TREE-RETARDANT CROSSLINKED (TRXLPE) REDUCED INSULATION WALL ACCELERATED CABLE LIFE TEST (ACLT) RESULTS

John T. **SMITH III,** General Cable, (USA), jsmithIII@generalcable.com

ABSTRACT

The IEEE P1407 Draft Guide for Accelerated Aging Tests for Medium-Voltage (5 kV – 35 kV) Extruded Electric Power Cables Using Water-Filled Tanks recommends that maximum conductor shield test stresses be limited to 12 kV/mm (300V/mil). This presentation will show historical and current Accelerated Cable Life Test (ACLT) results of reduced insulation wall test specimens that were wet-aged in the 8kV/mm (200 V/mil) – 25kV/mm (500 V/mil) test stress range. Test results will show that for several commercially-available conductor shields and TRXLPE insulation systems that were wet-aged in this test stress range, characteristic life and testing times are ≥ 2X that for full-size (4.45mm, 175mil) 15kV-rated insulation wall cables at the recommended maximum conductor shield test stress of 12kV/mm(300V/mil). This result is demonstrated in two (2) different ACLT protocols, and for two (2) different reduced insulation design thicknesses. ACLT results at higher aging test stresses (>16kV/mm (400V/mil) show significant reductions in characteristic life and testing times. Thermal preconditioning of the reduced wall test specimens to remove all crosslinking by-products (acetophenone, dimethylbenzylalcohol, alpha-methylstyrene) also contributes to a reduction in characteristic life and testing times. This also provides an estimation of the "true" dielectric life of the insulation system. Implications of these results on insulation wall cable design are discussed.

KEYWORDS

TRXLPE, ACLT, Water-Filled tanks, Reduced Insulation Wall, Characteristic Life, Medium Voltage Power Cable, IEEE Std 1407-2007

INTRODUCTION

Accelerated Cable Life Testing (ACLT) in water-filled tanks using full-size test cables, has been used in North America since the late 1970's/early 1980's to evaluate insulation materials for medium voltage (MV) underground distribution power cables [1]. In the late 1980's, the ACLT also began to be successfully used to evaluate performance differences of semi conductive conductor shield materials. "Full-size" cables used in ACLT evaluations (as opposed to insulated wires) are defined as cables having an aluminum or copper stranded conductor, covered with successive layers of a semiconductive shield material, insulation thicknesses in compliance with the 100% insulation level prescribed in Association of Edison Illuminating Companies (AEIC) cable specifications (CS), No. 5 through No. 8. , a semiconductive insulation shield material and a concentric copper wire metallic shield [2]. For 15kV-rated MV cables, the 100% insulation level over the conductor size range is defined such that the maximum stress at the conductor shield/insulation interface is limited to 2kV/mm (51V/mil). Typically, in ACLT evaluations, the test cable's insulation level is prescribed at 4.45mm (0.175"), and the cables tested at stresses in the 6 – 8kV/mm (150 – 200V/mil) range. Since the early 1990's, interest in reduced insulation wall MV cables has grown, and AEIC has published a document, which provides guidelines for insulation thicknesses that are less than 100% insulation levels [3]. Research efforts at cable manufacturers and testing laboratories have focused on wet-aged testing of cables with reduced insulation wall thicknesses [4,5]. However, other researchers and IEEE Std 1407™-2007 caution against testing cables at maximum conductor shield stress > 12kV/mm (300V/mil), under dry or wet aging conditions [6,7]. This paper will present ACLT results for reduced insulation wall tree retardant crosslinked polyethylene (TRXLPE) insulations, with two (2) different types of conductor shield materials, using two (2) different ACLT protocols. One (1) conductor shield type commonly known as "conventional" (CCS) and another known as "supersmooth" (SSCS) are evaluated with the TRXLPE materials. The test protocols recommended by IEEE STD 1407™-2007 are followed, with the exception that some test stresses do exceed the maximum recommended 12kV/mm wet-aging test stress.

