Can Cables Last 100 Years?

Michael **JOSEPH**, IMCORP (USA), michael.joseph@imcorp.com
Ben **LANZ**, IMCORP (USA); ben.lanz@imcorp.com
Rene **HUMMEL**, IMCORP (Germany), rene.hummel@imcorp.com
Darren **BYRNE**, IMCORP (USA), darren.byrne@imcorp.com

ABSTRACT

How long can solid dielectric cables last? The authors and many in our industry over the last few decades, would say 30 to 40 years, but what does science and industry experience tell us? This presentation will explore the known primary drivers of activation energies sufficient to initiate deterioration at the molecular level and eventually yield more commonly known breakdown mechanisms. Which drivers are common place? Which drivers are rare or application specific? Can cable owners eliminate or reduce the risk of these drivers, and if so, what does science and industry experience tell about the future of cable longevity? Is 100 years possible?

KEYWORDS

Cable Life, 40-Year Life, Defects, Partial Discharge (PD), Failure, Electrical Trees, Water Trees, cable testing, cable diagnosis, cable injection

INTRODUCTION

Reliability of power cable systems is a critical topic for ensuring continuous electrical service and predictable maintenance and replacement cycles. A commonly held belief is that extruded dielectric insulated cable has a design life expectancy on the order of forty years and cable replacement scheduling is often based on this figure. In practice, when cable and accessories are free of manufacturing and installation defects, the authors have found, that cables under moderate service conditions can perform beyond 40 years but suggests the industry needs to identify 'stressors' and remove them proactively to achieve reliable performance beyond 100 years [1].

Utility Case Study

The cable reliability experience of a utility is shown in Figure 1. The left-hand y-axis and data in blue represent the number of circuit kilometers added per year with the cyclic nature of infrastructure expansion clearly visible. In contrast, the right-hand y-axis and data in red represents the number of 100s of cable failures of cable installed in the year indicated. This data shows, that the majority of cable failures experienced are on lengths installed prior to the 1980's. While the data in terms of absolute number of failures may be concerning, it needs to be remembered that cable life expectancy is a statistically built probability. Building on the 40-year life expectancy figure, in 1956 Jack Crowds states "Half the [cable] samples (in a test) would fail by the 40th year." [2] This concept, combined with data from the subject utility shows, even though there is a measurable cable failure rate of assets installed in the 1970's and earlier, there is a still a statistically significant population still in service and operating. According to many utilities surveyed, operating beyond the 40 year life is a practical necessity due to budgeting constraints scheduling, and resource availability; replacing all in-service cable by their 40th year is nearly impossible. Replacement programs spanning multiple decades means, cables are already in service beyond forty years and could potentially be in service for sixty or more years. Investigation of the mechanisms and conditions of failure is the first key to understanding how some cable systems are achieving this extended reliable performance and is the subject of this paper.

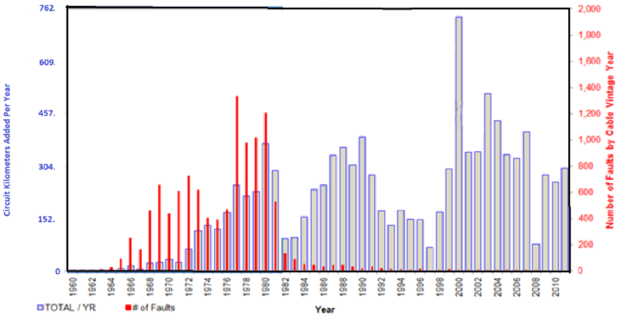


Figure 1: Utility study of cables installed and cables failed by vintage year.

High Voltage AC Breakdown Curves

Figure 2 shows the retained AC breakdown strength for three medium voltage cable populations with typical steady state service voltage stress represented by the blue horizontal line (~2kV/mm or ~50V/mil). In this case, cables were removed from service at intervals, and subjected to a high voltage time test to measure the AC breakdown strength. A common observation for this type of curve is, a significant drop in breakdown strength over the first 5 to 10 years of service life. In addition, the breakdown strength of the cable populations reaches a "perplexing equilibrium of at ~6U₀" (12kV/mm) after 10 years as noted by Nigel Hampton, et. al, in 2016 [3].

