Implementation of Ageing Laws and Cable Models to Estimate Service Life for MV Cable Designs using Laboratory Endurance Tests

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ABSTRACT

Investment in the distribution system continues, with a greater fraction than ever being directed at the use of underground cable systems. This is primarily due to the reported order of magnitude improvement in SAIDI and SAIFI with respect to overhead lines. Feedback from utility cable engineers consistently shows that the anticipated longevity of the cable system is the number one priority when deciding on which cable design to employ at their utility. Recent advances can be recognised with the almost 50% reduction in failure rate in the last 10 – 20 years. However, it is not clear what the longevity is and how much is contributed by the different elements of the cable design. This work uses laboratory data to detail the impact of design and installation / operating conditions.

KEYWORDS

Reliability, Extruded Cable Systems, Life Estimation

INTRODUCTION

Feedback from utility cable engineers consistently shows that the anticipated longevity of the cable system is the number one priority when deciding on which cable design to employ at their utility. Longevity is ranked significantly more highly than first cost or temperature rating etc. This finding can be understood when recognising that failures adversely impact SAIDI/SAIFI data and represent considerable Operations and Maintenance Costs. Thus anticipated life is a key factor in determining the total, rather than first, cost of a cable system.

Initial service performance of extruded cable systems is well documented and has led to many improvements in design, manufacturing, materials, specification and testing. The benefits of these developments are easily recognised through the non-reoccurrence of early poor performance, with useful service lives extending past 20 years. However, it is much more difficult to determine the anticipated life of a cable design and thus the benefits of a particular design element (jacket or WTRXLPE or supersmooth semicon etc). In principle, such lives could be determined from utility records. However, the volume and fidelity of records are not sufficient, in most cases, to support such analyses. Thus, the only recourse to garner these estimates is to return to laboratory test data and to model the impact of design elements on the life in service.

A multi-disciplinary team of experts drawn from utilities, manufacturers and academia examined the options and recognised that the most appropriate starting point was the Accelerated Cable Life Test (ACLT). The principle benefit was that the outcome of these tests were described in terms of time to a specified endurance for voltage / temperature / environmental acceleration; most usually mean life (B50). However, for practical cable designs these data are not directly usable as they are developed for short lengths of cable cores tested at elevated temperatures and voltages. Thus, the modeling activity needs to deconvolve these accelerating factors, which are used to make the tests to implement in practical timescales.

APPROACH

The approach used in this work was to collate the results of many public domain ACLT tests to model the impact of temperature, electrical stress and some elements of cable design. Algorithms were then constructed to scale test data on short cores to long cables in service using Life Expansion and Reduction Factors. The expansion and reduction factors for life are summarized:

- Life Expansion Factors
    - Lower voltages in service compared to test voltages
    - Lower temperatures in service compared to temperatures used in the tests
    - Use of jackets in service cables compared to jacketless cables used in tests
    - Lower load factors in service
    - Absence of water in the conductor interstices
- Life Reduction Factors
    - Longer lengths installed in service compared to the short lengths employed in lab tests
    - Higher volume of insulation used in service cables due to the larger conductor sizes compared to the relatively small conductors used in tests
    - Lower critical risk levels (B1 or B5) for cable failures considered by utilities compared to the mean lives (B50) considered by tests.

ACLT PROTOCOL

ACLT was initially proposed by Bob Lyle of Alcoa Cable Company [1]. Various compound manufacturers, cable manufacturers, and research laboratories adopted the aging program to evaluate cable core performance and to develop an understanding of how specific cable core designs perform. The test protocol including critical test parameters (i.e. sample, preconditioning, test conditions), techniques for measurement, control of the conditions and reporting were recommended in IEEE 1407 [2].

Compared to Accelerated Water Treeing Test (AWTT, a commonly used accelerated aging test qualification protocol), the principle benefit of using ACLT results for cable life estimation is that the data generated from ACLT is time-to-failure, the most relevant descriptor to a utility.

The disadvantage of ACLT is that the test duration is uncontrolled/undefined and sometimes can be too long to make economic sense or provide meaningful results in a timely manner. This is especially a problem when cables are expected to last longer with the advancement of modern cable technology. It thus becomes more and more difficult to fail a cable (i.e. require longer aging time) and less economical to conduct such a test. Sometimes, samples that do not fail within a reasonable timeframe are subjected to AC Breakdown test (ACBD) to obtain dielectric strength information.