ACLT Details

The details of the ACLT protocols are shown below in Table 1.

Table 1

ACLT Protocol Details

IEEE 1407 Std Test Element			
Tank Type	#1	#2	#3
Tank Materials of Construction	Stainless Steel	High Density Polyethylene	Stainless Steel
Tank Thermal Insulation	Redwood	Fiberglass	Redwood
Water Quality	Deionized	Deionized	Deionized
Conductor Metal	Aluminum	Aluminum	Aluminum
Conductor Size, (mm^2)	28, 53	53	53
Insulation Wall, (mm)	1.6, 3.18, 4.45	1.6, 4.45	1.6, 4.45
Test Voltage, (Multiple of U_0*)	4, 3	3, 2, 1	4, 3, 1
Preconditioning	"B", "J"	"B", "J"	"B", "J"
Conductor Temperature Control/Location	90 ± 2°C in air	75 ± 2°C Mid-Sample in Water	75 ± 2°C Mid-Sample in Water
Conductor Temperature Load-Cycle	8 hrs. On/16 hrs. Off	8 hrs. On/16 hrs. Off	8 hrs. On/16 hrs. Off
Tank Room Temperature,(°C)	35 ± 2°C	25 ± 3°C	25 ± 3°C
Tank Water Temperature Control	No	Yes	Yes

*U_0 – rated voltage to ground

Tank Types #1, #2 and #3 of IEEE 1407 were used in this testing, with Type #1 and Type #3 accommodating a maximum of twelve (12) specimens, and Type #2 a maximum of ten (10) specimens. Historically, the majority of published ACLT time-to-failure (life) results published utilize a protocol wherein the tank water temperature is not controlled, but is allowed to vary with the 8-hr current-on/16-hr current-off load-cycling periods. ACLT life results have also been reported using an alternative ACLT protocol wherein the tank water temperature is maintained at a constant level for the entire 24-hour load-cycle of the test. Both of these ACLT protocols were used in these investigations. The recommendations of IEEE 1407 were followed with the following deviations: maximum test stresses > 12kV/mm (300 V/mil), and preconditioning for 500 hours in air at a conductor temperature of 90°C instead of the recommended 360 hours in air at a conductor temperature of 90°C.

EXPERIMENTAL

Cable Manufacture, Selection and Preparation

The identities of the materials in this paper are coded to maintain anonymity. Cables were produced on manufacturing production scale equipment, and on full-scale research and development laboratory, dry-cure continuous vulcanization (CV) extrusion lines. All cables were subjected to industry standard factory production testing, including factory acceptance electrical testing. Sufficient lengths to provide ACLT populations were removed from cable reels and preconditioned in air at the selected preconditioning protocol. All individual ACLT specimens were terminated with pre-molded, slip-on stress cones. Immediately before entry into an ACLT tank, each test specimen was tested for partial discharge (PD) at 40kV in the case of 4.45mm (0.175”) insulated specimens, and at 26kV in the case of specimens whose insulation wall thickness was < 4.45mm (0.175”). Dissipation factor (DF) and capacitance (C) were measured at 8.7kV in the case of 3.18mm (0.125”) and 4.45mm (0.175”) insulated specimens, and at 12kV for 1.6mm (0.063”) insulated specimens.

Truncation and Suspensions

In some cases, populations were not allowed to remain under test until all specimens had failed in order to shorten the overall testing time. The technique consists of designating sub-groups of specimens within the total population before the ACLT aging begins. When the first failure of a sub-group occurs, the remaining specimens of that sub-group are removed at that time. Those removed specimens are treated as suspensions (a unit whose testing was interrupted before failure) in the data analysis, and the population’s size is denoted as “n/s”, where “n” equals the total number of specimens tested, and “s” equals the total number of specimens removed from test before failure. This technique, called “sudden death”, was used to make life estimates for those populations [8]. In the cases where the “sudden death” technique was implemented, a step-rise AC breakdown was performed immediately upon removal from the ACLT tanks in order to assess the remaining dielectric strength at that aging time. This paper will not discuss the AC breakdown strength results of those populations where the “sudden death” technique was employed, but will instead elaborate on the failure times of the specimens that failed while aging in the tanks.

