



CHAPTER 2

Medium Voltage Cable System Issues

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2.0 MEDIUM VOLTAGE CABLE SYSTEM ISSUES

“Cables,” in the context of this work, are long, insulated current carrying conductors that operate at elevated voltage with a grounded outer-surface [1- 5]. They are terminated and joined together using accessories to constitute a “cable system”. Cable systems form an important part of electrical power transmission and distribution networks, carrying electric energy to areas as an alternative to overhead lines. In general, cable systems have lower fault rates and lower maintenance requirements than overhead lines. It is amusing to note that in 1901, M. Gorham [2] stated the following “...waterproof for 100 years, flexible and extensible, so volt resisting that the thinnest film suffices, sufficiently firm not to decentralize...” Present-day cable technology is pursuing this ideal, but engineers have learned that many factors influence the goal of achieving a long-life, reliable cable system.

It is generally accepted that the first reference to cables or wires was reported in 1812 when a Russian named Schilling used rubber varnish-insulated wires to detonate explosives in a mine. Some of the first electric distribution systems in Chicago, London, and Paris were laid in sewers or under- ground drainage systems between 1870 and 1880. There has been a continuous evolution from the late 1800’s to the present day. The most significant advancement in recent years is the industry-wide conversion from lead-covered, fluid-impregnated paper insulated cable systems to polymer-insulated systems and now to EPR and WTRXLPE insulated cables. The primary drivers for moving from paper systems to polymer systems are,

- environmental concerns with lead
- increasing failure rates; initially with paper and then polymer (HMWPE and XLPE)
- reduced maintenance costs
- loss of expertise needed for installing and maintaining paper insulated systems
- reduced installation costs
- concern with fluid leaks that have to be located and repaired
- reduced weight, allowing for the installation of longer cable lengths
- reduced risk of fire
- reduced dielectric losses

Several historical milestones in cable usage appear below:

- 1812first power cables used to detonate a mine in Russia
- 1890Ferranti develops the concentric construction for cables
- 1900cables insulated with natural rubber
- 1917first screened cables
- 1903PVC first used
- 1937PE developed
- 1942first use of PE in cables
- 1963invention of XLPE
- 1967use of HMWPE insulation on underground cables in the US (unjacketed with tape shields)
- 1968first use of XLPE insulated cables (mostly un-jacketed, tape shields)
- 1972failures due to water tree growth in polymeric insulations revealed

- 1972introduction of extruded semiconducting conductor and insulation shields
- 1973super-clean XLPE insulation used in HV subsea cables Sweden to Finland at 84kV
- 1978widespread use of polymeric jackets in North America
- 1982water tree resistant (WTR) insulations introduced for medium voltage cables made in Canada, Germany, and USA
- 1989supersmooth conductor shields introduced for MV cables made in North America
- 1990widespread use of WTR-materials in Belgium, Canada, Germany, Switzerland, and USA
- 1995 use of water blocking in conductor strands (extruded mastic or swellable powders)
- 2000 use of metallic shields and water swellable tapes around the extruded cores

As discussed above, cable constructions have evolved with many major and minor iterations since approximately the mid 1960's (see some of the landmarks above). A number of manufacturing developments ensued. The evolution of cable development in North America is outlined in Table 1 and Table 2. These tables are not inclusive of all changes but rather represent the major changes important in making diagnostic testing decisions.

Table 1: Major Evolutionary Elements in MV Cable Construction (Excludes Wall Thickness)

Generation	Insulation	Semicons (conductor & insulation shields)	Jacket	Barrier
0	<i>Paper Oil</i>	<i>Carbon Tape</i>	<i>Jacket</i>	<i>Extruded Lead</i>
1	Thermoplastic HMPWE	Graphite / Carbon Tape	None	None
2		Extruded Thermoplastic		
3	XLPE or EPR	Graphite / Carbon Tape		
4		Extruded Thermoplastic		
5				
6				
7	WTR XLPE or EPR	Extruded Thermoset (crosslinked)	Jacket	
8				Conductor Water Blocked
9				Conductor & Core Water Blocked Metal Core Barrier
10	?	?	?	?

Table 1 represents the major changes in cable construction, excluding changes in wall thickness. These changes are represented as “Generations” (Generation 0 is the genesis for this work as it is the last incarnation of PILC cables). PILC cables continue to be manufactured today, although at a much-reduced rate. It is useful to note that this class does not include mass impregnated-non draining (MIND) cables. Installation of Generations 1 to 6 has ceased in the US and Canada for all practical purposes. Generation 6 is widely used outside of Canada and the US. Also note that from a non-Canadian/US perspective, Generations 3 to 6 include moisture cure silane cross-linked compounds using either Sioplas, Monosil, or vinyl silane copolymers (the current most popular approach). Consequently, care is necessary when looking at non-Canadian/US experience as the descriptor “XLPE” may pertain to Generation 6 moisture-cured cables, or “PILC” may actually refer to MIND cables.

Table 2 represents the major changes in cable core manufacturing. The numbers in Table 3 refer to the generations of the cable core constructions manufactured using these approaches.

Table 2: Major Elements in Cable Core Extrusion Correlated with Generations of Cable Construction from Table 1				
Material Handling	Extrusion Technology	Cure Technology		
		None	Steam	Dry (Nitrogen)
Open	Multiple Pass	1, 2	3	-
	1 + 2 2 + 1		4, 5, 6	4, 5, 6
Closed	True Triple	-	4, 5	5, 6, 7, 8, 9, 10

Table 3: Summary of the State of the Art for Both MV and HV Cables in North America		
Attribute	Medium Voltage (MV)	High Voltage (HV)
Voltage Range (kV)	5 – 30 (5 – 46 in North America)	30 -150 (46 – 150 in North America)
Typical Conductor Size Range (mm²)	34 - 500	240 - 2500
Mean Electrical Stress (kV/mm)	1.8	3.8
Conductor Screen Material	Thermoset Bonded Semi Conducting	Thermoset Bonded Semi Conducting
Insulation Material	Thermoset WTR XLPE Thermoset EPR	Thermoset XLPE Thermoset EPR
Insulation Screen Material	Thermoset Strippable Semi Conducting	Thermoset Bonded Semi Conducting
Metallic Screen	Wire Tape Foil	Wire & Foil Lead Aluminum
Protective Jacket	UV Resist LLDPE or HDPE	UV Resist LLDPE or HDPE
Accessories	Elbows Joints Terminations	Joints Terminations
Material Handling Systems	Closed Bulk Supply	Closed Box Supply
Extrusion Technology	True Triple CCV Dry N2 Cure	True Triple CCV & VCV Dry N2 Cure

In addition to the summary information provided in Table 1, Table 2, and Table 3, Figure 1 shows the voltage stress ranges for MV, HV, and EHV cables. In this chapter, the discussion pertains to the issues associated with MV cable systems (grey column in Table 3 and the green area in Figure 1). It is important to recognize that although they have many similarities, MV cable systems are distinctly different from HV cable systems with respect to insulation shield materials and stress control philosophies of the accessories as well as the levels of the electrical stress.