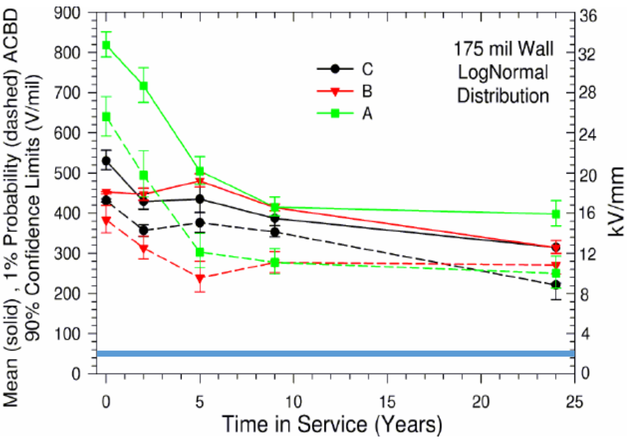


Figure 2: Mean AC Breakdown Strength of Field Aged Cables [4]

Close and Return

Measured AC breakdown strength of 8-16 kV/mm appears to contradict the occurrence of field failures that occur at service voltage around 2 kV/mm. A topic for discussion of how to reconcile these observations given the margin between service conditions and laboratory test conditions [3]. To answer, the mechanics of electrical failures needs to be considered. The growth of electrical trees tied to PD activity does not necessarily occur instantaneously or rapidly. Electrical trees can grow at various speeds within an insulation and these defects can be present in the cable for a significant time before a cable eventually fails. Therefore, cable defects and existing electrical trees may only grow during voltage transient and often grow rapidly to complete breakdown during the elevated stresses of a high voltage time test [7]. According to Al Mendelsohn in 2004, the AC breakdown test becomes a quality check of the cable, causing rapid failure of weak points in the cable, but does not necessarily correlate to a metric of cable life [5]. The data points out the need for adequate overvoltage protection.

Considering cable as a continuum chain of product, it requires only one substandard area or “weak link” to cause the chain to fail. Posited by E.F. Steenis, longer cables will have higher likelihood of the cooccurrence of these weak links [6]. As cables age and the AC breakdown strength is reduced, the limitation of overvoltage transients becomes ever increasingly important to the life extension by limiting the growth of electrical trees.

Even as cable insulation advances, the same observations of the retained AC breakdown strength curves can be made. As shown in the study by L. Gross represented in Figure 3 [8], Tree-Retardant XLPE (TR-XLPE), an evolution of natural XLPE insulation, insulated cables exhibit a similar reduction of mean breakdown strength within the first 5 to 10 years of operation before levelling off out to 20 years and further. It can also be seen that TRXLPE has numerically higher breakdown strength at all time intervals than the natural XLPE counter, creating an even greater margin between breakdown strength and service voltage.

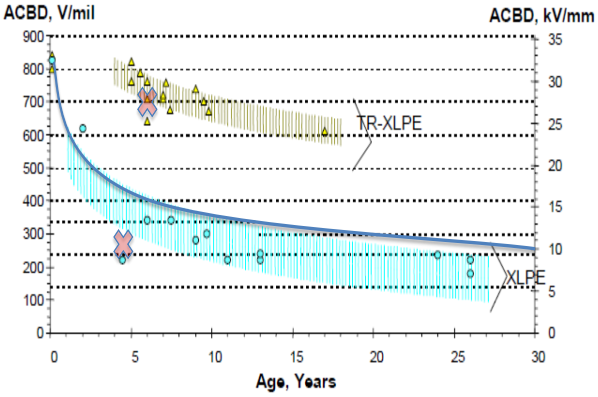


Figure 3: Retained AC Breakdown (ACBD) Strength of XLPE and TR-XLPE Cables [8]

The technology evolution yielding better breakdown performance is helpful in extending cable life, however, this does not address all of the factors that affect in-service cable reliability.

