LONG-LIFE XLPE INSULATED POWER CABLE

Nigel HAMPTON, NEETRAC, Georgia Tech, USA, nigel.hampton@neetrac.gatech.edu
Rick HARTLEIN, NEETRAC, Georgia Tech, USA, rick.hartlein@neetrac.gatech.edu
Hakan LENNARTSSON, Borouge Pty, Hong Kong, hakan.lennartsson@borouge.com
Harry ORTON, OCEI, Vancouver, BC, Canada, h.orton@ieee.org
Ram RAMACHANDRAN,The Dow Chemical Company, NJ, USA, ramachs@dow.com

ABSTRACT

Crosslinked polyethylene (XLPE) has become the globally preferred insulation for power cables, both for distribution and transmission system applications. This insulation system provides cost efficiency in operation and procurement, as well as lower environmental and maintenance requirements when compared to older impregnated paper systems.

The purpose of this paper is to outline some of the developments that have led to this position. Understanding these developments will assist utilities to continue sourcing, and installing, the reliable underground assets that they require for the future.

KEYWORDS

QUALITY, MEDIUM VOLTAGE, AGEING

INTRODUCTION

When medium voltage (MV) XLPE insulated cables were first installed in the late 1960's, cable manufacturers and electric utilities expected them to perform reliably for 20 or even 30 years. History has shown that the service life of some of these early cables was far shorter than expected. At that time, cable engineers and material scientists were not aware that moisture, voltage stress, omitting jackets and imperfections within the cable structure would combine to accelerate the corrosion of neutral wires / tapes and cause water trees. These defects degraded the cable performance so severely that many cables failed after only 10 to 15 years in service.

The consequences of this lack of understanding were profound. It has been estimated that for every dollar that utilities spent installing the cable, they had to spend at least 10 dollars to replace it. Resources that could have been used to build new infrastructure were now diverted to replace cables that were less than 20 years old. This had an impact on operating costs that electric utilities are still dealing with today [1].

Engineers and scientists now know what went wrong. They discovered that voids and contamination in the insulation, combined with ionic contamination in the semiconducting shields, as well as other design and manufacturing deficiencies, led to voltage stress concentrations within the cables. These elevated voltage stresses, combined with moisture ingress into the cable structure created what are known today as water trees. These dendritic growths of microscopic cavities degraded the insulation over time, ultimately causing the cables to fail.

Today there are XLPE insulations that can be designed to inhibit the growth of water trees, allowing for even greater reliability for distribution class cables. Semiconducting screens that are free of excessive ionic contamination are also available. Manufacturers have also learned how to produce cable with insulations that are free of voids and with smooth interfaces between the semiconducting screens and the insulation.

Cables must also be specified, designed, manufactured, tested and installed such that the desired life is delivered. It is clear that a high level of symbiosis is required by academics, cable manufacturers, compound suppliers and utilities. This paper sets out to provide the foundations for this by identifying the critical developments and understanding. Many of the comments are relevant for all cable voltages (LV to EHV). However we will focus on the MV arena in this paper and address the higher voltage issues in a subsequent publication.

CABLE STRUCTURE AND MATERIALS

The structure of underground power cables appears deceptively simple. However, each component has an important purpose and must be selected carefully to assure that the composite cable structure will perform reliably in service. The critical structural elements of underground power cables are discussed in the following sections.