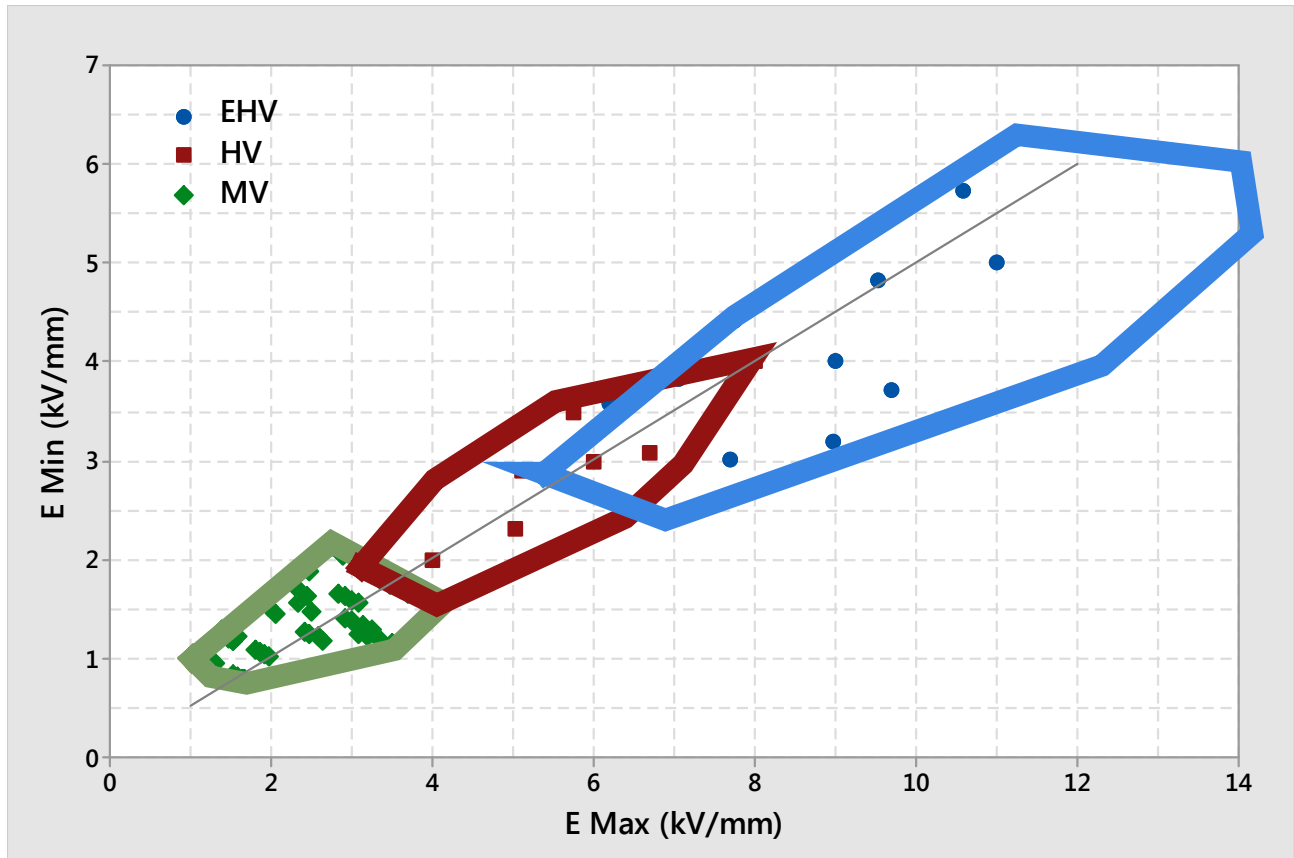


Figure 1: Range of Typical Electrical Stresses employed in cable systems - E_{max} = electrical stress in the insulation adjacent to the conductor, E_{min} = electrical stress in the insulation at the outer edge; note that the straight line represents the condition where $E_{max} = 2 E_{min}$

2.1 The Industry Problem

While the evolution in cable construction, materials, and manufacturing processes intended to produce continual increases in reliability with associated reductions in total cost of ownership, the process did not always yield the expected benefits. This observation is important because it drives much of need for and development of cable system diagnostics.

2.1.1 History

The earliest MV cables in North America (Figure 2) employed oil impregnated paper insulation with a lead sheath [1, 16] i.e. Paper Insulated Lead Cables (PILC). However by the 1950's – 1960's this was a mature technology. However, early work showed that the polymer (HMWPE and XLPE) insulated cables had lower failure rates with lower weights and costs coupled with the absence of the concerns/complexity associated with oil and lead (Figure 2). The acceptance of this technology was rapid. Within 15 years of its adoption, the length installed was more than twice that of PILC.

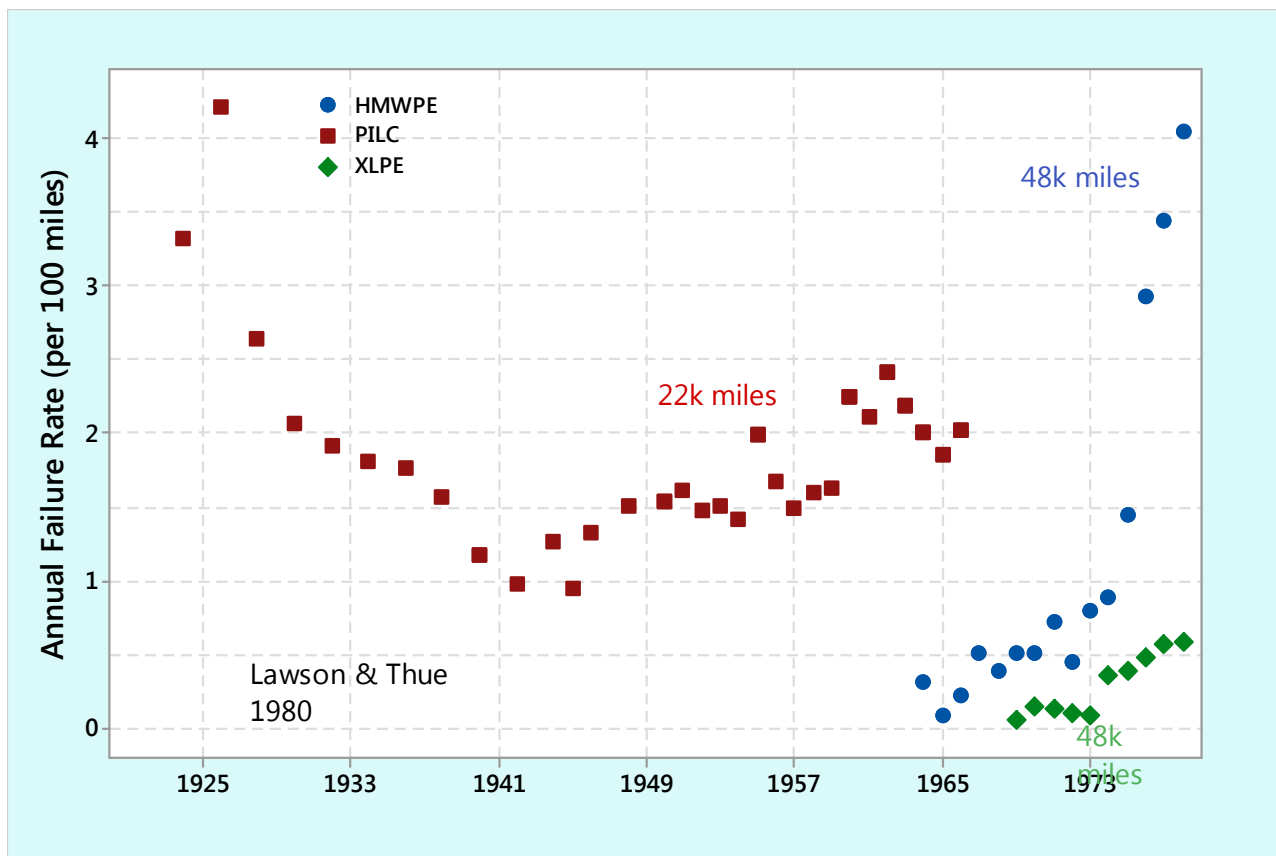


Figure 2: Failure Rates for PILC, HMWPE and XLPE Cables – 1924 to 1978; from Lawson and Thue (1980) [16]

Unfortunately, the initially low failure rate had increased (compare 1969 vs 1978 - Figure 2) due to what we now know as the phenomenon of water treeing. This was not just a North American issue [16] as water trees were found contemporaneously in Europe (Figure 3) and Japan. Figure 3 [4, 15] shows the ages at which cable failures started to occur and the lengths of trees that were observed. These data suggest that trees (on average) grow thru 27% of the insulation in eight years, which is on the order of 3.5% - 7% per annum or 0.12 – 0.24 mm/yr. At this rate, half of the cable would have full thickness (100%) water trees in 15 to 29 years.

The concern was that the treelike structure grows continuously across the insulation until it bridges the insulation so that failure occurs or it is weakened so that any transient might cause the growth of an electrical tree.

