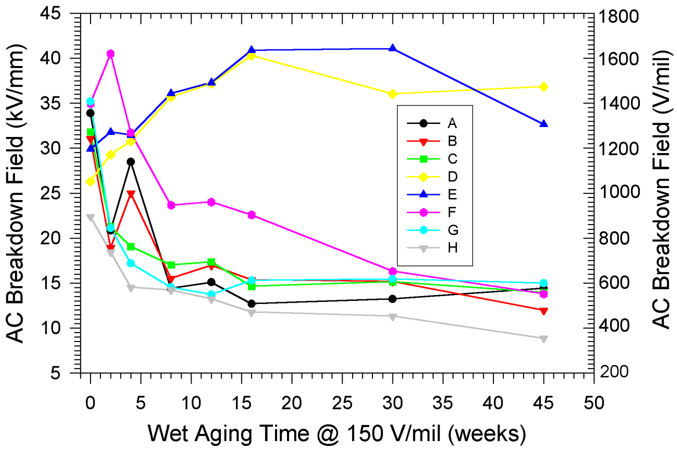

Figure 4. AC breakdown field vs wet electrical aging time. D, E, and F present data for TR-XLPE dielectrics while the remainder are for EPR dielectrics.

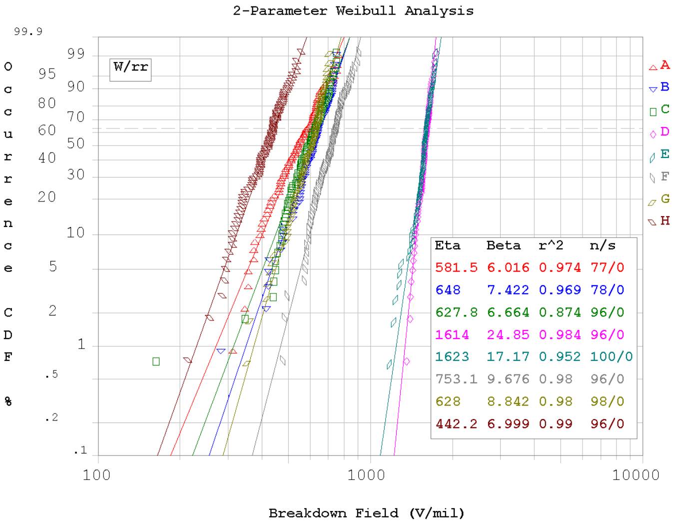

Figure 5. AC breakdown data at 26 weeks. The data provide an excellent fit to a 2-parameter Weibull distribution. TR-XLPE dielectrics E and F retain very high AC breakdown strength even though their impulse strength has dropped by about 50% at this time (Figure 2). The AC breakdown strength of TR-XLPE F is slightly greater than that of the EPR dielectrics but on a downward trend (Figure 4).

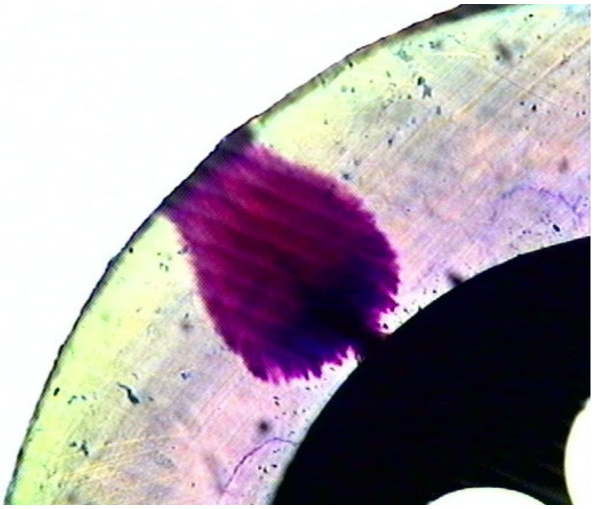

Figure 6. Water tree localized in TR-XLPE sample D through insulation resistance measurements. The water tree could be located to within a fraction of a mm using a moist q-tip as a probe with a "megger".

previously been found in D2 (Figures 6 and 7). These regions of low insulation resistance have yet to be investigated.

DISCUSSION

These tests clearly indicate that AC breakdown voltage is not a good indicator for the condition of TR-XLPE insulations D and E, as the AC breakdown strength remains very high until just before failure, even as the impulse strength drops substantially. The data suggest that impulse strength is a much more sensitive indicator of the insulation condition of these TR-XLPE formulations. This is probably the result of the mechanisms discussed in [2], i.e., because the water tree is resistively graded under AC excitation and does not cause a major distortion of the electric field until the water tree is very large. As always, failure probably results from an electrical tree initiated by the approach of the water tree to the opposite electrode. TR-XLPE F acts differently, as the AC and impulse strength appear to drop together, presumably as a result of water tree growth.