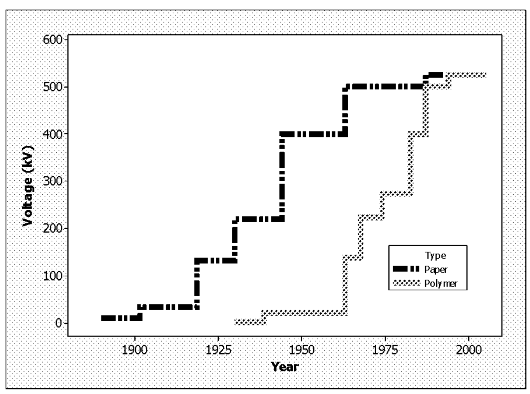

Figure 1 Evolution of the Highest AC Cable Voltage

Insulation materials used in MV power cables have long included the mature technology of fluid-impregnated Kraft paper. They have been successfully used for over 100 years. Today, extruded crosslinked polymer insulations are the standard for all voltages (Figure 1). The service experience that led to the impact of crosslinked polymers on utility systems is provided in (Table 1). Crosslinked compounds provide a better reliability and higher operating temperature that the thermoplastic (un crosslinked) analogues. Thermoplastic materials will deform upon subsequent heating, whereas thermoset materials will tend to maintain their form at operating temperatures. This experience coupled with the interest in ever higher operating temperatures mean that this preference for crosslinked solutions will endure for the foreseeable future.

Table 1.MV Cable Service Failures in Europe (median failures/100 circuit. km/yr) – UNIPEDE 1995

Type		10 kV	20 kV	30 kV
XLPE 1979 – 1994	Crosslinked	0.2	0.4	2.0
EPR 1979 – 1994		2.3	1.4	2.0
LDPE 1979 – 1989	Thermoplastic	1.5	3.5	4.5
PVC 1979 – 1989		5.0	3.5	16.0

XLPE INSULATION

XLPE is a thermoset material produced by the compounding of LDPE with a crosslinking agent such as dicumyl peroxide. Al Gilbert and Frank Precopio invented XLPE in March 1963 in the GE Research Laboratory located in Niskayuna, New York [2]. In this process, the long-chain PE molecules "crosslink" during a curing (vulcanization) process to form a material that has electrical characteristics that are similar to thermoplastic PE, but with better mechanical properties, particularly at high temperatures. XLPE-insulated cables have a rated maximum conductor temperature of 90°C and an emergency rating of up to 140°C.

Water Tree Retardant XLPE (WTR XLPE)

As noted earlier, the phenomenon of water treeing can reduce the service life of XLPE cables. Typical water trees are shown in Figure 3. Water trees grow relatively slowly over a period of months or years. As they grow, the electrical stress can increase to the point that an electrical tree is generated at the tip of the water tree [1,3-6]. Once initiated, electrical trees grow rapidly until the insulation is weakened to the point that it can no longer withstand the applied voltage and an electrical fault occurs at the water/electrical tree location. Many actions can be taken to reduce water tree growth, but the approach that has been most widely adopted is the use of specially engineered insulating materials designed to limit water tree growth. These insulation materials are called WTR-XLPE. These insulation materials, combined with the use of clean semicon shields and sound manufacturing processes have dispelled the concerns that many utilities had regarding the use of cables with a polymeric insulation.

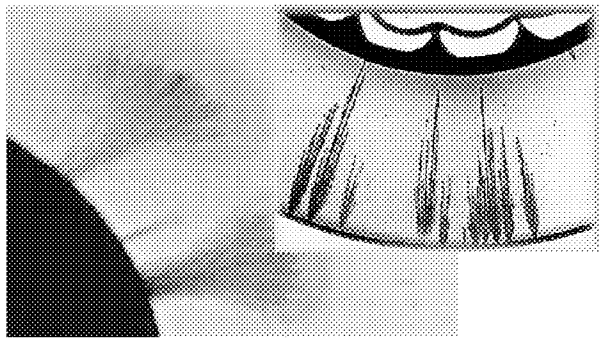

Figure 3 Water Trees Growing from the Inner (bottom) and Outer (top) Semiconductive Screens

Two approaches to insulation technology are in widespread use to retard the growth of water trees and each is a modification of the classic XLPE materials. These are:

- Modification of the polymer structure, "Polymer" WTR-XLPE; sometimes termed copolymer - modified XLPE
- Modification of the additive package, "Additive" WTR-XLPE; sometimes termed TR-XLPE

In both instances, the compounds maintain the excellent electrical properties of XLPE (high dielectric strength and very low dielectric losses). WTR-XPLE insulations were commercialized in the early 1980's and have now been performing reliably in service for over 20 years [3-7].