Thus included in the outcomes shown in Figure 2 and Figure 3 are the three phases of water treeing:

1. initiation
2. growth
3. transformation to an electric tree

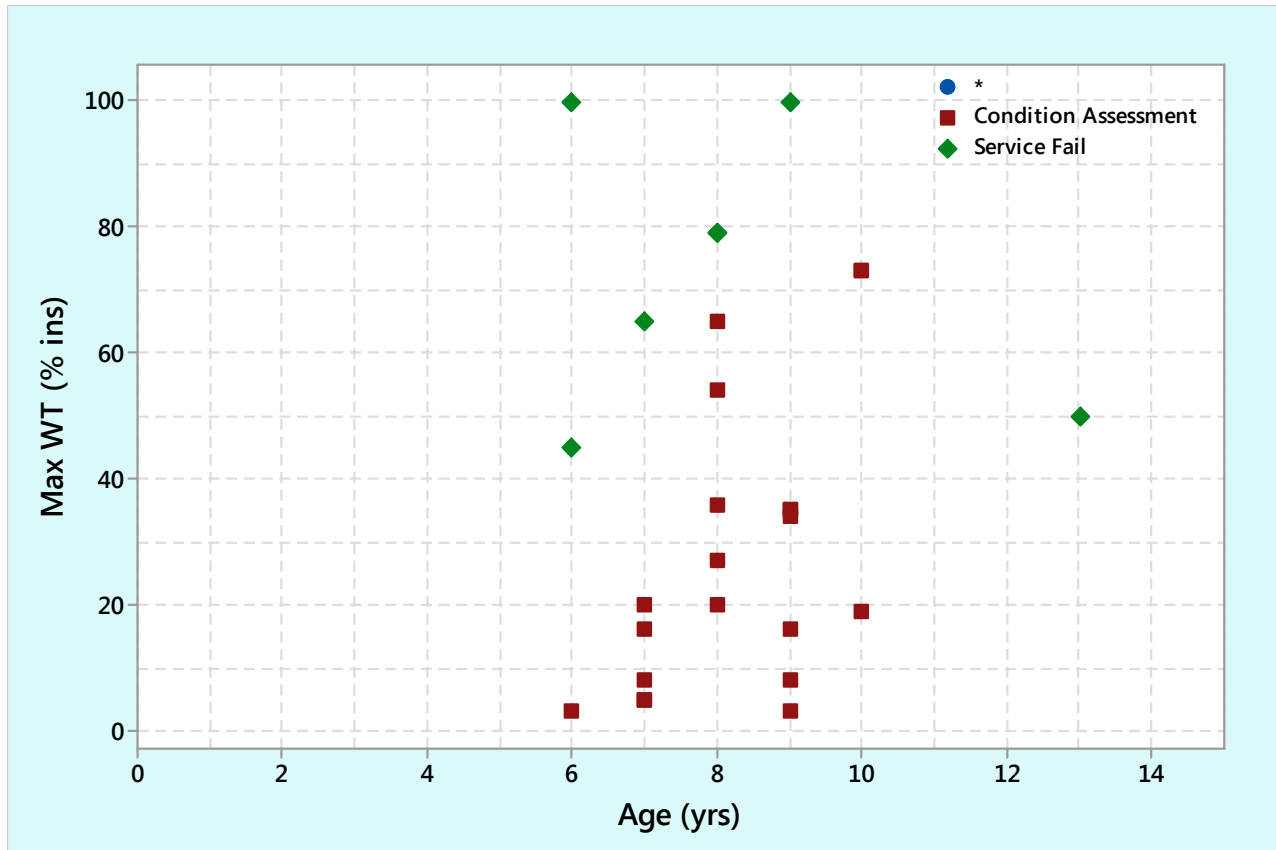


Figure 3: Water Tree Lengths (Maximum) versus cable age segregated by type of investigation for cables installed in The Netherlands (Steenis) [15] - Generations 3 and 4 Moisture Cure (Table 1)

Why do water trees have such a deleterious effect? Water has a higher dielectric constant than cable insulations (80 vs 2.5 or 3.5 for XLPE and EPR respectively) and is quite conductive. As the water tree grows so does the region of higher permittivity (due to the included water). This, in turn, increases the electrical stress in front of the water tree. Furthermore, the conducting water increases the dielectric loss within the water tree so that there is internal and highly localized dielectric heating. On a microscopic level, the breakdown strength of a dielectric decreases as the temperature increases. Thus, through multiple mechanisms (stress enhancement and dielectric heating), the integrity of the dielectric becomes more compromised as the water tree grows.

Some of the most comprehensive and widely disseminated work on the effect of tree growth on electrical performance was carried out by Fred Steenis (of TU Delft now of KEMA) in the mid 1980's [15]. His curves are not the only examples of the correlation, but they are famous and often quoted. This work sets the background for much of the current thinking in this area. Before describing the Steenis work, it is important to recognize the generation of cable constructions on which he has based his work – the data refer to Generations 3 and 4 (Table 1) manufactured using Steam and Silane technologies (Table 2).

The left hand side of **Figure 4** shows the impact of the water tree growth (as reflected by the longest water tree (bow tie or vented) on the breakdown strength of the samples in the laboratory. There are

two main classes of samples analyzed - cables that had previously failed in service and those which had not failed but were removed to assess their condition.

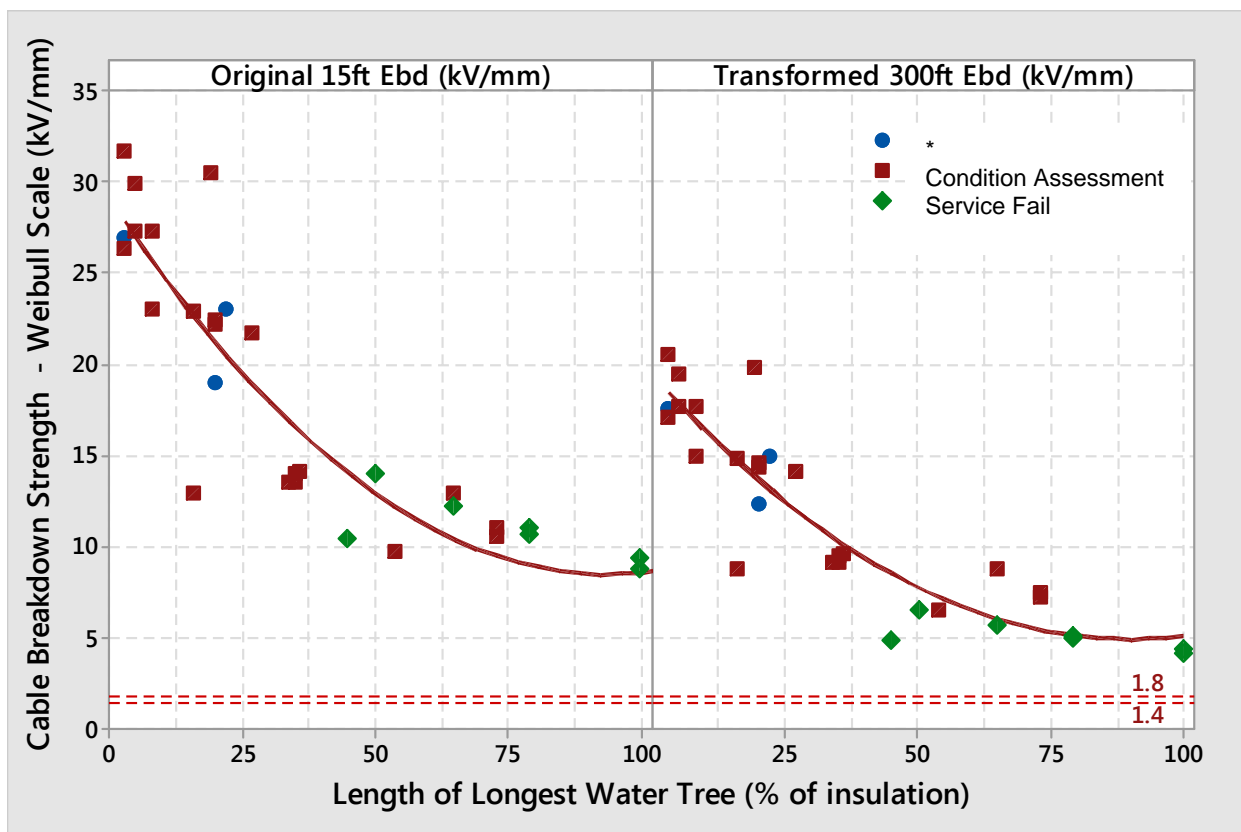


Figure 4: Cable Breakdown Strengths versus Water Tree Lengths (Maximum) segregated by type of investigation (Steenis 15)– left: measured for 15 ft test lengths, right: simulated for 300 ft installed lengths – 1.4 to 1.8 kV/mm indicate the typical mean operating stresses

Figure 4 shows that as the water trees grow, the breakdown strength diminishes. This reduction is due to two interacting effects:

- a) the electric stress is enhanced by the geometry and size of the tree
- b) the reduced strength of the insulation in advance of the tree front.