Perpetual Survivors

In some cases of ACLT evaluations, one (1) or two (2) specimens may survive in the test an inordinately longer amount of time under test, after n-1 or n-2 specimens have all failed. Inspection of the failure times and the survivors’ aging time may indicate that these “perpetual survivors” are not a part of the failure distribution. [8] An analysis of the failure times, with the unfailed perpetual survivor’s aging time taken as a failure, might indicate it to be a statistical outlier of the failure distribution. If so, these perpetual survivors can be removed from test and treated as suspensions.

Data Analysis

The Weibull distribution is the most widely used statistical model for life data analysis. The equation for the 2-parameter (2-*p*) Weibull cumulative distribution function (CDF) is given by:

$$\mathbf{CDF = F(x) = 1 - e^{-(x/\eta)\beta}}$$

... where **x** is the random variable (such as time-to- failure or breakdown voltage), ETA **(η)** is characteristic value/life, BETA **(β)** is the slope/shape parameter and **e** is the base of natural logarithms.

The ACLT failure times of this investigation were analyzed using widely accepted Weibull analysis techniques [8]. Outlier testing of the data was performed. Hypothesis testing of populations’ ACLT results was also utilized to determine statistically significant differences or equivalency. Regression analysis techniques of the ACLT results were also utilized to describe the relationships between reduced insulation wall, maximum stress at the conductor shield and ACLT life estimates.

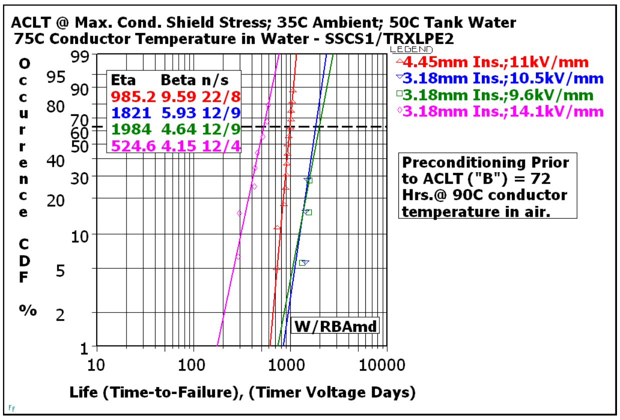
RESULTS AND DISCUSSION

Weibull and Contour Plots Analysis

TRXLPE2 and SuperSmooth Conductor Shield (SSCS1)

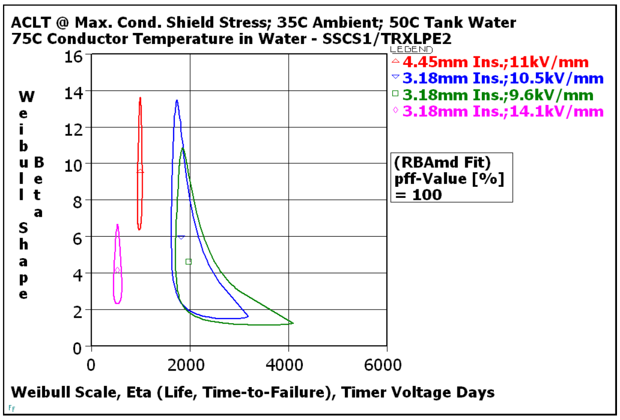
Figures 1 and 2 are 2-*p* Weibull cumulative distribution function and joint 90% confidence bounds likelihood ratio (lr) contour plots, respectively. This combination of conductor shield SSCS1 and insulation TRXLPE2 are of a currently commercially available supersmooth conductor shield and a previously commercially available TRXLPE insulation. The Weibull plot is a maximum likelihood solution (MLE) with reduced bias adjustment. This method of analysis used throughout this paper (W/RBAmd) is shown in the upper left corner of the plot. ”W” indicates the Weibull distribution, RBAmd is defined as **R**educed **B**ias **A**djustment with MLE **med**ian ranks, and is recommended when analyzing small sample populations [8]. The technique removes the small sample bias from the scale and shape parameters when using the maximum likelihood estimation technique. The cables of this materials combination received ”B” preconditioning (continuous conductor heating for 72 hours @ 90°C in air) before entry into ACLT. Tank water temperature for this ACLT was not controlled, but averaged approximately 50°C over the 24-hour load-cycle. Other specific details of the ACLT are shown on the plots. The lower right corner of the Weibull plot shows the characteristic 63.2% (Eta) value of the sample distribution.