Productivity

In addition to the two basic technologies for retarding water tree growth a number of modifications in the basic polymer structure can be made to maximize productivity during the cable manufacturing processes. In MV applications, the reactivity can be boosted significantly. This results in higher line speeds in the cases where there are limitations in either the curing or cooling processes within the continuous vulcanization (CV) tubes used to crosslink the insulation. XLPE insulations can also be modified to limit the amount of by-product gases that are generated during the crosslinking process. This is particularly useful for HV and EHV cable applications, where degassing requirements can significantly lengthen the time required to manufacture the cable.

INSULATION CURING PROCESSES

The crosslinking process begins with a carefully manufactured base polymer. A stabilizing package and crosslinking package are then added to the polymer in a controlled manner to form the compound. Crosslinking adds tie points into the structure. Once crosslinked, the polymer chains retain flexibility but cannot be completely separated, for example, transformed into a free-flowing melt. There are essentially two types of crosslinking processes that can be used for XLPE-insulated power cables:

Peroxide cure – thermal decomposition of organic peroxide after extrusion initiates the formation of crosslinks between the molten polymer chains in the curing tube. This process can be used for XLPE or EPR insulations. The peroxide cure method is the most widely used crosslinking technology globally and is used to manufacture MV, HV and EHV insulated cables. The moisture-cure approach is almost universally used for making LV cables and is sometimes used to manufacture MV cables.

Moisture cure – chemical (silane) species are inserted onto the polymer chain, these species form crosslinks when exposed to water. The curing process occurs in the solid phase, after extrusion. Moisture curing is most often preferred for the manufacture of MV cables when many different cable designs are made on the same extrusion line and/or when manufacturing lengths are relatively short. In these situations, the separation of the extrusion and curing processes is attractive from a production standpoint.

CONDUCTOR AND INSULATION SCREEN COMPOUNDS

Semiconducting screens (sometimes called semicons or semiconducting shields) are extruded over the conductor and the insulation outer surface to maintain a uniformly divergent electric field, and to contain the electric field within the cable core. These materials contain specially engineered grades of carbon black to attain the correct level of stable conductivity for the cable semicon or screens.

Semiconducting screening materials are based on carbon black (manufactured by the complete and controlled combustion of hydrocarbons) that is dispersed within a polymer matrix. The concentration of carbon black needs to be sufficiently high to ensure an adequate and consistent conductivity. The incorporation must be optimized to provide a smooth interface between the conducting and insulating portions of the cable. The smooth surface is important as it decreases the occurrence of regions of high electrical stress. To provide the correct balance of these properties, it is essential that both the carbon black and polymer matrix be well engineered.

Table 2 Typical Impurity Analysis on Semiconductive Conductor Screen Compounds Manufactured with Selected Carbon Blacks - ICP data in ppm

	Furnace Blacks			Acetylene Blacks
Elements	Low Quality	Standard Quality	High Quality	High Quality
Al	15	5	6	3*
Ca	160	3*	3*	3*
Cr	2	3*	3*	3*
Fe	8	3*	3	3*
Ni	2	3*	3*	3*
Mg	57	27	15	10*
S	3600	1900	100	3*
Si	47	10	4	3*
V	2	3*	3*	3*
Zn	3*	3*	3*	3*
K	125	12	3*	3*
Cl	105	13	11	3*

* value at the detection limit of the ICP equipment.