LONG-TERM RELIABILITY GROWTH

Developed by Dr. Larry Crow for use by U.S. Army Material System Analysis Activity in the 1970’s, the Crow-AMSAA reliability growth model was created as tool to predict long-term reliability of long-term service samples with mixed failure modes. When discussing reliability growth of power cables, the goal is to increase the likelihood of survivability of individual lengths after cumulative service time.

In general, the increase in reliability is visualized as a smooth curve as shown in Figure 4. In practice, variables affecting cable reliability are discovered, tested, and verified as discrete operations. As such, the reliability growth occurs by systematically identifying and eliminating these variables, called stressors, visualized by the red line. This links back to the estimation of 40-year life of cable being a statistical probability of a certain number of population failures. If the stressors that degrade reliability are identified and addressed, then the likelihood of cable survivability past the 40-year mark increases and the notion of 100-year cable life can become a possibility.

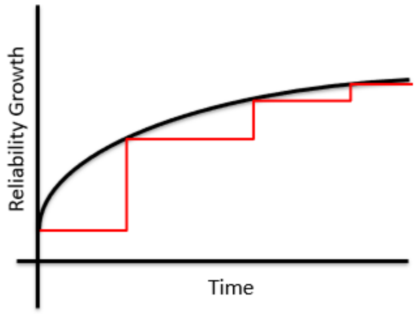
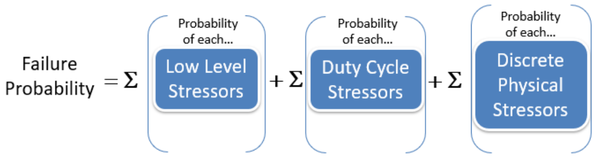


Figure 4: Representation of discrete step increase for reliability growth.

STRESSORS AFFECTING CABLE RELIABILITY

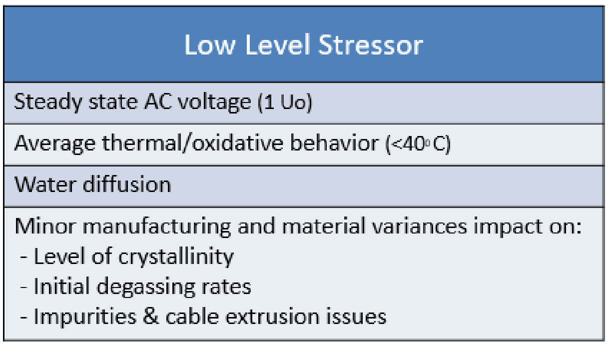
The presence of cable stressors increases the probability of failure at a given cumulative time interval. The total probability of failure becomes a summation of the probabilities of failure of the individual stressors. For in service cables, the probability of failure and categories of stressors can be represented in the following figure:



First, there are the low-level stressors. These are conditions that stress the cable at the molecular level and are linked to the chemical and dielectric behavior of the insulation material. Second, there are the duty cycle stressors attributed to the environmental and service conditions. Lastly, there are the discrete physical stressors which manifest as point defects in the insulation linked to manufacturing and installation issues.

Low Level Stressors on the Molecular Level

Low level stressors are identified in the following table:



Low Level Stressor
Steady state AC voltage (1 Uo)
Average thermal/oxidative behavior (<40°C)
Water diffusion
Minor manufacturing and material variances impact on: - Level of crystallinity - Initial degassing rates - Impurities & cable extrusion issues

Table 1: Low Level Stressors overview

Thue and Bernstein summarize the theory of steady state AC electrical stress well.[9] Under steady state AC voltage, the applied electric field polarizes the polymer insulation and cyclically moves the polar regions that exist in the crystalline structure. As these polar regions move and align, certain actions can take place. Carrier recombinations between the polar regions can occur, with charges moving unpredictably within the insulation. This can lead to the emission of UV photons that attack neighboring insulation causing degradation. Additionally, free hot electrons can be emitted and cause cascading bond breakage. The overall long-term affect is the possible lowering of the polymer activation energy due to the weakened dielectric properties. This effect is difficult to quantify and nearly impossible to measure and is believed to have a low impact on the long-term cable reliability.

