CORRELATION OF ACCELERATED AGEING PHENOMENA AND LONG-TERM CABLE PERFORMANCE

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ABSTRACT

Utilities, cable makers and industry experts generally agree that the results of medium voltage cable qualification testing are a good indication of ultimate cable performance and expected lifetime. Here we focus on the development of a new enhanced cable insulation material for distribution cables. While qualification tests can differentiate poor performing materials from those with superior performance, it will be illustrated that correlating such qualification data to life expectancy is much more complex. The data presented show that the enhancements observed during material development in water treeing behavior and breakdown strength measured in the short-term 30 day laboratory tests led to a moderate 15% improvement in qualification results. However, significantly larger increases in the time-to-failure and characteristic life time of 400% for cables in the ACLT test were recorded. It would be expected that similar enhancements would be achieved for cables under service conditions in the field.

INTRODUCTION

In the 1970s, unjacketed high molecular weight thermoplastic polyethylene and cross-linked polyethylene (XLPE) cables began failing prematurely with water treeing being associated with the cable failures [1-3]. While successive improvements to insulation, semicons and jacketing have enhanced the performance of XLPE cable, the development of water tree retarding XLPE insulation in the early 1980s is arguably the most significant advancement [4].

Since its introduction in 1983, Dow Electrical & Telecommunications' patented water tree retardant crosslinked polyethylene insulation (TR-XLPE) has replaced conventional XLPE to become the predominant medium voltage (MV) insulation for primary distribution cables in the U.S. and Canada. This insulation is also widely used in many countries, notably Germany and Russia in Europe, as well as other developed and developing regions.

In 2010, Dow Electrical & Telecommunications launched the latest generation of TR-XLPE insulation, DOW ENDURANCE™ HFDC-4202 (C4202) and the first full scale qualifications tests have now been completed. Utilities, cable makers and industry experts generally agree that the results of MV cable qualification testing are a good indication of ultimate cable performance and expected lifetime. The qualification of MV cable is possibly unique inasmuch as following an extended wet ageing protocol, such as CENELEC or AWTT testing, the cables are electrically broken down and their retained electrical strength measured. Although such qualification tests differentiate poor performing materials from those with superior performance, this paper will show that correlating qualification data to life expectancy is much more complex. Data from laboratory development to commercialization of the enhanced water tree retardant insulation C4202 are used to illustrate the complexity of correlating different test procedures with expected cable life. Throughout the study, the previous generation insulation material HFDB-4202 (B4202) is used as a benchmark.

EXPERIMENTAL

Water Tree Growth Rate

Water tree growth rate testing was conducted according to ASTM D6097-01a for "Relative Resistance to Vented Water-Tree Growth in Solid Dielectric Insulating Materials." Samples of the insulation compound were moulded and crosslinked into 2" diameter disks with a moulded-in defect produced by a conical needle with a precise tip radius (3 µm). The samples were then aged in U-tubes filled with a 0.01 molar NaCl solution. The samples were aged for 30 days under a constant AC voltage of 5 kV at 1 kHz.

Accelerated Cable Aging Tests

Acceleration of cable aging can be achieved by imparting higher electrical stress, high temperature, and the presence of a wet environment as accelerating aging factors. Several aging times are generally required and provide a means to monitor the deterioration of electrical breakdown strength as a function of aging time. In the Americas and in parts of Asia, a 1-year AWTT according to ICEA S-694-94 is utilized as a part of the qualification process and in Europe, the 2-year CENELEC HD 605 aging protocol has been adopted more broadly. Two of the accelerated tests presented here are the AEIC Accelerated Water Tree Test (AWTT) [5] and the Accelerated Cable Life Test (ACLT) [6].

Accelerated Water Tree Test

In AWTT, twelve samples of 1/0 15 kV cable core (no jacket) with 4.4 mm (175 mil) insulation wall thickness are aged in PVC conduits. The specimens are subjected to a 60 Hz test voltage. A 14 day preconditioning was conducted to ensure that the test is not influenced by the presence of volatile byproducts from the crosslinking reaction. The first three samples are tested for AC breakdown (ACBD) after the initial preconditioning. The other nine samples are then tested for a year under 'wet' conditions. Three samples each are removed after 120, 180, and 360 days and tested for ACBD. The requirements are 26, 22.8, and 15 kV/mm respectively for three aging times.