It has long been recognised that the highest levels of smoothness and cleanliness are achieved when Acetylene based carbon black are used within the semiconducting matrix (Table 2) [8]. In recent years, furnace black chemical impurities and ash content have been adjusted to achieve optimal levels required for semiconductive screen applications. In 1973 the ash content for a conventional furnace black was 0.73 percent Today, a carbon black with 0.01 percent ash content is available. Similarly, the total sulphur content has been reduced from 1.26 % to 0.01 %, while over the same period, the compound smoothness based upon a contaminant count, has gone from 90 pip/cm^2 to 15 pip/cm^2. However this improvement is not universal and cannot be taken for granted. Table 2 shows the range of cleanliness levels

FREEDOM FROM DEFECTS – CLEANLINESS & SMOOTHNESS

The critical importance of cleanliness (of both the insulation and the semiconducting screens) and smoothness (insulation screen interface) has been a hard learned lesson (Figure 2) [1, 6, 8, 9]. Improved cleanliness and interface smoothness increases operating stresses (important for HV & EHV) and delivered life. The cleanliness of all cable materials has improved significantly over the last 15 years. Cleaner raw materials, improved manufacturing technology, and handling techniques have all contributed to enhanced cleanliness. Out of these many initiatives, new generations of XLPE and WTR-XLPE materials have emerged. These are generally supplied with designations that define the cleanliness and voltage use levels.

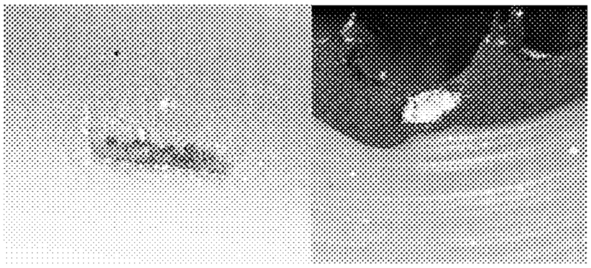

Figure 2 Typical defects (contaminants – left & right, and screen distortion – right) found in extruded cables

Cable manufacturers, in turn, have implemented material handling systems to prevent contamination during the course of manufacturing. One example is that clean rooms have been installed in most cable manufacturing plants and separate handling facilities for insulation and semiconductor materials have been implemented.

Table 3 Relationship Between Voltage Class and the Generally Accepted Cleanliness Levels

	MV 6 – 36 kV	HV 36 – 161 kV	EHV > 161 kV
Mean Electrical Stress (kV/mm)	2	6	10
Contaminants Excluded (μm)	200 – 500	100 – 200	70 – 100
Contaminants Controlled (μm)	100 – 200	70 – 100	50 – 70

The cleanliness of insulation materials (both peroxide and moisture cure) is often assessed by converting a representative sample of the polymer into a transparent tape, then establishing the concentration of any inhomogeneities. The inhomogeneities are detected by identifying variations in the transmission of light through the tape. The data processing is carried out by a microcomputer, which is able to produce size segregated concentration data for a number of selected levels of obscuration [Table 3]. These cleaner XLPE insulation materials lead to a much longer in-service life for cables. Utility acceptance of the cleaner compounds has been rapid and widespread.

CORE MANUFACTURE

An extruded cable production line is a highly sophisticated manufacturing process that must be run with great care to assure that the end product will perform reliably in service for many years. It consists of many subprocesses that must work in concert with each other. If any part of the line fails to function properly, it can create problems that will lead to poorly made cable and will potentially generate many metres of scrap cable [1].

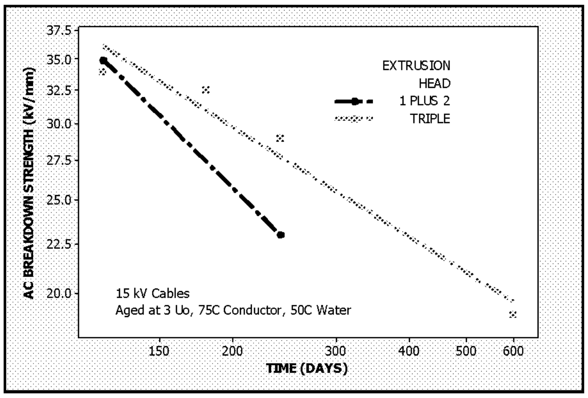

Figure 3 Influence Of Extrusion Head Configuration on Cable Aging, As Measured By Breakdown Strength [7]

The process begins when pellets of insulating and semiconducting compounds are melted within the extruder. The melt is pressurised and this conveys material to the crosshead where the respective cable layers are formed. Between the end of the screw and the start of the crosshead it is possible to place meshes or screens, which act as filters. The purpose of these screens was, in the earliest days of cable extrusion, to remove particles, or contaminants that might be present within the melt. While still used today, the clean characteristics of today's materials minimize the need for this type of filter. In fact, if these screens are too tight, they themselves can generate contaminants in the form of scorch or precrosslinking. Nevertheless, appropriately sized (100 to 200-micron hole size) filters are helpful to stabilize the melt and protect the cable from large foreign particles that most often enter from the materials handling system.