Drazba et al [10] demonstrate thermal-oxidative behavior is another factor possibility affecting cable performance. Normally, this variable can have an impact on mechanical properties such as the modulus and density by affecting the crystalline structure. Once again the impact on electrical performance is difficult to quantify, especially under steady state operating conditions. However, it has been observed that electrical performance can be quantifiably affected, when combined with extreme stresses well above established emergency overload temperature and voltage stress conditions, such as 150°C at 40kV/mm.

Even under ideal conditions, the presence of moisture will lead to diffusion activity in the insulation. The action of random water diffusion within the insulation has been found not to cause significant stress enhancements. The presence of water will make the insulation quantifiably more lossy, but the lack of stress concentration means that it is not a factor in the cable reliability concern. One study performed by Katz et al [11] in Figure 5 demonstrates that not only does AC breakdown strength stabilize in the presence of moisture, but drying the cable by injecting dry nitrogen has a positive effect on the AC breakdown strength. Therefore, the presence of moisture does not constitute significant permeant material damage impacting long term electrical performance .

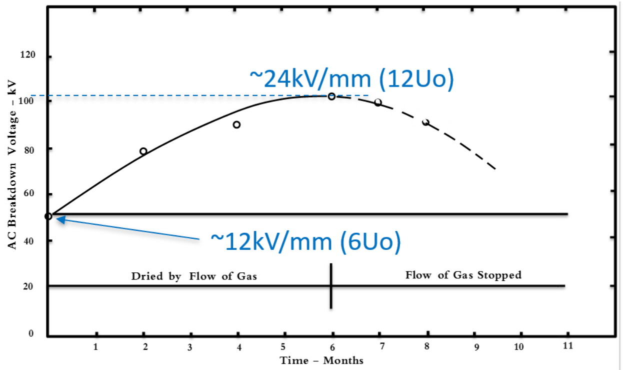


Figure 5: Dry Nitrogen Gas Injection Study [11]

Sarkar et al [12] show the level of crystallinity (or degree of cross-linking), is another factor difficult to quantify and appear to be of little consequence in terms of long-term performance at service conditions. Typical processing of XLPE targets a 95% crystalline structure with the remainder being amorphous regions. If the crystallinity is reduced, the insulation would have more polar regions that could result in greater AC field interactions. As discussed previously, this could potentially have the effect of the reduction of long-term AC breakdown strength.

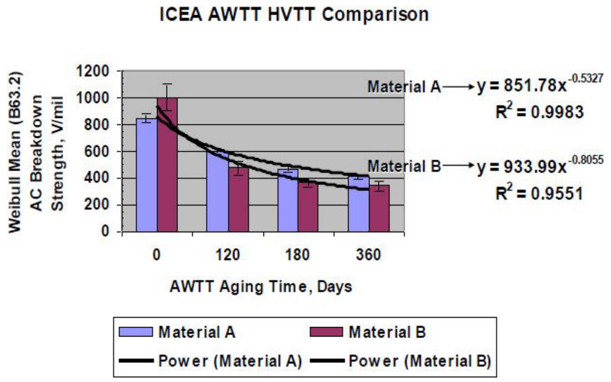


Figure 6: Wet aging comparison of unmodified and modified EPR insulation [12]

In a study of modified EPR insulated cables (Figure 6), EPR insulation loaded with greater than 72% ethylene content for higher crystallinity (Material A), had a statistically higher retained ACBD strength after aging compared with the same material with normal ethylene levels (Material B). Also observed, under ICEA AWTT testing the higher crystalline insulation material had a retained 34% higher ACBD strength over time. Yet, the ACBD of the lower crystalline material still maintains ACBD strengths up to 6Uo leaving plenty of margin to operate without failure.