These curves reveal the important implications for diagnostics:

1. The dielectric strength reduction is not linear with tree growth and the rate of reduction diminishes as the tree advances.
2. The dielectric strength reduction is insufficient to reduce the strength to zero i.e. water trees do have some dielectric strength.
3. There are general trends, but the results show that there is an associated uncertainty band indicating the probabilistic nature of the relationship between water tree growth and dielectric strength.

At first sight there is another perplexing aspect of this data, namely that the strength reductions establish an equilibrium at approximately 8 to 9 kV/mm, a figure six times higher than the operating stress (even though the factor has reduced from 20 when new). Thus, it is difficult to reconcile why failure should have occurred given this margin. Steenis himself makes an important comment on this, namely that lab tests use short samples whereas cable systems employ longer lengths, which are likely to have a higher likelihood of containing more “weak links”.

An estimate of the impact of this uses the well-known Enlargement Law:

$$\alpha_L = \alpha_l \left(\frac{L}{l}\right)^{1/\beta} \quad \text{Equation 1}$$

Where

α_L is the characteristic breakdown strength (Weibull Scale) on length L

α_l is the characteristic breakdown strength (Weibull Scale) on length l

l is the length used for the tests

L is the length for which the breakdown strength (α_L) estimate is desired

β is the Weibull shape parameter for the tests

This equation provides a means of estimating the lower strengths that would reasonably be expected on longer lengths of cable. In these tests, 5m (15ft) were used for the measurements but it was assumed that the length of interest is more likely to be 90 m (300ft). With β values between 7 and 2 for new cables and cables that failed in service, the reduction multipliers are 0.65 to 0.17. These factors result in the left hand curve of **Figure 4**. These strengths are lower than those for the tests are (short lengths) and show a reduction to levels that are much closer to the operating stresses.

Consequently, this work shows that:

- trees grow slowly – Figure 3
- they grow to sizes that can be detected – Figure 3
- there is an increasing risk of failure with increasing tree length, failure is not certain – **Figure 4**

2.1.2 The Present Day

There are many studies in the literature on water treeing and we have selected only two to illustrate the important issues related to cable system diagnostics. However, it would be wrong to assume that water treeing is only of historical interest. The current generations of cable (Generation 9 of Table 1) now installed have characteristics that retard the growth of water trees so that significant initiation is not observed until after 25 to 35 years, as compared to the 5 to 10 years of the first cables with polymer-based insulations (Figure 2 and Figure 3). However, these early generations with lower water tree initiation ages represent a significant portion of the population of installed cable. Utilities are currently dealing with the consequences of the installation of Generations 1 to 6 (Table 1).

Examples of how this affects utilities appear in the recently conducted Weibull analyses based on data gathered by NEETRAC during the course of *Phase I* and *II* of the *CDFI*. See Figure 5 (Weibull Curve for different components of the cable system) and Figure 6 (Survivor Curve – the decrease in population with time - derived from a number of Weibull Curves).

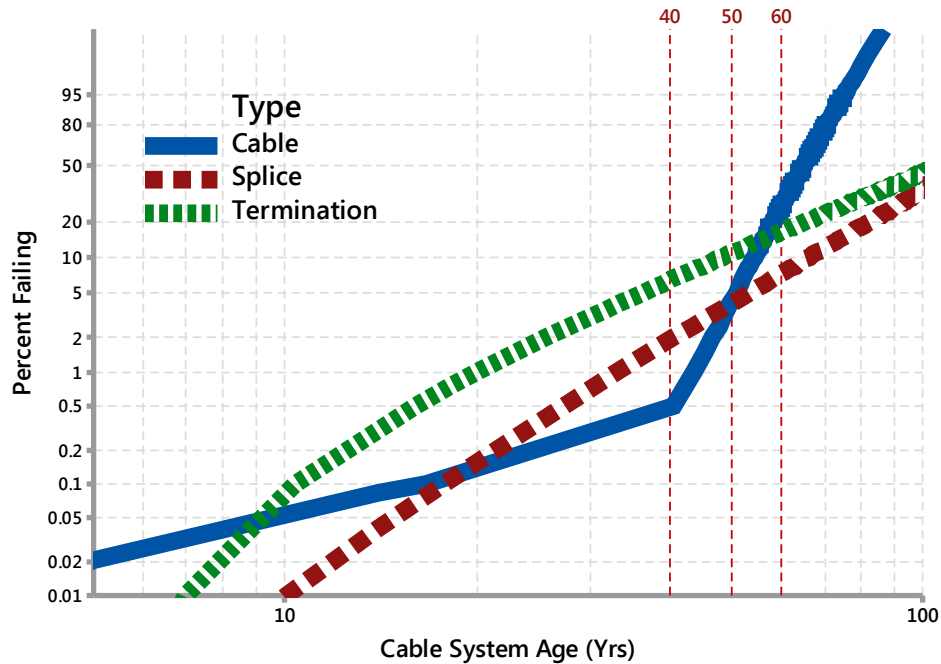


Figure 5: Component Segregated Weibull Curves for Failures in Service on an XLPE Cable System – Estimated in 2014

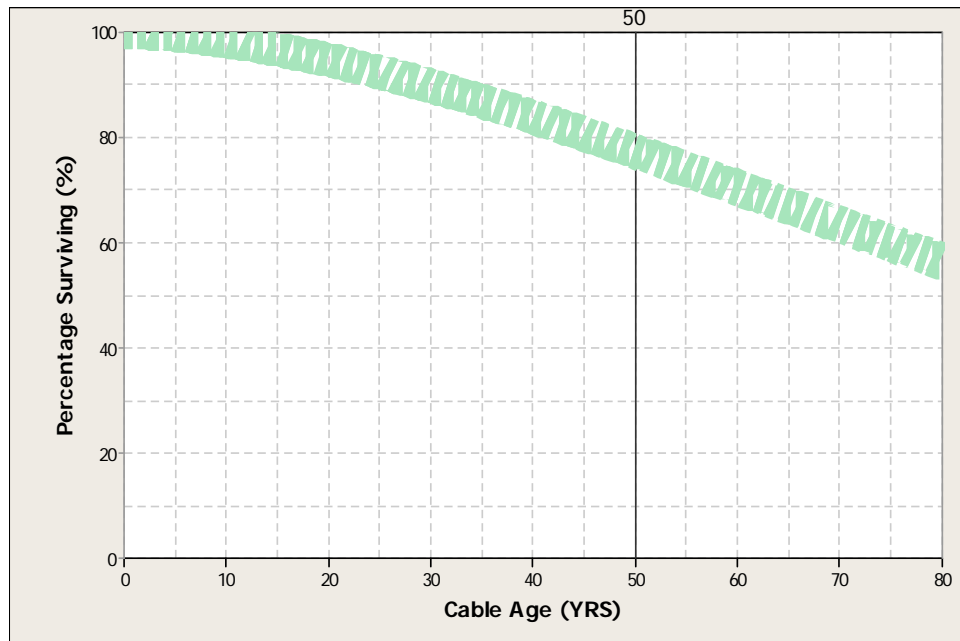


Figure 6: Survivor Curve for Cable Only Failures on an XLPE Cable System – Estimated in 2014

It is useful to comment on one of the most appropriate ways of expressing the information contained in Weibull or Survivor Curves. When cables with polymeric insulations were first installed, it was often stated that they were expected to last for 20 years – this being the common statement attributed to PILC at the time. This was soon revised to a 40-year life expectancy once the full life of PILC was considered. However, these are difficult statements to interpret. What does 20 years refer to? The average life, i.e. the time by which 50% have failed? Additionally under what conditions (loading, environment, cable construction, etc.)? Thus, to describe cable life in a practical and useful manner the life statement needs to include not only the time, but also the amount of cable affected at a specific time and include as much precision about the conditions as can be determined.

Thus, a cable life statement consists of three parts. As such, Figure 6 helps fashion reasonable life statements for a given utility cable system:

78% of direct buried un-jacketed MV cable segments using polyethylene-based insulations at utility Q are expected to survive to age 50.