Except for a limited study by EPRI [3] using specially produced cables, other research on ACLT has not attempted to estimate cable service life. Those ACLT data are more often used to evaluate cable core endurance performance (i.e. to compare the core performance of two cable designs and to verify design improvements) [4]-[13].

TEST DATA VS. SERVICE LIFE

Although the ACLT has a metric of time (the language of cable life), there are many adjustments required to bridge the gaps between the test conditions and actual service operating conditions. The gaps include,

- Voltage (Electrical Stress). ACLT tests a standard cable configuration, i.e. 15 kV, 1/0, 175 mils, and at four times the nominal operating voltage (Uo). The average electrical stress in the cable insulation during the aging test is 8 kV/mm, compared with a typical average operating electrical stress in the cable insulation of 2 kV/mm. Depending on the insulation thickness, i.e. 100%, 133%, and other thicknesses, the average electrical stress can be different from 2 kV/mm but much less than 8 kV/mm.
- Operating Temperature. In the test protocol, cables are aged at a programmed conductor temperature (30 °C to 75 °C) and loaded 8 hours on and 16 hours off. This controlled condition does not exist in the field. A recent study by the authors indicated that half of the underground distribution (URD) cables operate at the conductor temperature of 45 °C to 60 °C. The majority (>80%) of feeder cables operate at the conductor temperature of 75 °C to 90 °C [14]. These temperatures are likely not the same as the aging temperature in an ACLT. Moreover, the operating temperature of a real system is load dependent and typically not operated at a constant temperature for a fixed number of hours.
- Conductor Size. The insulation volume of a cable, which is an enlargement/reduction factor of the cable life, is dependent on the conductor size. ACLT commonly tests 1/0 AWG cable, although #2 AWG cable was also used in earlier tests before IEEE 1407 was established. The conductor size used in the field could, however, vary from 4/0 AWG to 1,500 kcmil AWG depending on its application.
- Cable Length. Cable length is another factor in cable life. A typical testing length is 15 ft. Test lengths of 30 ft. or 35 ft. were also used if the residual breakdown strength was to be measured after cable aging. The typical length of a cable section is, however, 100 ft. to 300 ft. for a URD system and approximately 1,000 ft. for a feeder system.
- Environmental Conditions. Moisture is one of the critical components for water trees to develop in the extruded cable insulation and cause cable failure in service. During an ACLT test, the cables are placed in a tank. Both the interstitial spaces of the cable's conductor and the tank are filled with deionized water or tap water. In other words, cables are continuously exposed to water from both the inside and the outside of the cable. During field operations, cables are typically exposed to a wet environment only on the exterior surface and primarily at discrete locations. In extreme cases where the cable termination/joint is broken, water may get into the conductors.
- Jacket. One of the primary functions of the cable jacket is to limit moisture ingress into the cable insulation. ACLT evaluates the cable core, which does not include a jacket. Modern cables are typically jacketed, although there is still plenty of unjacketed legacy cable installed.
- Performance Requirement. The ACLT runs the test until all of the samples (100%) fail. Anecdotal evidence provided through utility interactions indicates that utilities generally become concerned when 10% of the field cable population first fails. In other words, the B10 life (time at which 10% fails) is more relevant to utilities. This is further confirmed by a recent study with utilities to establish the critical failure rate for batteries used in distribution automation devices. The poll results indicate that utilities would be concerned and act to correct the problem when 5% of those batteries fail or become unavailable [15]. Although the reliability requirement varies by the type of devices, the consensus is that the device life that matters to utilities is significantly lower than the B50 or B100 life (time at which 100% fails) and is more likely in the range of the B5 life to the B10 life.

All these gaps between test data and service life need to be bridged to derive the cable life at service conditions.

SOURCE OF DATA

This work collated extensive ACLT data from 10 organizations. The majority (~80%) of the data included in this work are from cables examined in the 1980's to pre-2000. Cables serving the underground systems from this period are 20 to 40 years old. They are the backbone of the present URD systems and are of the most interest to utilities from an asset management perspective.