The most current technology uses a method called a *true triple* extrusion process where the conductor shield, insulation and insulation shield are coextruded simultaneously. The cables produced in this way have been shown to have better longevity (Figure 3) [7].

After the structure of the core is formed the cable is crosslinked to impart the high temperature performance. When a CV tube is used fine control of the temperature and residence time (linespeed) is required to ensure that the core is crosslinked to the correct level.

JACKETS

In most MV, HV and EHV cable applications, the metal sheath/neutral is itself protected by a polymeric oversheath or jacket. Due to the critical performance needed from the oversheath, there are a number of properties that are required, such as good abrasion resistance, good processability, reasonable moisture resistance properties, and good stress cracking resistance. Experience has shown that the material with the best composite performance is a PE-based oversheath, though PVC, Chlorosulfonated Polyethylene and Nylon have been used as jacket materials. Tests on XLPE cables retrieved after 10 years of operation show that the mean breakdown strength falls by almost 50% (from 20 to 11 kV/mm – HDPE & PVC, respectively) when PVC is used as a jacket material. Many utilities now specify robust PE based jackets as a result. The hardness of PE is also an advantage when protection is required from termite damage.

Jackets extend cable life by retarding the ingress of water and soluble ions from the ground, minimizing cable installation damage and mitigating neutral corrosion. Ninety-three percent of investor-owned utilities in the USA specify a protective jacket. The semiconductive jacket or oversheath is recommended for high lightning incident areas or joint-use trenches where telecommunications cables co-exist with power cables.

The selection of the oversheath material and the cable design including water-swellable tapes or powders, has a strong influence on the water ingression rate from the outside of the cable to the conductor. A comparison of the physical properties of most of the most common jacket materials is given in Table 4.

Table 4 Physical Properties of Jacket Compounds.

Compound	Base Resin Density (g/cm^3)	Hardness (Shore D)	Moisture Vapor Transmission ATSM E 96 ($g/day/m^2$)
LDPE	0.92	43	1.16
LLDPE	0.92	45-48	0.74
MDPE	0.93	53-54	0.51
HDPE-1	0.941	-	0.58
HDPE-2	0.948	57-61	0.32
PVC	1.4-1.5	35-43	10

PRODUCTION TESTS

Production tests are conducted to assure that cables are good quality and made according to required specifications. Cable manufacturers conduct these tests before the cable leaves the factory. Most of the widely used cable standards [10,11] include production test procedures and requirements. However, it should be recognized that these tests represent the minimum requirements. Experienced cable makers will very often complement these minimum requirements with extra or extended tests (Figure 4) to provide additional assurance that the cable is well made. When considering production test programs the frequency of tests are equally as important as the tests themselves, especially when the periodic nature of the typical defects are considered.

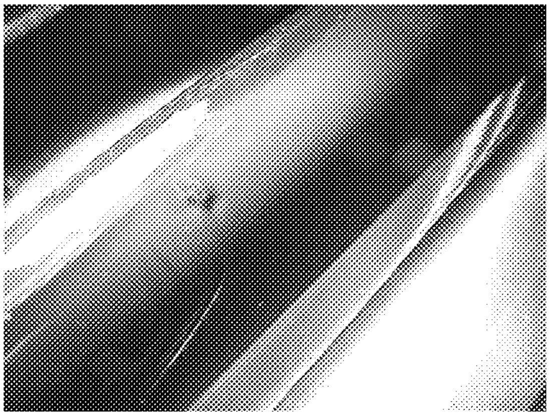

Figure 4 Conductor Shield Defect Revealed In A "Hot Oil" Test, When The Insulation Is Rendered Transparent.