Or

A 30-year life for direct buried un-jacketed MV cable segments using polyethylene based insulations at utility Q is based upon the survival of 90% of the cable segments.

Although the cable life statement is an unfamiliar concept for cable systems, it can be very useful, especially when considering cable system diagnostics. A utility engineer is likely to interpret a “life expectancy” as being the time that a set of components will last without any failures i.e. a deterministic view. Unfortunately, that is not how life expectancy works. Consider the current human life expectancy at birth of 67 years. We all know there are earlier and later fatalities. Not everyone will live to age 67. Consequently, life expectancy is probabilistic. Furthermore, life expectancy depends on locality, among other factors. Life expectancy is 84 years and 46 years in Japan and Sierra Leone respectively. Suffice it to say, age is not a precise indicator of future performance as life expectancy is imprecise. Diagnostic condition assessment provides additional resolution on the cable system health beyond that provided by age alone. Although diagnostics will improve clarity, they themselves are probabilistic. Consequently, the image will be sharper, but not necessarily crystal clear. This represents a significant challenge for utility engineers who are used to considering life from a deterministic point of view.

2.2 Aging In MV Cable Systems

We have seen that power cable systems, regardless of the dielectric, age, and fail. To further understand the process, it is useful to consider the mechanisms of aging (and subsequently failure). A power cable system fails when the *local* electrical stresses (E) are greater than the *local* dielectric strength (α) of a given dielectric material. The reliability and thus the rate of failure of the whole system depends on the difference between the *local* stress and the *local* strength. Failure of the dielectric results in an electrical puncture or flashover. The failure can result from the application of

the normally applied 60 Hz voltage or during a transient voltage such as a lightning or switching surge.

The probability of a failure occurring is described by Equation 2.

$$P_f = 1 - e^{-\frac{E^\beta}{\alpha}} \quad \text{Equation 2}$$

Where

P_f is the probability of failure

α is the characteristic breakdown strength (Weibull Scale) associated with the length tested

β is the Weibull shape parameter for the tests

E is the relevant stress that is considered to drive the system to failure;

- in a ramp or step test then this will be the appropriate electric stress,
- in a constant electrical stress test then it will be the time at which failure occurs (Figure 5)

In MV cable systems, failure is generally treated as an *increasing local stress (an increasing E)* problem rather than a decreasing strength (a decreasing α). As time progresses, conditions that raise the local stress (primarily water trees, loss of bonding between contaminants and the surrounding dielectric or the development of voids) can occur over time. The net effect appears as aging.

Figure 7 shows the effect of different electrical stresses on the endurance (time to failure) for cables when tested in the laboratory after selected aging times. The estimates have been transformed from laboratory lengths to more practical lengths using the approach suggested by Steenis. The figure shows that as the electric stress is increased, the endurance (or the time to failure) will decrease. This is not a linear effect, as can be seen by the log-log scales. It is generally accepted that a twofold increase in stress (such as increasing the stress from 300 V/mil to 600 V/mil) will cause a fivefold reduction in time to failure. This is why so much attention is focused on the increasing electrical stress enhancement that occurs when a water tree grows in an MV insulation.

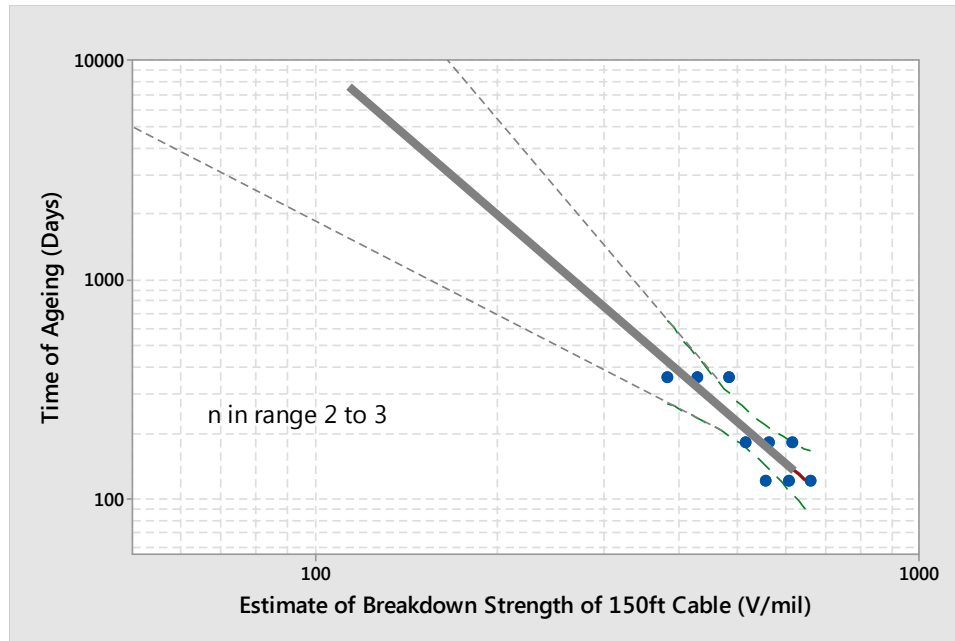


Figure 7: Endurance Reduction in a MV Cable with Elevated Electrical Stresses in laboratory tests (Fitting the Inverse Power Law $E^n t = K$ to data gives n in range 2 to 3)

This is also why it is possible, and often common, for a system to experience aging at different rates along the cable length. In a cable with an isolated, large vented tree, there can be a low level of bulk aging but a high level of local aging at the water tree due to the higher stress at the contaminant or other artifact that caused the water tree initiation. Therefore, the area that immediately surrounds the artifact experiences the dual effects of higher stress and higher aging. On the other hand, in a cable with many bow tie trees distributed throughout the insulation, there will more likely be a moderate level of general, bulk aging. The distinctions may seem arbitrary, as failure will always occur at the weakest point. However, this does have a notable impact on how repair decisions are made. In the case of an isolated defect, a repair after the failure will result in a system with dielectric strength that is very often quite high. If the failure was due to more dispersed deterioration, then repairs may not provide much benefit as the remaining system is only marginally stronger than the weakest part that failed.

Figure 7 and most related references represent dielectric strength and endurance as lines, implying that they are single valued or deterministic results. Nothing could be farther from the truth. Even in well-controlled laboratory assessments there is considerable scatter, or randomness, in the data. Furthermore, this scatter is enhanced when considering the less well-controlled environment of a cable system. This is important for engineers to bear in mind because diagnostic tests, in general, determine if there are weak locations within the cable circuit. A cable system will begin failing long before the average dielectric strength of the system is below the operating stress. It is not only the dielectric strength that displays statistical scatter, but it applies to all measured characteristics of a cable system.

As noted earlier, utility engineers often anticipate that there will be no failures up to the anticipated life expectancy of the cable system, but we know that some number of failures will occur over time. Engineers are likely to be quite concerned long before 50% of the population experiences a failure.

Thus, it is the lower strengths represented by the lower dotted line of Figure 7 rather than the average that are the ones that are probed by diagnostic techniques. Additionally it is the reason why the cable life statements generally consider 90%, 80%, or 70% survival when making their estimates of life.

2.3 Causes of Increased Local Stress

Turning to the specific mechanisms by which the electrical stress is increased, excessive electrical stress in the cable system dielectric can result from,

- Manufacturing imperfections: tends to increase the local stress leading to either initial failure or higher rates of aging.
 - voids
 - contaminants in insulations
 - poor application of shield material
 - protrusions on the shields
- Poor workmanship: tends to increase the local stress leading to either early failure or higher rates of aging.
 - cuts
 - interfacial contamination in accessories
 - missing applied components or connections
 - misalignment of accessories
- Wet environment: tends to reduce increase the local stress after ingress of water (either through normal migration through polymeric materials or breaks in seals or metallic sheaths):
 - bow tie trees
 - vented water trees
 - high rates of corrosion
- Changed electrical environment: tends to reduce the dielectric strength. The impact is usually local if the environmental influence is local.
 - neutral corrosion causing a change in the external ground plane

Although increased local stress is considered the main concern in MV Systems, a reduced local strength can contribute resulting from,

- Overheating: tends to reduce the dielectric strength. The impact can be restricted to short lengths (local) if the adverse thermal environment is localized.
 - poor accessory workmanship – mostly connectors
 - incorrect choice of accessory
 - excessive conductor current for a given environment and operating condition (global)
 - proximity to other cable circuits or other heat sources for short distances (local)

- Aggressive environment: tends to reduce the dielectric strength. The impact can be local if the environmental influence is local.
 - chemical attack (transformer oil leaks, petrochemical spills, fertilizer)
 - flooding that creates a step change in environmental conditions

Defects in cables with extruded insulation that can lead to failure are shown schematically in Figure 8. These defects include protrusions, voids, cracks, delamination, conductor shield interruptions, water trees, and electrical trees [5].