Fig. 1: 2-*p* Weibull Plot of Full-Size (4.45mm) and Reduced Wall (3.18mm) TRXLPE 15kV Cables



It also shows the Beta value of the sample population, a measure of the variation or spread in the data, and categorizes the failure mode of the sample population. The value "n/s" provides the sample population size; total number of specimens tested, "n", and "s", the number of specimens suspended.

Fig. 2: 2-*p* Weibull Contour Plots (graphical hypothesis testing) of Full-Size (4.45mm) and Reduced Wall (3.18mm) TRXLPE 15kV Cables



The contour plot of Figure 2 shows a 90% confidence contour in the Beta/Eta plane. The limits of the contours in the Eta/Beta plane, are defined by two-sided joint 90% confidence bounds for Eta and Beta. When contours from different data sets overlap and the data is from the same type of testing, then these data sets can be mixed together to increase overall data confidence. Contour plots essentially represent a statistical and graphical hypothesis test. The contour plots shown in Figure 2 provide a clear picture of the performance of the cables under the indicated ACLT conditions, at various conductor shield maximum stress levels and insulation wall thicknesses. The note on the contour plot showing a pff-Value of 100% indicates that there is 100% chance or a probability of 1.00 that the data sets are statistically significantly different. For data sets to be statistically different, the pff-Value must be at least 90%. If the pff-Value is <90%, data sets are deemed statistically equivalent, and as having been sampled from the universal population of values. The Weibull plot (Figure 1) shows that at ~11kV/mm (280 V/mil) equivalent maximum stress, the reduced wall (3.18mm (0.125")) cable design (on average) shows ~ 2X the characteristic life performance of the full-size (4.45mm) cable. At 14kV/mm (356V/mil), the reduced wall cable shows an approximate 50% reduction in characteristic life performance, essentially reducing the testing time and cost. Although the reduced insulation wall populations' ACLT life are numerically reduced by ~45% of the full size wall insulation cables, the Beta values of the full and reduced insulation wall cables are > 4, and do show overlap in the Beta (y) axis for the 9.6-11kV/mm (244-279 V/mil) stress range. For the case of the reduced wall cable tested at 14kV/mm (356 V/mil), the change in Beta indicates that such a high stress level (> 12kV/mm) may be causing a change in the population's mode of failure [6]. This change in Beta could cause an increase in the number of failures at low (0.01 – 0.1) B-lives of the CDF. However, since all of the Beta values are > 4, representing old age wear out failure mode [8], and the reduced wall cables' characteristic life is very high, earlier failures than those predicted for 4.45mm (0.175") insulation wall, are not predicted at the test stress of 11kV/mm (279V/mil)for this combination of SSCS1 and TRXLPE2. In addition, all of the 90% confidence bounds for Beta overlap for all of the 4.45mm (0.175") and 3.18mm (0.125") test sets (Figure 2), indicating no statistical difference in their failure mechanisms. As Beta is approximately lognormally distributed, the mean (F_{50}) Beta value for this material at these test conditions is 5.75, with lower and upper 90% confidence bounds of 4.12 and 8.02, respectively. Although the observed Beta value of 9.59 for the 4.45mm (0.175") cable at 11kV/mm (279 V/mil) is outside the upper 90% confidence bounds value, it does not compute to be an outlier value.