Table 2. Collated ACLT Data Coverage

Voltage Class	**Conductor Size**	**Wall Thickness**	**Insulation Type**
15 kV 20 kV 35 kV	#2 1/0 4/0	175 mil 200 mil 220 mil 345 mil	HMWPE XLPE TRXLPE EPR
Jacket	**Test Length**	**Test Voltage**	**Test Temperature**
Jacketed Non-jacketed	15 ft. 30 ft. 35 ft.	$2U_o$ $3U_o$ $4U_o$	45 °C 60 °C 75 °C 90 °C

The data covers 124 unique datasets including 1,398 cable segments tested under accelerated conditions that add up to 32,000 feet (6.1 miles) of cable cores.

Data collated in this work covers a wide range of cable configurations, test lengths, and test conditions. A summary of the data coverage appears in Table 2. The variety of data sources, testing conditions, and cable configurations makes the model developed in this work immune to overfitting issues.

DATA SUMMARIES AND PARAMETERS

The method used to analyze the time-to-failure data is the

Weibull Analysis. The Weibull distribution is widely used in reliability and life data analysis due to its versatility and its essentially graphical approach [16] and is recommended by IEEE 1407 [2].

Examples of the Weibull analysis on the individual data set appear in Figure 2. This graph shows the analysis of 20 typical, out of the 124 collated, datasets that are tested at different temperatures, voltages, length, insulation volumes, etc. The estimated correlation coefficients for the individual datasets indicate a good fit of the data to the Weibull distribution.

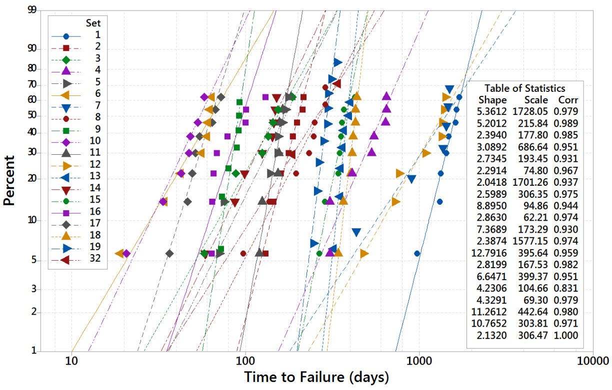

Figure 2. Examples of Weibull analysis for the individual dataset.

The scale parameter, α, gives an indication of the predicted life and is the value of the measured variable at a probability of 63.2%. The expansion and reduction factors will be applied to the scale parameters unless a change in the failure mechanism is resulted from those factors.

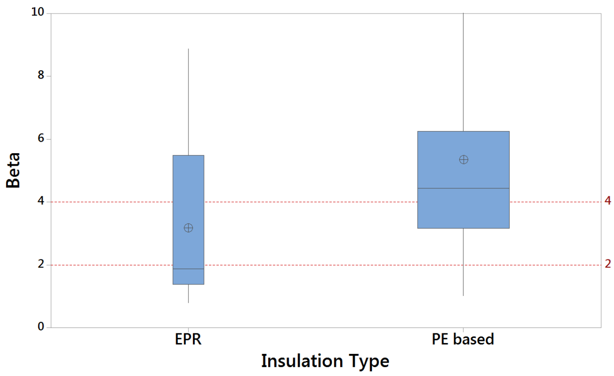

Figure 3. Boxplot of the shape parameters by insulation type – median given by central line within box.

The shape parameter, β, is the slope of the Weibull distribution curve. The value of the shape parameter indicates the characteristic failure mechanism. Figure 3 shows the boxplot of the shape parameters of the collated ACLT data by insulation type. Assuming that the failure modes for high molecular polyethylene (HMWPE), XLPE and cross-linked polyethylene (TRXLPE) are the same, the shape parameters for these PE based insulation test data are lumped together. It is noted that the shape para-meters for EPR insulation have a larger variation than those for PE based insulation. This is possibly due to the differences in chemical ingredient composition of EPR compound in its chemical ingredient compositions from manufacturer to manufacturer. Based on the results from Figure 3, the shape parameter is assigned as 4 for PE based insulation and 2 for EPR insulation.