Other manufacturing and processing issues can impact performance such as degassing concerns and cable extrusion variances. One possible reason for the initial drop in AC breakdown strength can be attributed to the truly non steady-state condition of cable shortly after manufacturing. Even a well degassed cable still contains polar extrusion byproducts and help reduce the effects of stress enhancements yielding partial discharge (PD) and insulation breakdown. As a cable is load cycled in service, these remaining byproducts are continuously diffused out of the insulation system resulting in long term equilibrium observed. However, before equilibrium, it is possible the persistence of polar extrusion byproducts not degassed properly could have two significant effects on cable performance. First byproducts create field gradients, which improve the initial breakdown performance of the cable, but quickly diffuse during normal service. The second is, gas inside that cable can pressurize voids and due to the observation of Paschen's law, exhibit an increase in the ionization energy inside a void. This would give false passing PD result and allow possible PD inception site to make it to the field, adversely affecting cable reliability. In conjunction with degassing issues, extrusion variances such as contaminations, ambers, protrusion of the insulation or semi-conducting shields can create optimized conditions for the concentration of moisture and lead to further stress enhancement. However, proper quality controls make these cases exceptions in the manufacturing process, and not the rule.

Duty Cycle Stressors

The authors have reviewed what is believed to be the most significant low-level stressor indicated in the literature and have yet to find stressors in this category with significant impact long term reliability. Now the focus of this paper moves forward to significant duty cycle stressors, which can be determined by considering what can impact the activation energy for the formation of free electrons in the insulation triggering PD events. The table below categorizes the typical sources of activation energy and compares the design capability and typical service observation of these sources for medium voltage cable.

Activation Energy Source	Design Capability	Typical Experience
Voltage Stress	12kV/mm (300 V/mil)	≤ 2.4kV/mm (60 V/mil)
Temperature	90C	40 C
Mechanical	Significant	Minimal
Radiation	Moderate	Very little
Chemical	Dense & robust	Most cases, none

Table 2: typical sources of Duty Cycle Stressors

- *Electrical (Voltage Stress):* Cables can still reliably retain AC breakdown values in the range of 12kV/mm even after significant aging times. Normal service conditions up to 35kV-rated cable are only 2.4kV/mm, well below this breakdown limit.
- *Temperature:* Thermally, insulations are designed for maximum operating temperatures of 90°C-105°C, but rarely are operated near this condition and typically see temperatures of 50°C or less.
- *Mechanical:* Power cable development includes a thermo-mechanical qualification component, which demonstrate an ability to perform even with significant and prolonged heating at the emergency overload temperature.
- *Radiation:* Unless utilized in specific nuclear applications, cables will rarely be exposed to significant radiation sources. One common concern is ultraviolet radiation from the sun, however, carbon black content of cable jackets and cores provide resistance to UV radiation effects.
- *Chemical:* Cable construction materials are testing for compatibility with different types of substances that could be encountered in the desired field application.

Among these duty cycle stressors, the voltage stress and temperature are the two factors that could potentially fall into an extreme range if care is not taken with operational and design control. Figure 7 represents a study performed by Gorur et al [13] on medium voltage field aged cables, subjected to an accelerated cable life test at varying voltages and temperatures. A regression was fit to the time-to-failure curves for each voltage level and a relationship between temperature and expected life was determined. Inspection of curves d and e can be used as an analogue to normal service conditions between 2 kV/mm and 5 kV/mm. At normal service conditions of nearly 50°C, the life curves appear to approach an asymptote and rise well in excess of 10^6 hours – or 114 years.