TRXLPE4 and Conventional Conductor Shield (CCS1)

Figure 3 shows the combination of currently commercially available conventional conductor shield CCS1 and TRXLPE4 insulation. The cables of this materials combination received "J" preconditioning (continuous conductor heating for 500 hours @ 90°C in air) before entry into ACLT tanks. Tank water temperature was controlled at 50 ± 2°C for the entire 24-hour load-cycle. Other specific details of the ACLT are shown on the plots.

Fig. 3: 2-*p* Weibull Plot of Full-Size (4.45mm) and Reduced Wall (1.6mm) CCS1/TRXLPE4 15kV Cables

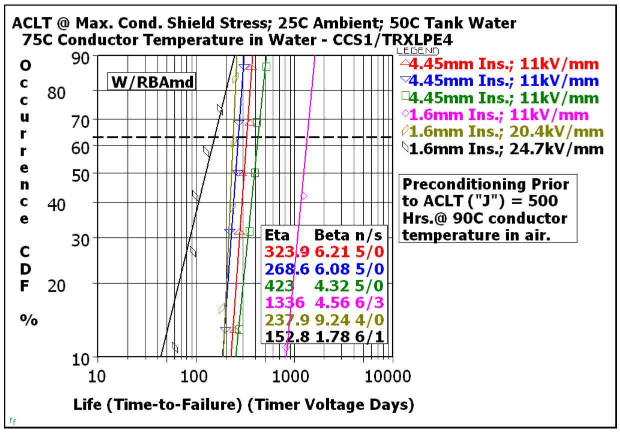
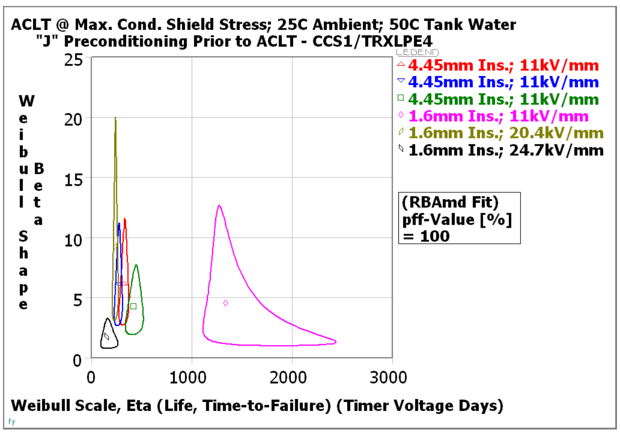


Figure 3 shows repeat ACLT results at 4.45mm (0.175") insulation thickness and 11kV/mm (279 V/mil) for this combination of materials. Hypothesis testing and contour plots (Figure 4) of these three (3) 4.45mm (0.175") data sets show overlap of the first (red) and second (blue), and overlap of the first (red) and third (green). The result for reduced wall (1.6mm (0.063")) at 11kV/mm (279 V/mil) indicated that a mixed failure mode (a failure distribution having 2 separate Beta values) was present. Statistical techniques were used to resolve the mixture and select the appropriate Beta value and resultant failure distribution that most likely represents the true failure mechanism of the material combination. Mixture resolution always results in suspensions because failures occurring outside of the intended test failure mechanism do not represent the primary mode of failure of the material.

The reduced wall results at 11kV/mm (279 V/mil) indicate a 3 – 5X increase in ACLT life for this combination of materials versus full size 4.45mm (0.175") wall cables.