ANALYSIS

The approach used in this work was to collate the results of many public domain ACLT tests to model the impact of temperature, electrical stress and some elements of cable design. Algorithms were then constructed to scale test data on short cores to long cables in service using Life Expansion and Reduction Factors.

Volume and Stress Multipliers

ACLT is performed at discrete aging conditions. As an example, ACLT testing at the average electrical stress of 2 kV/mm (U_o), 4 kV/mm ($2U_o$), 6 kV/mm (3 U_o) and 8 kV/mm ($4U_o$) in the cable insulation for the standard cable configuration. The average electrical stresses at field operating conditions for many cable configurations are different from any of the tested stresses. For example, the average electrical stress in the cable insulation of a 15 kV with 220 mil insulation thickness cable is 1.55 kV/mm. To estimate cable life for any medium voltage class cable configurations (i.e. cables operated at any given electrical stress) operating at any conductor temperature between ambient temperature to 90 °C or even 105 °C, a regression model is needed to

- interpolate data at the region where test data is available at discrete test conditions;
- extrapolate data at the region beyond where test data is available at discrete test conditions (Figure 4).

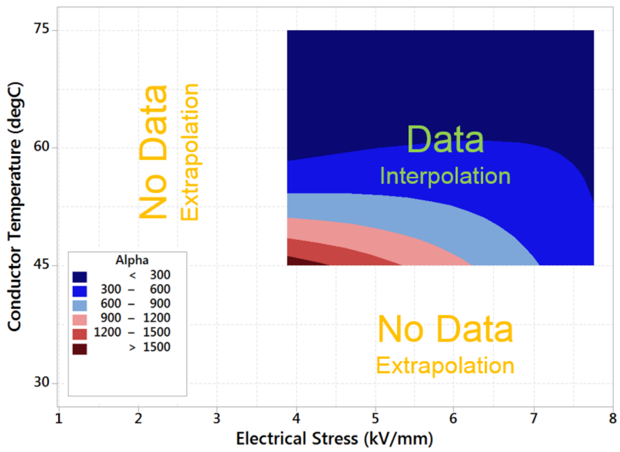

Figure 4. Illustration of using contour plot for data interpolation / extrapolation for XLPE data as.

A regression model was constructed to predict cable life based on electrical stress and conductor temperature using the scale parameters calculated for XLPE insulation data. A statistically significant equation was developed,

$$\alpha_T = 8445 - 988 \cdot E - 91.4 \cdot T + 10.85 \cdot E \cdot T \quad [1]$$

- E is the average electrical stress in the cable, kV/mm
- T is the conductor temperature, °C

The following equation is derived in order to start from given ACLT data at a known testing condition (E_T, T_T).

$$\alpha_1 = \alpha_T \cdot R(E,T) \quad [2]$$

$$R(E,T) = \frac{\alpha(E,T)}{\alpha(E_T,T_T)}$$

Close and Return

- α_T from ACLT data at a known testing condition (E_T, T_T)
- α_1 is the characteristic life after (E,T) transformation

Length Adjustment

A typical ACLT test length is 15 ft. A significant portion of the test length is submerged under the water and the rest above the water for termination purpose. This cable length is, however, not typical in field applications. A URD cable segment, which connects distribution transformers, is typically in the range of 100 ft. to 300 ft. A feeder cable, which emanates from substations to the distribution network, is typically in the range of 1000 ft. These lengths are significantly different from the tested cable length in the ACLT environment. The well-known enlargement law [17] exercised in Equation 2 is thus applied to include cable length effect on cable service.

$$\boldsymbol{\alpha_2} = \boldsymbol{\alpha_1} \cdot R(L) \qquad [3]$$

$$R(L) = \left[\frac{l}{L}\right]^{1/\beta_T}$$

- α_2 is the characteristic life at the cable service length L
- α_1 is the characteristic life at the tested cable length l
- *R(L)* is the cable length enlargement coefficient
- β_T is the shape parameter of the tested cable core (unjacketed cable with water-filled conductor strands) for specific insulation type.

Since the standard ACLT test length is 15ft., the length enlargement coefficient with reference to 15 ft. is commonly used. As an example, the cable length enlargement coefficient for a 250 ft. cable to a 15 ft. test length is 0.5 for TRXLPE insulated cable and 0.25 for EPR insulated cable.