Production tests are vitally important and must be taken seriously by the cable manufacturer <u>and</u> the user. These tests are the last chance to assure that the cable is made correctly and avoid the consequence of premature field failure. A user may specify high-quality, high-performance materials for use in the manufacturing processes. However, if problems occur during manufacture the cable performance may be severely compromised, leading to high replacement costs in the future. Some utilities require that a factory tests are supplemented testing at independent laboratories.

Cable standards and specifications prepared by the IEC, ANSI/ICEA, JEC and CENELEC [10,11] include a variety of production test requirements, as well as established long term aging test protocols for type or qualification of cables. Electrical production tests are performed on the entire production length, often by testing every shipping length.

PLANT AUDITS

Cable users often find great value in visiting the manufacturing plant that produces their cable. This confirms the purchaser's genuine interest in purchasing and installing a high-quality cable. It provides the opportunity for the purchaser to provide feedback to the cable manufacturer. The primary purpose is to better understand the complete manufacturing process and assure that the manufacturer is operating in the expected manner (conducting all required tests and has organized, uniform procedures, and that the plant is clean and well organized).

QUALIFICATION TESTS

Qualification tests is a very large subject and their details are the subject of many technical papers. Thus their detailed discussion is outside the scope of this paper [10 -13]. However they are the bedrock of high quality cables ; they provide the proof that the cable complies to with the requirements. Consequently it is important that a user statisfies themselves that cables are suitably qualified. Of equal importance is the need for users to verify that they remain valid in the light of the minor changes that can often occur in designs, manufacture, test methods and uses.

FIELD PERFORMANCE OF MV CABLES

High quality cables are required to assure that cable systems deliver the required reliability. Therefore having addressed various ways and means of ensuring quality (consistency, design, materials), we briefly review some relevant information from utility experience.

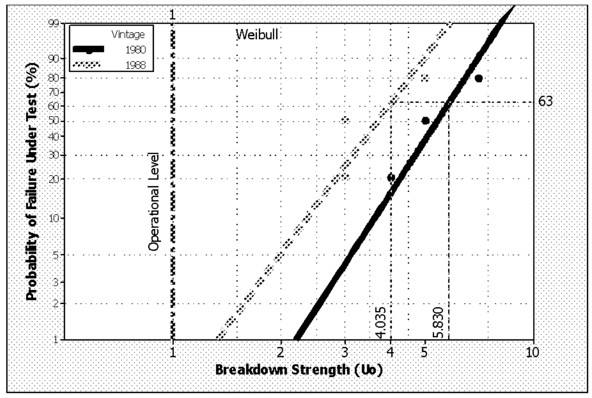

Figure 5 AC Step (Uo/5min) Breakdown Tests On XLPE Unjacketed Cables Identified As Poor Performers. Vertical Dashed Lines Show The Weibull Scale Parameter.

Figure 5 shows results from a study carried out in Sweden and Norway, to assess the condition of unjacketed cables made with Classic XLPE [9]. Diagnostic tests showed that a significant percentage of these cables had degraded dielectric characteristics. As a result, two 12 kV cables were removed from the Swedish network and subjected to ramp AC breakdown tests. The Weibull characteristic AC breakdown strength for these cables was between four and five times Uo, the operating service voltage. When they were new, these cables had AC breakdown strengths between 15 and 20 Uo. The breakdown strengths indicated that the cable insulations had deteriorated significantly as dissection, showed trees bridging the whole of the insulation. It is interesting to note that 1980 vintage cable has a higher dielectric strength than the 1988 vintage cable. This is an important observation which has been confirmed by many different utilities. Cables do not fail simply as a function of their age, but rather as function of their age, loading <u>and</u> quality.