Results for the reduced wall cable at test stresses in the HV and EHV operating stress range for 400 – 500kV class cables (20 – 25kV/mm) (508-635 V/mil)), show significant reductions in ACLT life performance (Figure 3), while also showing visual overlap of the Weibull shape parameter, Beta (see Figure 4. below). Analysis of the Beta values of these ACLT populations as a function of insulation thickness (4.45mm (0.175") vs. 1.6mm (0.063")) indicates that the Beta value of 4.32, generated at a test stress of ~11kV/mm (279V/mil) is an outlier for the 4.45mm (0.175") wall data sets, while the Beta value of 1.78 is not an outlier for the 1.6mm (0.063") data sets. Deletion of the 4.32 outlier value and resultant hypothesis testing of the distribution of Betas, leads to the conclusion that the Beta values are lower for the reduced wall data sets in the stress range of 9.6 – 25kV/mm (244-635 V/mil). This suggests that a change in the failure mechanism occurred specifically in the 20 - 25kV/mm (508-635 V/mil) test stress range, as deletion of the 1.78 Beta (generated at 24.7kV/mm (627 V/mil)) leads to equivalency of the failure mechanism at 4.45 mm (0.175") and 1.6mm (0..063") wall thicknesses. Although the Beta value of 4.32 was a statistical outlier, its value was > 4, still indicating an old age wear out failure mechanism.

Fig. 4: 2-*p* Weibull Contour Plots of Full-Size (4.45mm) and Reduced Wall (1.6mm) CCS1/TRXLPE4 15kV Cables



TRXLPE4 and SuperSmooth Conductor Shield (SSCS4)

Figures 5, 6 and 7 show results of ACLT life and failure mechanisms for the combination of a currently commercially available supersmooth conductor shield SSCS4 and TRXLPE4 insulation. In addition to SSCS4, contour plots of Figure 5 show individual data sets of various other supersmooth conductor shields having the same formulation design, but with slight differences. Their overlap in the Eta/Beta plane justifies their combination into single data sets for a given test stress. SSCS11 represents a significant difference in material formulation design. Figure 6 shows the resultant Weibull plots of the merged data sets, while Figure 7 is the contour plots of the merged data sets.

Close inspection of Figure 5 shows that all 4.45mm (0.175") wall thickness data sets as well as the 14.1kV/mm (358 V/mil) and the 8.8kV/mm (224 V/mil) data sets can be appropriately merged into 3 separate data sets. The merging of these sets provides larger populations for analysis, increasing the confidence and validity of the results.

Fig. 5: 2-*p* Weibull Contour Plots (graphical hypothesis testing) of Full-Size (4.45mm) and Reduced Wall (1.6mm) SSCS4/TRXLPE4 15kV Cables

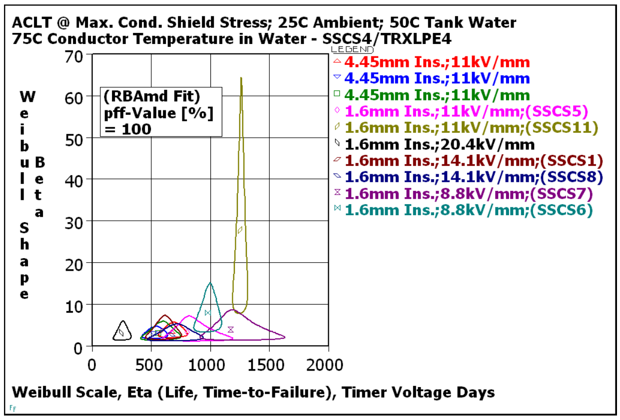
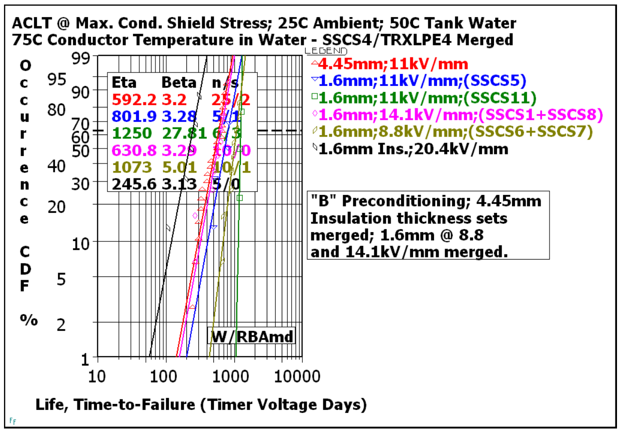