Insulation Volume Adjustment

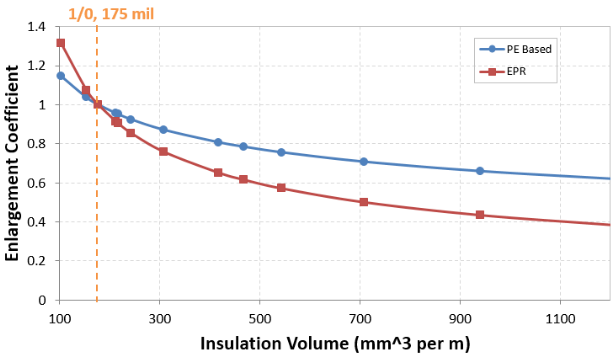

Figure 6. Enlargement coefficient for insulation volume adjustment.

The enlargement law (Equation 4) is also applicable to adjust for insulation volume effect. This allows users to estimate service life of cables that have a conductor size and/or insulation thickness and hence volume *V* different from that of a standard test cable (*v*).

$$\boldsymbol{\alpha_3} = \boldsymbol{\alpha_2} \cdot R(V) \qquad [4]$$

$$R(V) = \left[\frac{v}{V}\right]^{1/\beta_T}$$

- α_3 is characteristic life with insulation volume of *V*
- α_2 is ttested cable characteristic life with volume of *v*
- *R(V)* is the insulation volume adjustment coefficient

The insulation volume adjustment coefficient with reference to a 1/0 AWG, 175 mils insulation thickness standard test cable is plotted in Figure 6.

Jacket / Moisture Adjustment

Upon research of public domain ACLT data, there is not any external ACLT program that investigated the effects of the cable jacket. A prior NEETRAC baseline project 97-409 focused on developing a new cable design aging protocol and tested 20 cable design/test conditions with moisture-blocked conductor and an overall jacket [18]. These data were analyzed using Weibull distribution and compared to unjacketed data, as shown in Figure 7. A three-parameter Weibull was used to fit the ACLT data of jacketed cables. The adjustments for jacket/moisture effect were applied to both the scale parameter and the shape parameter using

$$\alpha_S = \alpha_3 \cdot 5.89 + 367 \qquad [4]$$

$$\beta_S = \beta_T + 2 \qquad [5]$$

- α_3, β_T are the Weibull parameters of unjacketed cable with water-filled conductor strands
- α_S, β_S are the Weibull parameter of jacketed cable with blocked conductor strands

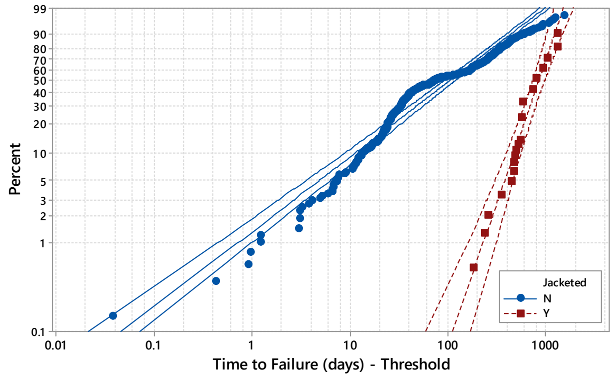

Figure 7. Weibull analysis of un-jacketed and jacketed ACLT data.

Life Statement Calculation

When discussing cable life, it is common to refer to the average life. The average life is also known in the reliability industry as the B50 life, the age at which 50% of the units will experience their first failure. In general, B life is the age at which a certain percentage of the units will experience their first failure. The number following the letter B indicates that percentage. Depending on the consequence of the failure, the tolerance to failure could be significantly different for different industries. As an example, B0.01 life is used for critical parts that can lead to catastrophic failures in the civilian aerospace industry. Considering the utility industry, it is our impression from anecdotes that utilities generally become concerned when 10% of the field cable population experiences its first failure. In other words, the failure becomes noticeable and utilities would start to develop plans of action. The consensus is that the device life that matters to utilities is significantly lower than the B50 life (time at which 50% fails) and is more likely in the range of the B5 life to B10 life.