Within PILC cables, areas with insufficient oil due to oil migration and water ingress can also create failures over time [5].

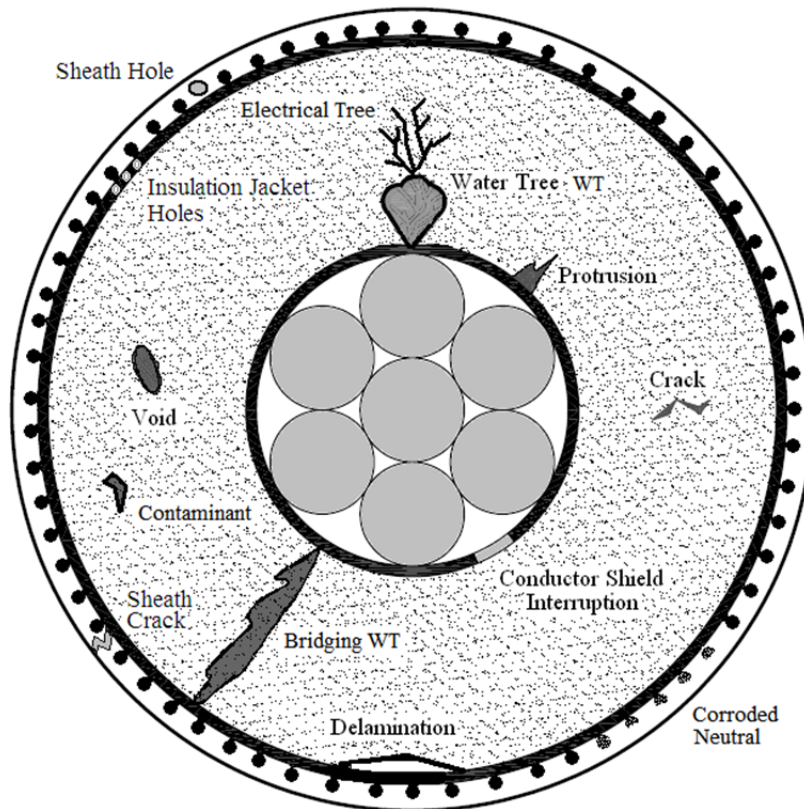


Figure 8: Typical Power Cable Defects

In addition, typical defects that can evolve into failures in a cable joint installed on cables with polymeric insulations appear in Figure 9. These defects include voids, interface discharge (tracking between the interfaces of the cable insulation and the joint insulation), and knife cuts made during the insulation shield cutback operation. The same types of defects that can occur in joint constructions, both taped and prefabricated, can also occur in terminations.

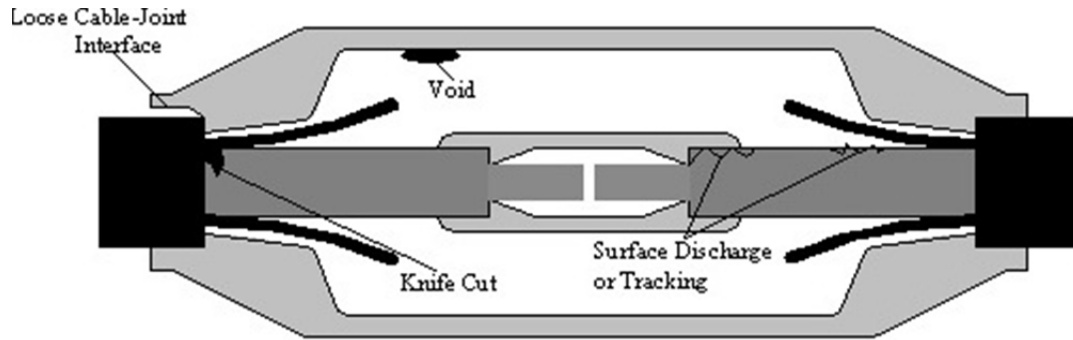


Figure 9: Typical Cable Joint Defects

As the system ages, the dielectric strength of various components tends to weaken. Since the aging mechanism depends on factors that involve the cable characteristics, accessory characteristics, and operating conditions, different power cable systems will age in different ways. Because the aging process is statistical in nature, there can be substantial variations in how the mechanisms develop and evolve over time with respect to cable length and accessories. This leads to significant differences between power cable systems operating under the same conditions and exposed to similar environments. Moreover, the power cable system properties measured through diagnostic testing will also show statistical features. This means that when utility engineers try to estimate the statistical time to failure for a given cable segment, the data should be interpreted correctly, e.g. with a sufficient number of data points to provide a reasonable assessment of trends and predictions.

Table 4 through Table 7 list typical deterioration or aging mechanisms along with the associated causes of each for various accessory and cable types. Mechanisms that lead to rapid failure (thermal runaway and extremely high local stresses from contaminants) are omitted as they typically bypass the degradation step and lead to failure before any type of intervention is possible.

It is useful to recall that the dielectric loss within a system depends upon the electrical stress (E), frequency (ω), permittivity (ϵ), and $\text{Tan } \delta$:

$$\text{Dielectric Loss} \propto \omega E^2 \epsilon \text{Tan } \delta \quad \text{Equation 3}$$

Before any failure, there is either tracking or an electrical tree. Thus, it should be noted in all of the flow diagrams in Table 4 that tracking and electrical treeing precede all failures. The only question is how long they can be observed before the failure occurs.

Table 4: Aging and Degradation Mechanisms for Extruded MV Cable

Type of Deterioration	Aging Process	Typical Causes	Example
Large Water Trees		Moisture ingress	
Neutral Corrosion		Unjacketed cable in soil Water retained in jacketed cables Sometimes enhanced by chemicals in the soil	
High Density of Small Water Trees		Moisture ingress (external and via conductor)	
Thermal		Poor connector installation Incorrect choice of accessory Excessive conductor current for given environmental and operating conditions	
Dry Electrical		Manufacturing imperfections (voids, contaminants)	
Chemical		Petrochemical spills (transformer oil leaks, fertilizers)	

Table 5: Aging and Degradation Mechanisms for PILC Cable

Type of Deterioration	Aging Process	Typical Causes	Example
Oil Starvation	<pre> graph TD OM[Oil migration] --> PD[Partial discharge] OM --> LDH[Localized dielectric heating] PD --> PO[Paper oxidation] LDH --> PO PO --> CPC[Changes in paper characteristics] CPC --> IDFI[Increase in dissipation factor] CPC --> DDI[Decrease in dielectric strength] </pre>	<p>Extreme elevation changes, Lead (Pb) breach (cracks and corrosion)</p>	
Thermal	<pre> graph TD AT[Abnormal Temperature] --> PO[Paper Oxidation] AT --> PD[Paper Deterioration] PO --> RPI[Reaction Products ions] PD --> RPI RPI --> ID[Insulation Degradation] ID --> IDFI[Increase in dissipation factor] ID --> DDI[Decrease in dielectric strength] </pre>	<p>Excessive conductor current for a given environment and operating conditions</p>	
Water Ingress	<pre> graph TD WI[Water ingress] --> LDH[Localized or bulk dielectric heating] WI --> ILI[Insulation losses increase] LDH --> PO[Paper oxidation] ILI --> PO PO --> CPC[Changes in paper characteristics] CPC --> IDFI[Increase in dissipation factor] CPC --> DDI[Decrease in dielectric strength] </pre>	<p>Lead (Pb) breach (cracks and corrosion)</p>	