Accelerated Cable Life Test

The ACLT evaluates comparative life of combinations of insulating and semiconductive shielding material designs of 15 kV cable specimens in water-filled tanks. Completion of the ACLT is defined as failure of all of the test specimens. The test was performed on 1/0 15kV cable core with 4.4 mm (175 mil) insulation wall thickness. A continuously applied test voltage of $4V_g$ (4 times rated voltage to ground of a cable rated for a 15 kV phase-to-phase voltage) and current loading to achieve a conductor temperature of 90 °C in air was utilized until all test specimens failed. Time-to-failure statistical analysis is commonly achieved through fitting the population of failure data to a Weibull (or log-normal) failure distribution function. The Weibull plot compares the cumulative failure distribution versus time-to-failure on a special coordinate system which will yield a straight line which is characterized by two parameters: "Eta" (the characteristic time, where 63.2% of the population has failed) and "Beta" (the slope or shape factor).

RESULTS AND DISCUSSION

Research during the development of C4202 involved studying the influence of the material composition on its resistance to growing water trees and electrical breakdown strength over different timescales. Data were benchmarked against conventional XLPE and the existing generation water tree retardant product B4202.

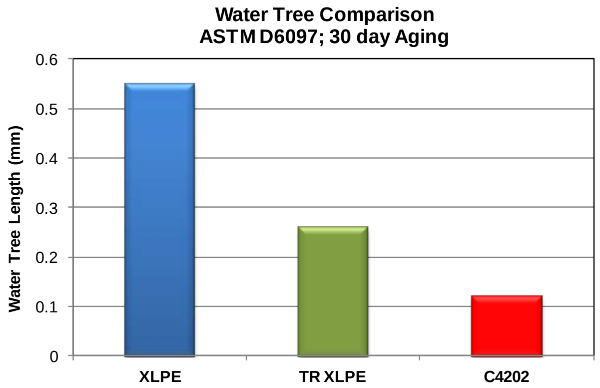

Figure 1. Water tree length comparison after 30-day wet aging according to ASTM D6097-01a Water Tree Test of XLPE, previous generation TR-XLPE (B4202) and new generation TR-XLPE (C4202)

Utilizing the water tree growth rate test, water trees were grown and measured from a point defect moulded into the insulation material test sample. As depicted in Figure 1, water trees formed during this test are significantly smaller with the new enhanced insulation, approximately 50% shorter than the incumbent insulation grade. As shown in Figure 2, the C4202 TR-XLPE grows smaller and more constrained water trees compared to conventional XLPE and B4202 TR-XLPE.

Short-term laboratory scale tests such as water tree growth rate and AC breakdown are convenient tools for quickly screening multiple material formulations for performance. Such tests have been shown to correlate with cable performance [7].

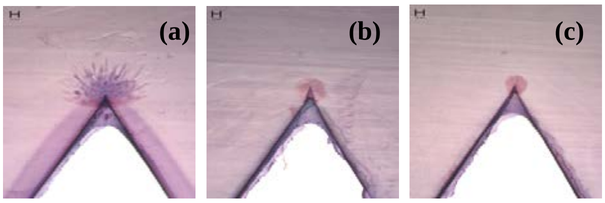

Figure 2. Cross-sectional micrographs of water tree growth after 30-day wet aging according to ASTM D6097-01a Water Tree Test of (a) XLPE, (b) previous generation TR-XLPE (B4202), and (c) new generation TR-XLPE (C4202)

Full scale cable testing, according to the AWTT qualification protocol, has been completed by cable manufacturers in North America for the new insulation material. Testing according to the European CENELEC HD 605 protocol is still ongoing due to the longer (two year) qualification period.