As discuss earlier, the scale parameter gives the B63 life. The following equation, derived from Weibull distribution, can be used to obtain the B life at the reliability level of the user's interest.

$$\boldsymbol{B(p)\ Life} = \alpha_S \cdot [-\boldsymbol{ln}(\boldsymbol{1}-\boldsymbol{p})]^{1/\beta_S} \qquad [6]$$

Close and Return

- α_s, β_s are the Weibull parameters derived from the acceleration/reduction adjustments
- *p* is tolerance of failure or unreliability level
- *B(p) life* is the age at which *p%* of the cables will experience their first failure.

CASE STUDY

A few case studies show how the modeling may be used. A summary of the tested case studies appears in Table 3. These case studies also illustrate how the model may be used.

Table 3. A Summary of Tested Case Studies

Case	ACLT	Service
1	α_T,β_T @ ACLT (4,4) conditions from collated library	15kV, 1,000 kcmil 100% XLPE wall, Jacketed 300 ft. (100 m) Operated at 30 °C
	Estimated service life – first failure: B50 21 years	B10 16 years
2	α_T =260, β_T =4 @ ACLT (4,4) conditions from user test data	15kV, 1,000 kcmil 100% WTRXLPE wall, Jacketed 300 ft. (100 m) Operated at 30 °C
	Estimated service life – first failure: B50 35 years	B10 26 years
3	α_T,β_T @ ACLT (4,3) conditions from collated library	35 kV, 1,000 kcmil 100% WTRXLPE wall insulation, Jacketed 2,000 ft. (610 m) operated at 60 °C
	Estimated service life – first failure: B50 7 years	B10 5 years
4	α_T,β_T @ ACLT (4,3) conditions from collated library	15 kV, 350 kcmil Reduced wall (83%) EPR, Jacketed 300 ft. (100 m) Operated at 75 °C
	Estimated service life – first failure: B50 4 years	B10 3 years
5	α_T=1019, β_T=2 @ ACLT (4,4) conditions from user test data	15 kV, 350 kcmil 100% EPR wall, Jacketed 300 ft. (100 m) Operated at 75 °C
	Estimated service life – first failure: B50 18 years	B10 11 years

The first case study starts with ACLT test results for a standard ACLT cable configuration at (4,4) test condition. The interest is in using the composite ACLT core experience to estimate the service life, for first failure, of a 15 kV, 1,000 kcmil, 100% XLPE insulated jacketed cable operated at (1,1) condition with a service length of 300 ft. (experience shows that this is a typical length of cable between transformers in a residential sub division).

Weibull curves were generated based on the adjusted scale parameter and shape parameter and were displayed separately by the expansion factors (Figure 8) and the reduction factors (Figure 9). The survival curve for the service cable was also plotted in Figure 10. It shows that if 100 of these 300 ft. cables with this specific cable configuration and operating conditions were installed in the system at year 0,

- 1 out of 100 would experience its first failure by year 10;
- 10 out of 100 would fail for their first time by year 16;
- 90 out of 100 would see first failure by year 25; and
- The average life (B50, 50 out of 100 would fail by this age) of this cable is 21 years.

Such a segment may well be repaired and remain in service after the first failure. However, the reliability of this segment will decline due to the continued ageing of the remaining original cable, the introduction of one or more joints and potentially deleterious effects of fault location. The jointing process introduces potential week links and the joints themselves will age in service. Thus, the time in service is likely longer than estimated by this current modeling. Although it should be recognised that the segment is not the same, after the repair, as the one that was installed.

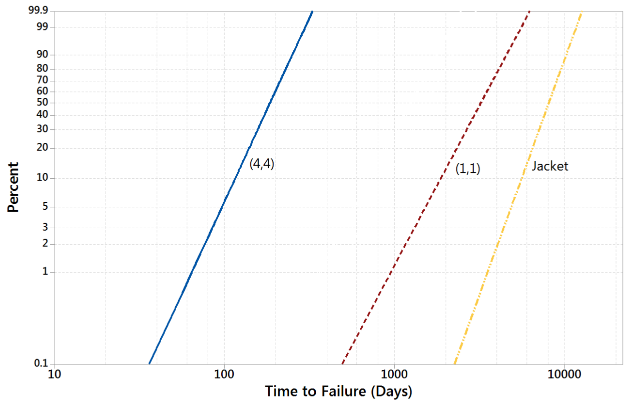

Figure 8. Case 1 Weibull curves (adjusted scale and shape parameter) for life expansion factors. Curves move right (longer life) as expansion factors applied.