Table 6: Aging and Degradation Mechanisms for Accessories of Extruded MV Cable

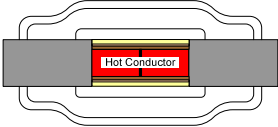
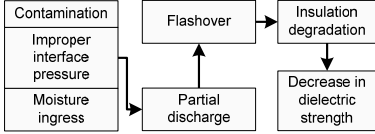
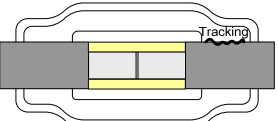
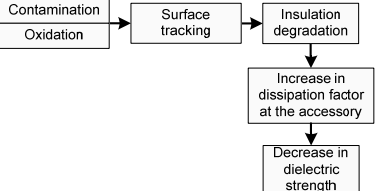
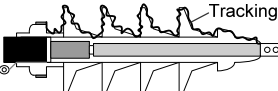
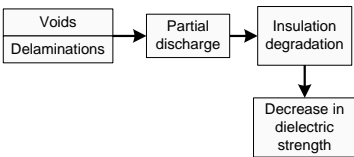
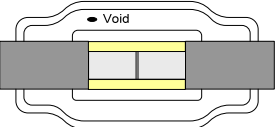
Type of Deterioration	Aging Process	Accessory Type	Typical Causes	Example
Thermal	NEW	Joint, termination, separable connector	Poor workmanship Incorrect choice for the application	
Contaminated Interface		Joint, termination, separable connector	Moisture ingress Poor workmanship	
Electrical External		Termination	Pollution, Ultraviolet (UV) degradation	
Dry Electrical		Joint, termination, separable connector	Manufacture defects, Natural aging Poor workmanship	

Table 7: Aging and Degradation Mechanisms for Accessories of PILC Cable

Type of Deterioration	Aging Process	Typical Causes	Example
Oil Starvation	<pre> graph TD OM[Oil migration] --> OX[Oxidation] PD[Partial discharge] --> OX LDH[Localized dielectric heating] --> OX OX --> CPC[Changes in paper characteristics] OX --> DIES[Decrease in dielectric strength] </pre>	<p>Extreme elevation changes, lead (Pb) breach: cracks and corrosion</p>	
Thermal	<pre> graph TD AT[Abnormal temperature] --> RP[Reaction products ions] OX[Oxidation] --> RP ID[Insulation Deterioration] --> OX RP --> IG[Insulation degradation] RP --> DIES[Decrease in dielectric strength] </pre>	<p>Poor workmanship</p> <p>Moisture ingress</p> <p>Excessive conductor current for a given environment and operating conditions</p> <p>Poor connector design for installation</p>	
Localized Electrical Stresses	<pre> graph TD LS[Localized stresses] --> OX[Oxidation] PD[Partial discharge] --> OX OX --> CDC[Changes in dielectric characteristics] OX --> DIES[Decrease in dielectric strength] </pre>	<p>Tearing or separation of cable paper due to poor workmanship</p>	
Oil Contamination from Paper to Extruded Cable in Transition Joints	<pre> graph TD OC[Oil contamination] --> SW[Swelling] OC --> CC[Chemical cracking] SW --> IG[Insulation degradation] CC --> IG IG --> DIES[Decrease in dielectric strength] </pre>	<p>Poor accessory design,</p> <p>Poor workmanship</p>	

2.4 Installed Population

The diversity of cable system failure mechanisms comes not just from the different ways that a given dielectric can age and ultimately fail, but also from the broad array of different cable systems currently in service (Generations 1 to 6 in Table 1). Figure 10 provides an estimate of the quantity of different cable system insulation types used in North America. Although this survey was

conducted in 2006 – 2008, it still represents the best available estimate. An update was attempted within *CDFI Phase II* but there were insufficient responses to provide a higher quality update. This figure shows that the diversity in the cable infrastructure is significant. Thus, it is important to understand how to match a given diagnostic technology to a specific cable system problem, but also to a specific cable system generation/design. It is also important to recognize that the wide variety of issues associated with the degradation of various cable system designs, implies that it is very unlikely that one diagnostic technique will be effective for assessing the true condition of each system.

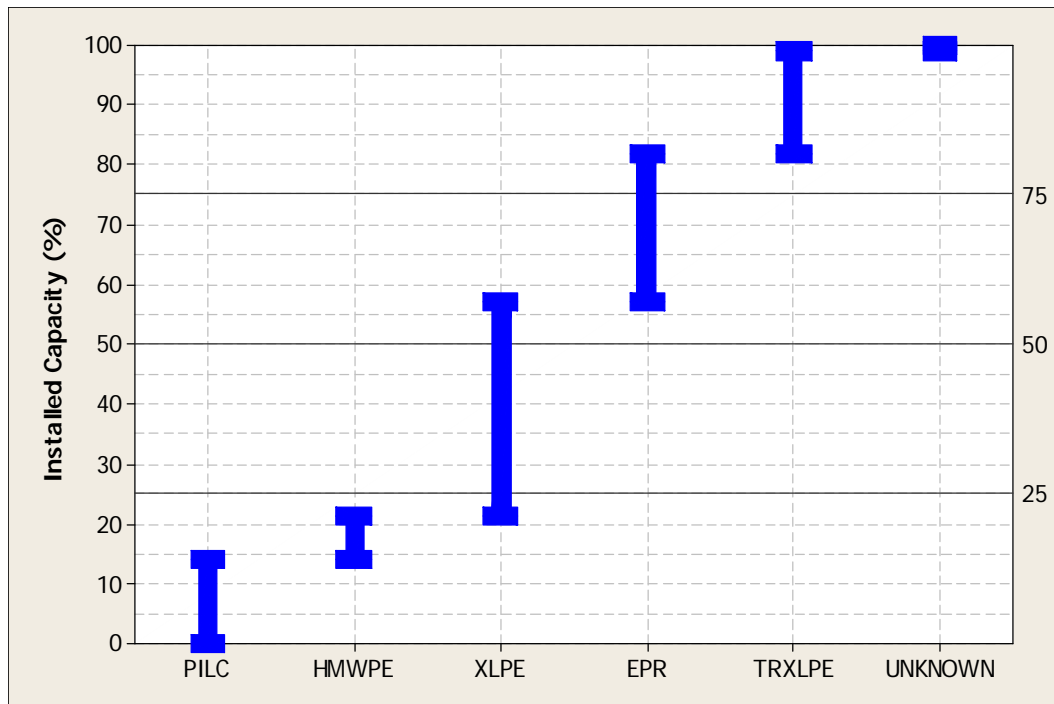


Figure 10: Estimate of North American Installed MV Cable Capacity, Segregated by Cable Insulation Type from Surveys Conducted 2006 To 2007 – from Table 1: PILC= Generation 0, HMWPE = Generation 1 to 2, XLPE = Generation 3 to 6, WTR XLPE = Generation 7 to 9, EPR = Generation 7 to 9

Additionally, it is important to know which portion of existing cable systems are failing and at what rate. Figure 11 suggests that while some utilities are experiencing very high failure rates of over 100 failures/100 miles/year, the mean is approximately 12 failures/100 miles/year. This information is useful because it sets the stage for understanding the economic considerations associated with diagnostic testing as well as setting expectations for improved reliability.

Figure 12 shows that failures occur not just in cable, but also in joints (splices) and terminations, so diagnostic technologies must be able to detect weaknesses in all cable system components. Finally, this figure shows that a significant percentage of utilities do not deploy cable system diagnostic testing programs and about half of those use only one technique. This information implies that in general, utilities do not fully appreciate the potential benefits of performing diagnostic test programs on their cable systems and the importance of using the right technique for the application. It is instructive to note that these data come from surveys conducted in 2006 and 2007.