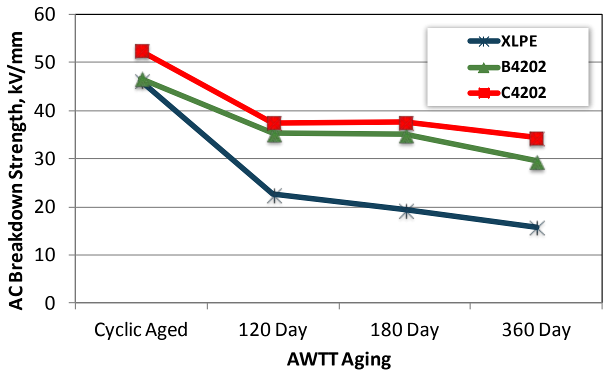

Figure 3. AC Breakdown strength following AWTT ageing protocol.

The average high-voltage AC breakdown strength results are shown in Figure 3 and compared to typical values for B4202 (the previous generation material) and XLPE insulation. The enhanced TR-XLPE material offers retained wet-aged electrical strength at the end of testing of over 34 kV/mm (800 V/mil) average: this easily surpasses the AWTT industry requirement of 15 kV/mm (380 V/mil), at the end of one year. The breakdown strength of C4202 has increased by 15% over B4202 after 360 days of wet aging.

This increase in retained breakdown strength may seem small compared to the 50% decrease in water tree length observed in Figure 1; however, there are significant differences between the tests. Most notably the AWTT protocol uses tap water which is separated from the insulation by the semicon layers, whereas ASTM D6097-01a uses a saline solution to accelerate tree growth [8] from artificial defects intimately in contact with the water source. It is generally considered that under service conditions XLPE cables which do not employ a radial water barrier (so called “wet design”) will likely last 25 years, whereas those using water tree retardant insulation will surviving in excess of 40 years [9,10]. This is corroborated by very few reported failures due to insulation degradation in cables made with TR-XLPE in close to 30 years of service operation [9]. The higher retained breakdown strength following AWTT testing of cables made with water tree retardant insulation compared to conventional XLPE is generally seen as an indication of the superior life expectancy (40 versus 25 years) for this insulation. As such a 15% improvement in retained breakdown strength following AWTT testing for the new enhanced TR-XLPE may not be considered striking and its impact on service life might be predicted to be limited.

The results in Figure 4 show time-to-failure data in the ACLT test for cables manufactured with different insulation materials but the same grade of semicon. Even during the development phase for the new enhanced insulation (Prototype and Pilot C4202), the characteristic time-to-failure is more than double the existing grade (B4202); approximately 750 days versus 350 days. The Prototype and Pilot plant C4202 made insulations have the same chemical composition as the commercial grade, but have been manufactured in small volumes for research purposes and lack the high level of cleanliness of the commercial grade. It is therefore surprising that these materials still outperform the commercial B4202 insulation by over 100%.

To date cables made from the commercially available C4202 insulation have shown no failures after 805 days, as such a Weibayes analysis [11] has been used where it is assumed that a failure occurred at the current time and the shape parameter is assumed similar to that of the prototype and pilot samples; and will thus be a “worst case” estimate (dashed line) of a 1-parameter Weibull distribution. Applying this method an estimated characteristic time-to-failure close to 1500 days is achieved. This is a four-fold increase in life compared to the previous insulation grade.

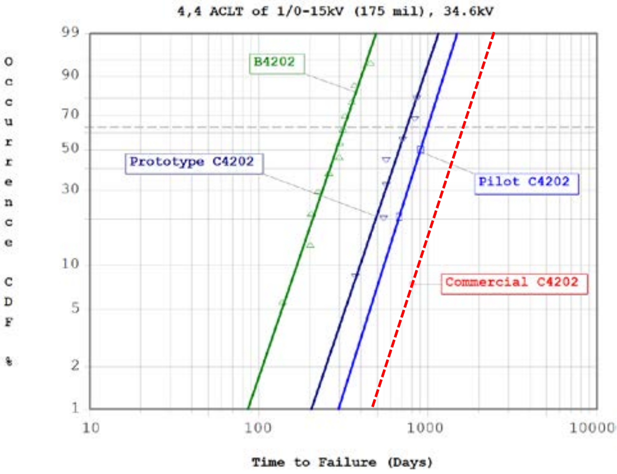

Figure 4. 4,4 ACLT Weibull Failure Distribution Analysis comparing the previous and new TR-XLPE formulations throughout development.