In Germany, a great deal of cable failure data has been gathered in an attempt to understand cable performance. Figure 6 shows the in-service cable (insulation) failure rate for Germany as a function of the year of installation [1,13]. Early designs used poor-quality extrusion technology, taped semicon screens and XLPE insulations that were not nearly as clean as today's insulations. The data clearly shows the improvement in system reliability from the mid-1980's. This improvement has primarily come from the move to "Polymer" WTR-XLPE insulations.

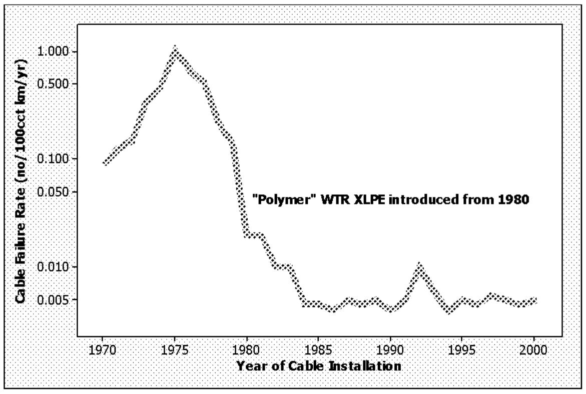

Figure 6 In-service Cable (Insulation) Failure Rate for Germany as a Function of the Year of Installation [1,13].

One element that is missing from Figure 6 and most analyses in the literature is a representation of the relationship to the amount of cables installed in each year. Much more cable was installed in 1995 than in 1985. The importance of this concept can be seen in a USA study. At TXU Electric, a large utility located in Texas, an extensive analysis was conducted on their MV cables to understand how they have performed [1,14]. These cables were installed in the 1970's and early 1980's. One method of analyzing the data, which allows for the amount of cable installed as well as its age, is provided in Figure 7. In this graph, the x axis is the cumulative product of the amount of cable installed in a given year and the number of years that the cable was in service (∑ cable length x cable age for each year) [1]. A constant gradient shows a constant failure rate, however a downward curvature (lower gradient) shows a lower failure rate.

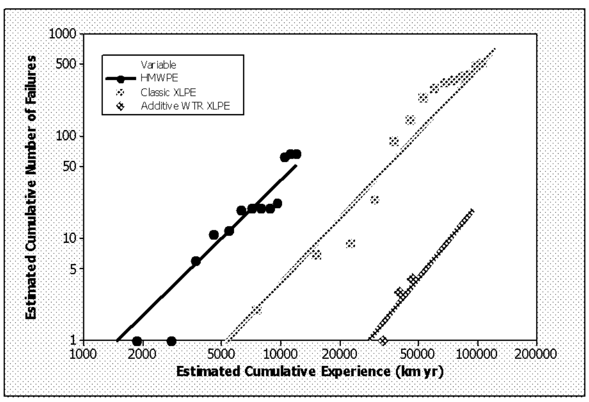

Figure 7 Failure Data for Three generations of MV Cables Installed at TXU.

The figure is best understood by examining the km-year value for a given number of failures for each cable design, for example 30 failures occurred after only 9,000 km years for HMWPE. It took 22,000 km years for the XLPE cable to experience 30 failures. Furthermore, the graph enables predictions to be made, for instance it will likely take over 100,000 km years before 30 failures will occur on the "Additive" WTR-XLPE cable.

Figure 6 & Figure 7 provide dramatic and practical examples of how cable performance has improved for each new generation of cable, from the original thermoplastic cables to the Classic XLPE, to more modern WTR-XLPE cables. These performance improvements are responsible for the current trend of installing cables with WTR-XLPE insulations in preference to Classic XLPE - shown by Figure 6 after 1990.

CONCLUSIONS

Achieving a long cable life using XLPE compounds is not difficult. However it does require attention to details that may, on the surface, appear to bring little immediate benefit. The purpose of this paper is to outline some of the most common practices that can help industry and electric utilities obtain a cost- effective XLPE-insulated cable with long, reliable service life. The most critical element within the whole process is the awareness of Quality Issues and its ultimate value within the Utilities.

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