By eliminating extreme operational duty cycle stressors (overvoltages and overcurrents), cables have demonstrated the ability to survive beyond the 40-year mark. In general, extreme voltages can be controlled with proper surge protection and extreme temperature can be controlled with proper connector installation and limiting the loading. If extreme events have been documented, it is quite possible that discrete physical stressor have developed and a condition assessment such as a factory comparable Partial Discharge (PD) test can readily locate the defect sites so repairs can be made. (Offline 50/60Hz PD test with better than 5pC sensitivity)

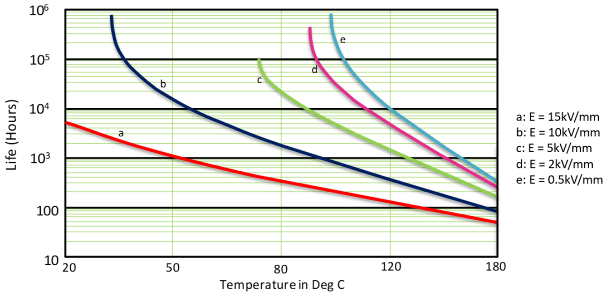


Figure 7: Insulation Life Expectancy vs. Electrical Stress and Temperature [13]

Overvoltage events have the capability of increasing electric field strength within the cable insulation beyond the point where PD events are "switched on", known as the PD Inception Voltage (PDIV). Once PD has started, it takes a certain reduction in field strength to stop the PD from occurring, known as the PD Extinction Voltage (PDEV). With respect to electrical tree inception and growth, the necessity for overvoltage protection becomes apparent. Simply stated, insulation degradation can be minimized, if PD activity is removed or prevented. Appropriate overvoltage protection can maintain nominal field stress level below that for successful PDIV and/or stabilize conditions to normal operative voltage that may be below the PDEV level.

Discrete Physical Stressors

Even when voltage and temperature are controlled, cables still exhibit unexpected failures. This is most likely due to the third category of stressors linked to discrete physical abnormalities. Discrete physical stressors are typically the manifestation of manufacturing defects in cable that are not caught by the quality control process and workmanship issues during installation. These defects, include insulation damage, voids, contaminations, localized overheating, and formation of concentrated moisture (water trees) contribute to stress enhancement within the cable insulation. These stress enhancements can lead to Partial Discharges within the cable, and finally to the propagation of electrical trees, the primary mechanism of cable failure [9]. Failure at defect sites can occur under operating conditions well under the residual level of surge arrester protection. To ensure discrete physical stressors do not impact the reliability of cable systems, they must be removed. This can be accomplished using a factory comparable Partial Discharge test.

Recalling that the cumulative probability of failure is the summation of the of the stressors exhibit on cable, the increase to cable reliability can be established:

- *Low Level Stressors*: In general, these stressors are of low significance and do not significantly contribute to the factors concerning cable life.
- *Duty Cycle Stressors*: Proper operation and design including overvoltage protection and limiting extreme loading can reduce the main contributing factors to the generation of new physical stressors.
- *Discrete Physical Stressors*: Robust quality control systems in the factory and in the field, combined with periodic condition assessment and rehabilitation of the cable system

The systemic elimination of extreme duty cycle stressors, performing factory comparable PD condition assessments to identify and repair physical stressors will result in the systematic reliability growth. The authors have witnessed over 10 times increase in reliability on thousands of 30 to 40 year-old cables by following this prescription with nearly decade of experience to confirm the resulting reliability growth to levels better than some new cable performance. [1]

CONCLUSION

The notion of 40-year cable life is a widely held belief in the industry. The concept of this life expectancy, however, is a statistical probability, and there are numerous utilities observing cables lasting longer than the 40-year mark. To determine the 100 year life potential, an investigation into retained AC breakdown strength curves was used to demonstrate cables aged in the field exhibit withstand levels well in excess of service conditions and could potentially survive for an undetermined time, provided they see moderate operating conditions and discrete defects are removed. After extensive field work and literature review, the authors have not be able to find any contradicting science to suggest cables cannot last 100 years or longer and by this paper welcome industry engagement in this discussion.

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