Fig. 6: 2-*p* Weibull Plots Merged Data Sets of Full-Size (4.45mm) and Reduced Wall (1.6mm) SSCS4/TRXLPE4 15kV Cables



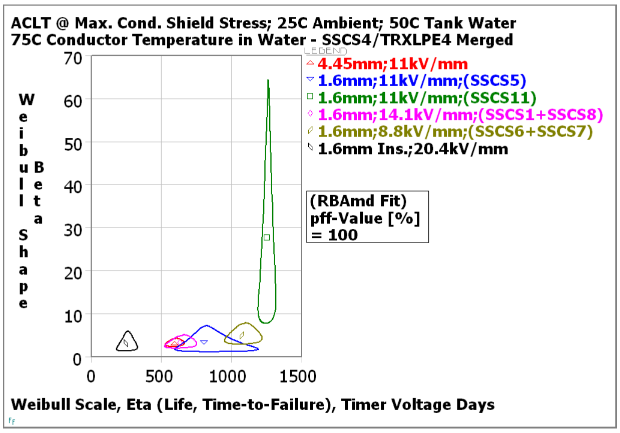
The data set for SSCS11 contained a mixed failure mode. After its resolution, the resultant Beta value was 27.81. The original Beta values of the 8.8kV/mm (224 V/mil) data sets were ≥ 4, but differed by 100% (3.9 vs. 7.9). In order to determine if the failure mechanism of this materials combination was affected by the high-test stresses, original Beta values of the 4.45mm (0.175") and 1.6mm (0.063") datasets were analyzed as in the previous

Close and Return

analysis. The analysis determined that 2 outlier Beta values existed among the 1.6mm (0.063") datasets; 7.9 and 27.81. When these 2 outliers are removed from the 1.6mm (0.063") data sets' analysis, the failure mechanism of the 1.6mm (0.063") data sets (as defined by Beta), is equivalent to that of the 4.45mm (0.175") data over the 8.8-20.4kV/mm (224-518 V/mil) test stress. The Beta failure values are 3.2 for 4.45mm (0.175") insulated cables, and 3.3 for 1.6mm (0.063") insulated cables. Both values represent an early-age wear out failure mode.

The 1.6mm (0.063") life performance of SSCS5 shows an ~1.35X increase over the merged 4.45mm (0.175") data set, while the performance of SSCS11 provides an ~2X increase

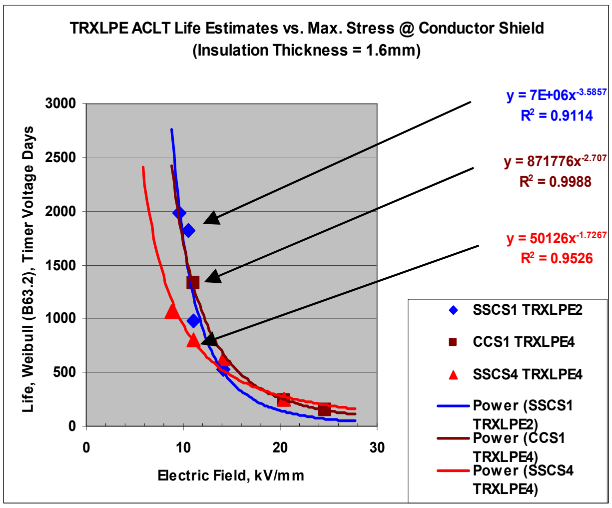
Fig. 7: 2-*p* Weibull Contour Plots (graphical hypothesis testing) of Merged Full-Size (4.45mm) and Reduced Wall (1.6mm) SSCS4/TRXLPE4 15kV Cables



Implications of the Results for Medium Voltage cable Design

The results of the investigations of these reduced wall insulated cables having a complete cable core design and under wet aging conditions can be utilized to determine the life exponent "n" for the combinations of materials evaluated in this study. Figure 8 below shows the results generated in this study as an Inverse Power Law (IPL) regression plot.