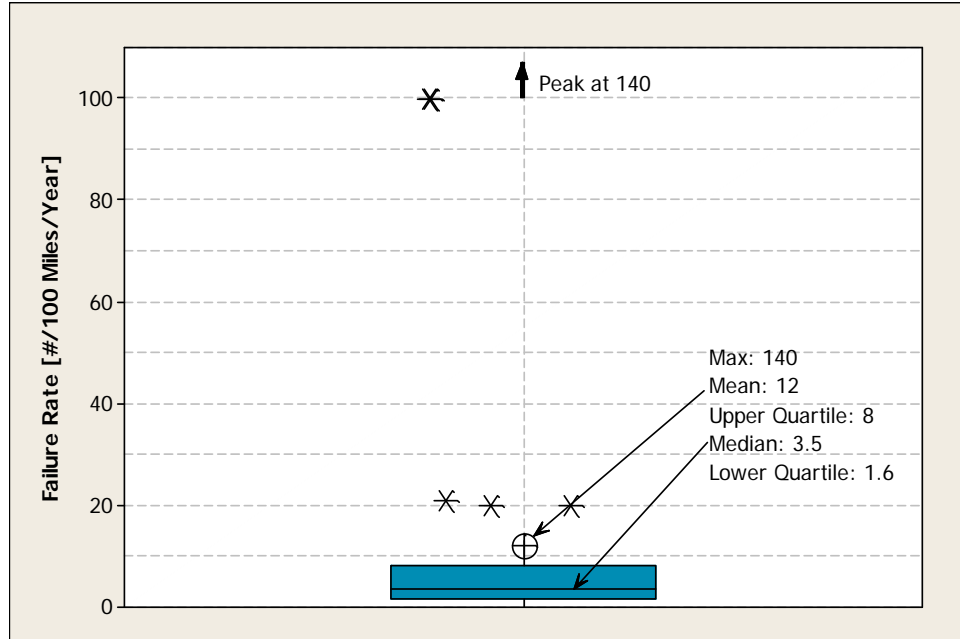


Figure 11: Estimate of North American MV Cable System Failure Rates

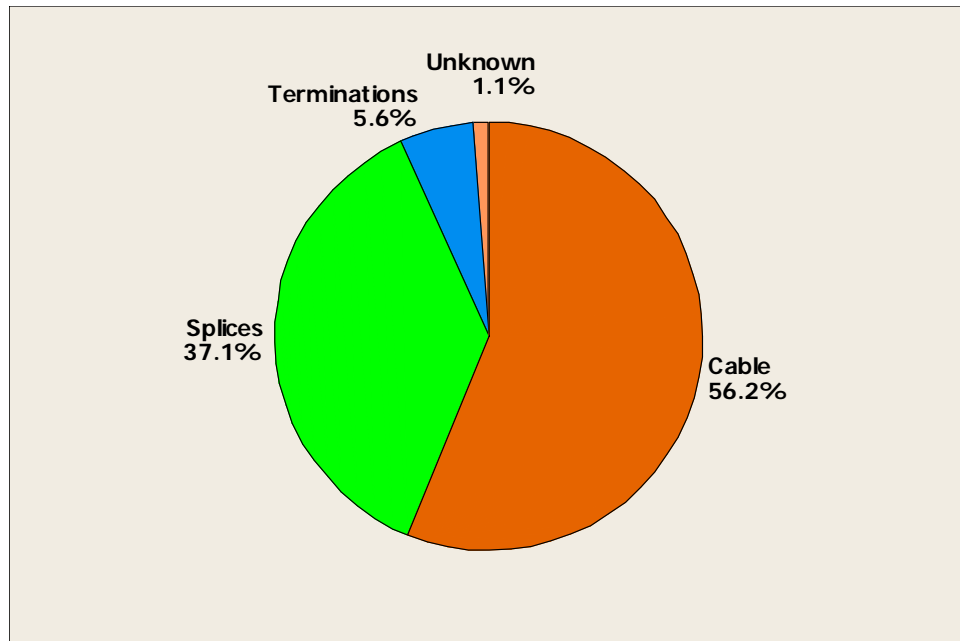


Figure 12: Estimated Dispersion of North American MV Cable System Failures by Equipment Type as Reported by Utilities

2.5 Conclusions

Returning to the discussions of MV cable system degradation that started this chapter it is possible to relate the preferred usage of diagnostics to the degradation. Data in Chapter 3 shows that the

Hipot (short for High Potential) or Simple Withstand testing is often the preferred diagnostic approach because it is so straightforward and easy to use. The Hipot or Simple Withstand Test approach makes use of the findings in **Figure 4** (reproduced again here as **Figure 13**).

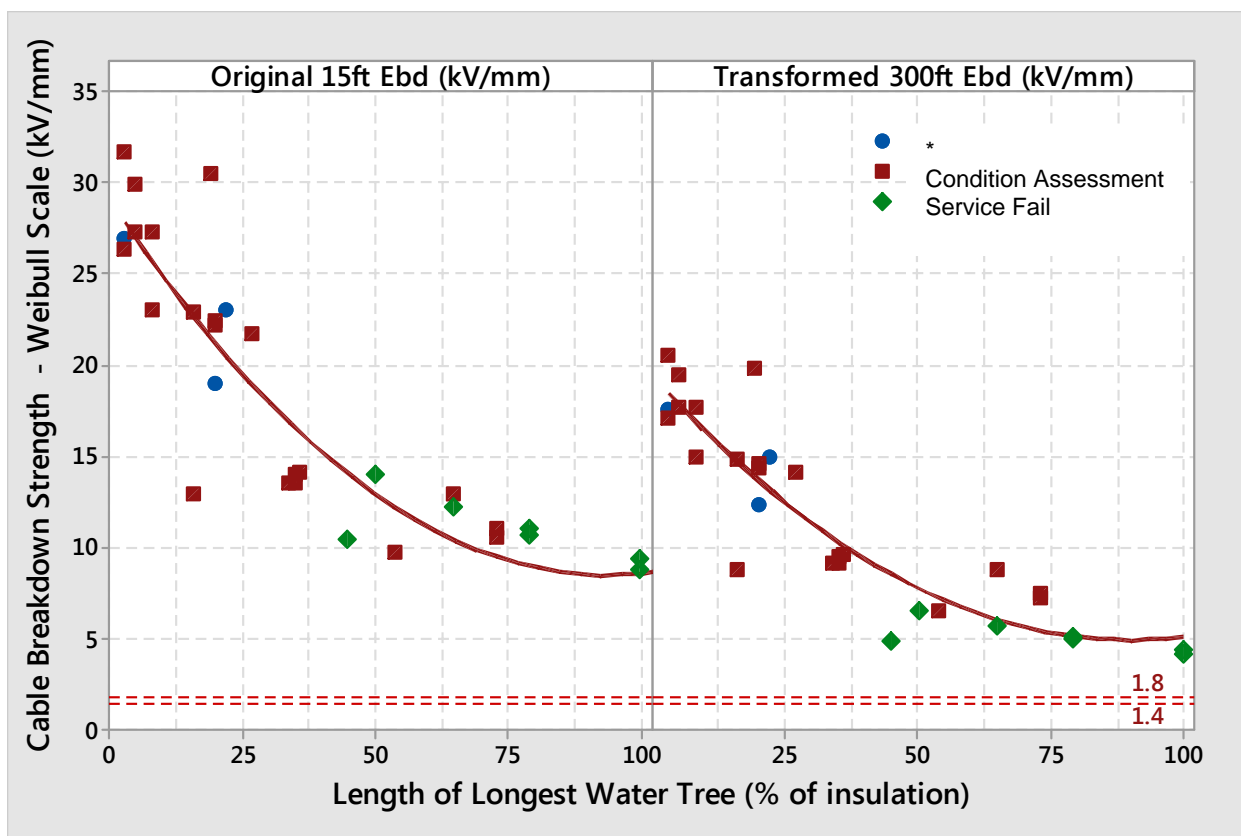


Figure 13: Cable Breakdown Strengths versus Water Tree Lengths (Maximum) segregated by type of investigation (Steenis 15)– left: measured for 15 ft test lengths, right: simulated for 300 ft installed lengths – 1.4 to 1.8 kV/mm indicate the typical mean operating stresses

It seeks to find an appropriate time/voltage combination that can be applied to the cable system so that weak spots (in the cable or the accessory) may be caused to fail in a reasonable time. However, the nonlinearity in the aging rate (Figure 7) means that the defects (water trees) only grow infinitesimally and will not be detected using this technique.

Using a more discriminating diagnostic approach (approximately 17% of utilities utilize such an approach as discussed in Chapter 4) does not make use of the reduction of the insulation strength as the diagnostic mechanism but probes the growing degradation caused by water tree growth. The water tree growth is assessed by measuring the change in the dielectric loss due to the water entrapped within the water trees and the water dissolved in the surrounding insulation. This useful measurement has grown in popularity with the increased use of $\tan \delta$ (TD) diagnostic methods. Partial discharge methods become useful later in the degradation chain when either water trees convert, irreversibly, to electrical trees or when discharges occur within voids in a cable accessory (most usually along the interface).

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