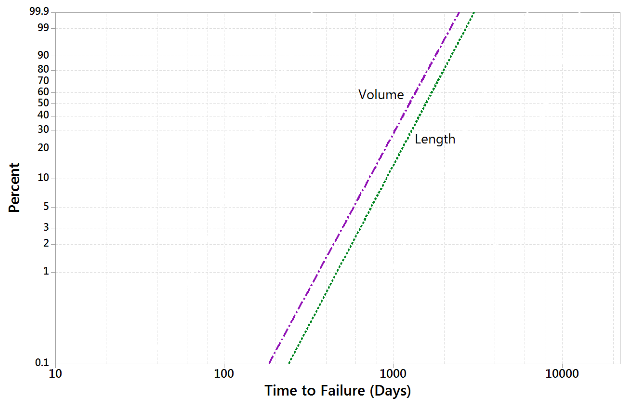

Figure 9. Case 1 Weibull curves (adjusted scale and shape parameter) for life reduction factors. Curves move left (shorter life) as reduction factors applied.

Thus the Life Statement from this case would be; *"10% of 300 ft cable segments (15kV 1000kcmil jacketed XLPE 100% wall) would be anticipated to experience their first failure in service (operating at 30 °C) on or before age 16 years"*.

Close and Return

OTHER MODEL APPLICATIONS

The challenge of running an ACLT test is the unpredictable end of test time. As cable technology improves, cable samples require a longer time to fail which increases the economic burden of conducting such tests. This model performs a backward calculation to estimate how long the test needs to run if no failures were observed for a specific life requirement. As an example, if a service life of 40 years at a 10% survival rate were desired for a cable design, the reverse calculation would help to answer how long the ACLT test should run if no failures are observed. If, by way of an example, a 15kV 100% wall WTRXLPE 1000kcmil jacketed cable is desired to have a B10 life of 40 years, then the reverse calculation indicates that at a minimum ACLT Scale parameter of 800 days would be required from the testing of a standard core. Bayesian analysis [13] is often used by the authors in such a backward calculation, in this case no failures should be observed within 400 days.

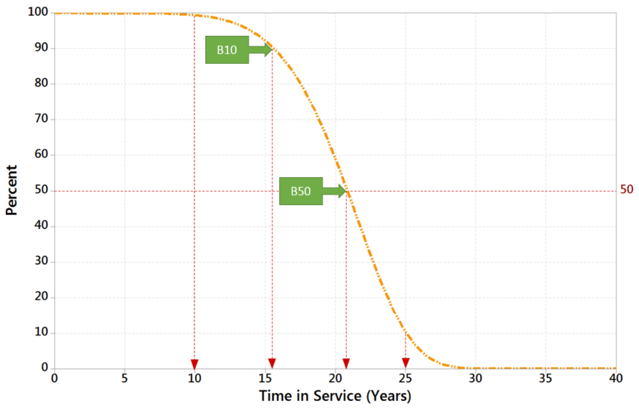

Figure 10. Case 1 Survival curve with B lives.

CONCLUSIONS

This work collated extensive ACLT data (124 unique datasets) from nine organizations including internal and external data. These data come from research projects, published external laboratory reports, peer-reviewed papers, and business brochures. The data covers 1,398 cable segments tested that sum to 32,000 feet (6.1 miles).

The model developed in this project considers expansion/contraction factors including electrical stress, operating temperature, cable length, cable jacket, and water presence. The model, however, does not explicitly consider load factors. Case studies using this model provide reasonable results.

The model and its process can be used to,

- Estimate cable life at a desired percentile,
- Estimate cable service life at desired percentile with specific life data at elevated testing conditions,
- Establish the required test performance of a cable design with pre-determined expected service life.
- Derive a specific and useful Life Statement which has to refer to specific cable and operating criteria

A benefit of the approach described here, over a multi factor regression model, is that the impacts of each factor are considered separately. Thereby enabling the user to better visualise the impacts of each choice of system architecture and operation on the longevity.

ACKNOWLEDGMENTS

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