Table 1 summarises the results of the laboratory scale tests and full cable tests comparing the change in performance for C4202 versus B4202. From the perspective of a cable owner/operator the results in Table 1 are highly positive. The laboratory test results translate to improved retained electrical breakdown strength following wet ageing of full scale cables. Though it may be considered that the 15% improvement in retained breakdown strength following AWTT qualification testing is moderate, it has been shown that this small change leads to a large increase in the time-to-failure and characteristic life time; a worst case increase of four times the results for the incumbent insulation has been achieved in the ACLT test.

Table 1. Change in various performance measures between enhanced water tree retardant insulation (C4202) and previous generation (B4202)

Test	Laboratory Scale Tests		Full Cable Test	
Result	Water tree length after water tree growth rate test	Retained electrical breakdown strength in plaques	Retained electrical breakdown strength in cable testing	Time to Failure Characteristic Life
Change for C4202 compared to B4202	Decreased 50%	Increased 25%	Increased 15%	Increased 400%

These data suggest that the ACLT protocol gives a more meaningful indication of cable life than one or two year qualification tests (AWTT or CENELEC). These standards do nevertheless differentiate high performing cables from those with lower performance. It is also important to note that the performance of a cable is determined by the combination of insulation, semicons and quality of manufacture.

During AWTT testing bow tie trees tend to initiate in the first 120 days of ageing and subsequently not increase significantly in size over the rest of the ageing period. Figure 3 could be interpreted as mirroring this behavior, the initial fall in breakdown strength accompanies the growth of bow tie trees, which then tend to self-limit, and then only decreases slowly with further ageing. There is little difference in the size of number of bow tie trees in B4202 and C4202; consequently there is little difference in the breakdown strength of the materials following the AWTT ageing protocol. XLPE on the other hand grows larger and more highly branched bow tie trees over the same time frame, which in turn, leads to a higher localized stress and larger impact on the breakdown strength compared to TR-XLPE materials.

In contrast the ACLT protocol records the time to failure and is consequently a measure of the resistance to initiate vented trees and the rate at which these trees grow. The cable fails once these vented trees either bridge the insulation or grow beyond some critical length and initiate electrical trees that progress through the insulation. In either case the cable fails when the degraded insulation can no longer hold the applied voltage resulting in a phase-to-earth fault. C4202 retards the growth of vented trees more effectively than B4202, as seen in Figure 1 and Figure 2, and this is reflected in the much longer characteristic time to failure (Figure 4). The ACLT mirrors the real-world ageing mechanism of cables in service, and is thus arguably a better indication of the manner in which cables will perform in service than the AWTT test.

The AWTT (or European equivalent CENELEC) and ACLT measure different aspects of cable ageing. Utilities generally base specifications on the AWTT or CENELEC standards to ensure a desired level of performance (and life expectancy). However as has been shown above, the ACLT method is a better discriminator of anticipated life. Longer cable life leads to lower life cycle costs [12] for the asset owner.

CONCLUSIONS

The development of an improved MV cable insulation, from laboratory to commercial deployment, has been reviewed. It has been shown that:

- Improvements in data seen in short-term laboratory tests translate to increased performance in full size cables.
- These enhancements in water treeing behavior and breakdown strength lead to moderate improvement in the qualification results.
- However a minimum four-fold increase in the time-to-failure and characteristic life time for cables in the ACLT test is observed.

While qualification tests can differentiate poor performing materials from those with superior performance, correlating these results to life expectancy is much more complex and the ACLT protocol is a useful tool to aid utilities in this regard. It would be expected that similar enhancements would be achieved for cables under service conditions in the field.

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