The EPR insulations act as expected, with a substantial initial drop in AC withstand and a much smaller drop in impulse withstand, after which both the AC and impulse withstands tend to be stable. Given that past work by EPRI [3] concluded that no evidence relates water tree growth to failure of EPR insulation, the cause of the drop in withstand is not clear. However, the reduction in the AC and impulse withstand of EPR insulations appears to be related to absorption of moisture by the insulation, which changes the global material properties, and not to development of any discrete "defects" such as localized electrochemical degradation. The very rapid drop in the AC strength of EPR insulation, on the scale of the time for diffusion of moisture through the insulation and far too rapidly for electrochemical degradation, is strong evidence for this hypothesis.

CONCLUSIONS

Reliable long term cable performance in a distribution network requires an AC withstand well in excess of 5 pu and an impulse withstand in excess of 10 pu. These levels must be maintained over the entire cable plant, without development of localized electrochemical or other degradation which reduces the withstand at any point along any cable to below these levels. Even a low probability of localized degradation can compromise the entire cable infrastructure.

This investigation indicates that insulation characteristics under wet electrical aging can be complex, and no one test, such as AC breakdown vs time during wet electrical aging, can be taken as indicative of good insulation performance in the field. One problem with enshrining test protocols in standards is that systems will be optimized to meet those standards, and other performance characteristics required for long term reliability may be sacrificed in the process.

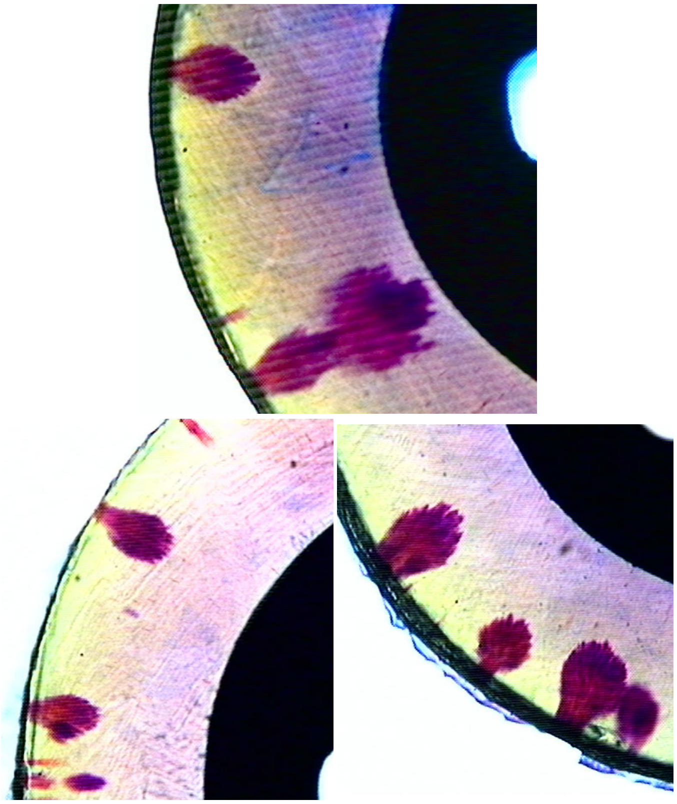

Figure 7. Water trees found in the vicinity of the low insulation resistance point shown in Figure 6. Note that the black region at the outer diameter of the samples is not semicon as none was extruded.

Table 1

Insulation Resistance for 15 m Lengths after 60 Weeks of Wet Electrical Aging at 150 V/mil

Sample	1	2	3	4	5
A	Inf	10 TΩ	10 TW	23 GΩ	34 GΩ
B	26 GΩ	20 TΩ	1.2 TΩ	4 TΩ	800 GΩ
C	Inf	17 GΩ	190 GΩ	210 GΩ	1.6 TΩ
D	Inf	30 TΩ	Inf	Inf	Inf
E	20 TΩ	20 TΩ	Inf	20 TΩ	5 TΩ
F	800 GΩ	620 GΩ	20 TΩ	1.2 TΩ	N/A
G	4 TΩ	5 TΩ	3.5 TΩ	3 TΩ	1 TΩ
H	4.5 GΩ	4.5 GΩ	4.5 GΩ	2.3 GΩ	8.9 GΩ

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