Fig. 8: IPL Regression Analysis of 2-*p* Weibull Results of Reduced Wall (1.6mm) TRXLPE Cables



The relationship between applied electrical stress (E) and the endurance or time-to-failure (t or Eta) of model cables or press-cured plaques of small volumes of insulation, is typically modeled using the IPL model. The IPL is normally used in the form, $\mathbf{Y = t * E^n}$, where "n" is the aging or "life" exponent. In cable design for HV and EHV cables, insulation thicknesses are determined with this empirical model, and have been shown to be a very practical way to represent experimental data. For HV and EHV cables, the experimental AC voltage breakdown strength data is usually generated under dry conditions using thin-wall (5 - 6mm) insulated cables. The life exponent "n" for HV and EHV XLPE cables has been determined to be in the 10 – 15 range under dry aging conditions, and more typically, 12. For XLPE MV cables "n" is normally in the range of 5 – 8 [6]. Life exponents reported in the literature are usually developed under dry experimental conditions, providing a bias in the values. It can been seen from the regression plots that life exponents "n" for the two (2) TRXLPE insulations used in this study are in the 1.8 – 3.6 range, depending upon the TRXLPE and the conductor shield type being investigated in the cable design.

CONCLUSIONS

Table 2 below summarizes the ACLT life improvements of the 1.6mm (0.063") cable evaluated in this study. It has been demonstrated that it is possible to obtain significant improvements (1.2X – 5.0X) in wet-aged cable life performance with significantly reduced insulation wall thicknesses in at least 2 TRXLPE insulations.

Table 2

Conductor Shield/Insulation Combination	ACLT Max. Stress @ Cond. Shield	Insulation Thickness, mm		ACLT Life Performance Improvement
		4.45	1.6	
CCS1/TRXLPE4		Eta	Eta	
ACLT LIFE	11kV/mm	324	1336	4.1
ACLT LIFE	11kV/mm	269	1336	5.0
ACLT LIFE	11kV/mm	423	1336	3.2
Average Life Increase				4.1
SSCS1/TRXLPE2				
ACLT LIFE	11kV/mm	986		
ACLT LIFE	10.5kV/mm		1821	1.8
ACLT LIFE	9.6kV/mm		1984	2.0
Life Increase				1.8
SSCS4/TRXLPE4				
ACLT LIFE	11kV/mm	671	802	1.2
ACLT LIFE	11kV/mm	520	802	1.5
ACLT LIFE	11kV/mm	560	802	1.4
ACLT LIFE	11kV/mm	671	1250	1.9
ACLT LIFE	11kV/mm	520	1250	2.4
ACLT LIFE	11kV/mm	560	1250	2.2
Average Life Increase				1.8

This performance improvement is thought to be primarily a result of the volume effect, i.e., the probability of a failure-causing defect being in the insulation is itself a function of the volume of insulation present in the cable core design.

Failure mechanisms can change beyond some threshold test parameter or operating stress. That threshold stress value above which failure mechanisms can change is dependent upon the materials combination, the conductor shield type and the quality of cleanliness. However, for the TRXLPE insulations and conductor shields evaluated in this study, that threshold value is in excess of the IEEE Std 1407TM-2007 recommendation of 12kV/mm. Results obtained up to, and including 20kV/mm (508V/mil) maximum test stress showed no change in Weibull shape (failure mechanism) parameter. The threshold stress level where failure mechanisms can change can be determined by analyzing shape parameter values over a range of test stress levels to determine at what stress level the shape parameter Beta of the 2-p Weibull failure distribution changes, or is demonstrated to consist of a mixed failure mode.

Material evaluation test times for MV cable products intended for use in wet cable designs and/or in application, environments where wet aging will occur can be shortened by employing increased test stresses, and by utilizing a range of test stresses in the presence of shielding materials so that materials compatibilities are also taken into consideration.

Further work is needed to evaluate treeing characteristics of MV insulating materials subjected to such high wet-aged testing and operating stresses.

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