MAINTENANCE & TEST ENGINEERING, LLC

Medium Voltage XLPE Cable RCM Analysis

Executive Summary:

A medium size utility has a large installed population of second generation Cross-Linked Polyethylene Cables (XLPE) insulated cables operating at both 13.8 kV and 34.5kV. The vast majority of these Medium Voltage XLPE cables have been in service since the early 1980's and are approaching 35 years old, the age most utilities consider their nominal service life. The failure rates for these cables has been increasing in recent years.
An RCM (Reliability Centered Analysis) was undertaken by a group of experts from the utility and Maintenance and Test Engineering LLC. This analysis was triggered by:

- Concerns that this aged population may be reach its end-of-service life.
- Degradation of the utility service reliability and availability metrics, SAIFI and SAIDI, because of the increasing number of in-service failures.
- Manhole degradation and water ingress.
- A need for a comprehensive approach for managing cable lifecycle.

The utility's cable experiences are like many utilities around the world. Challenges confronting Utilities around the world include:

- Large distributed infrastructure that is costly to maintain and replace.
- Extreme difficulties in determining cable condition and remaining life.
- Severely limited number of technical and economic options for renewing cable life.

The utility does have two conditions that make the lifecycle management of cables easier:

- The population is homogeneous allowing for a statistical approach for predicting cable life.
- Installation in duct banks greatly reducing the operational, customer and economic impacts associated with a replacement and maintenance program.

The results of the RCM analysis are based on guidance from Subject Matter Experts (SMEs), The utility trouble and failure data, utility industry best practices and a team consensus. The analysis revealed that:

- Failure rates will continue to increase as the cable ages, a failure/aging model was developed that correlates very well with historic failure experience.
- A life limit should be placed on the current population of 2nd generation cables. This recommended limit will allow the utility to better manage the impacts of a failing cable population. Replacement of the current populations should be planned with those cables representing the highest risk being replaced first.
- A series of condition cable assessment tasks are recommended as part of the utility's cable maintenance program. These tasks are to be applied to all new cables to monitor the aging process. They should also be applied to the current aged cable population on a limited basis as a feedback mechanism for the cable aging/failure model.

- A series of recommended maintenance tasks are to be performed on the other elements of the underground system including manholes, joints/splices, earthing system and terminations.

The RCM analysis also identified other opportunities for improving service reliability. These opportunities include:

- Performing a transient voltage study to determine the benefit of installing surge arresters on the underground.
- If installation of surge arresters is of merit, elbow specifications should incorporate arresters.
- Perform quality audits on cable manufacturers to ensure cable of the highest quality is delivered.
- Validate proper installation practices are followed when cables are replaced.

Executives are reminded that the recommendations being made by the RCM team are based on the best technical and operational information available now. While the next generation of XLPE insulated cables promise to have better performance, they need to be managed throughout their whole life, from time of procurement to end-of-service life replacement. This dynamic management will undoubtedly reveal new information or be presented with new technologies and opportunities that must be prudently adopted and integrated into a "living" RCM program.

Introduction:

The utility strongly desires to improve the reliability of its electric network, and while their SAIFI (System Average Incident Frequency Index) and SAIDI (System Average Incident Duration Index) reliability and availability metrics are like most North American utilities, there is room for improvement. The single largest contributor to electric service unavailability is medium voltage cable failures (see **Error! Reference source not found.**). The vast majority of these failures are from second generation cable designs having XLPE (Cross-Linked Polyethylene) insulation systems, currently this cable population exceeds 30 years of age.

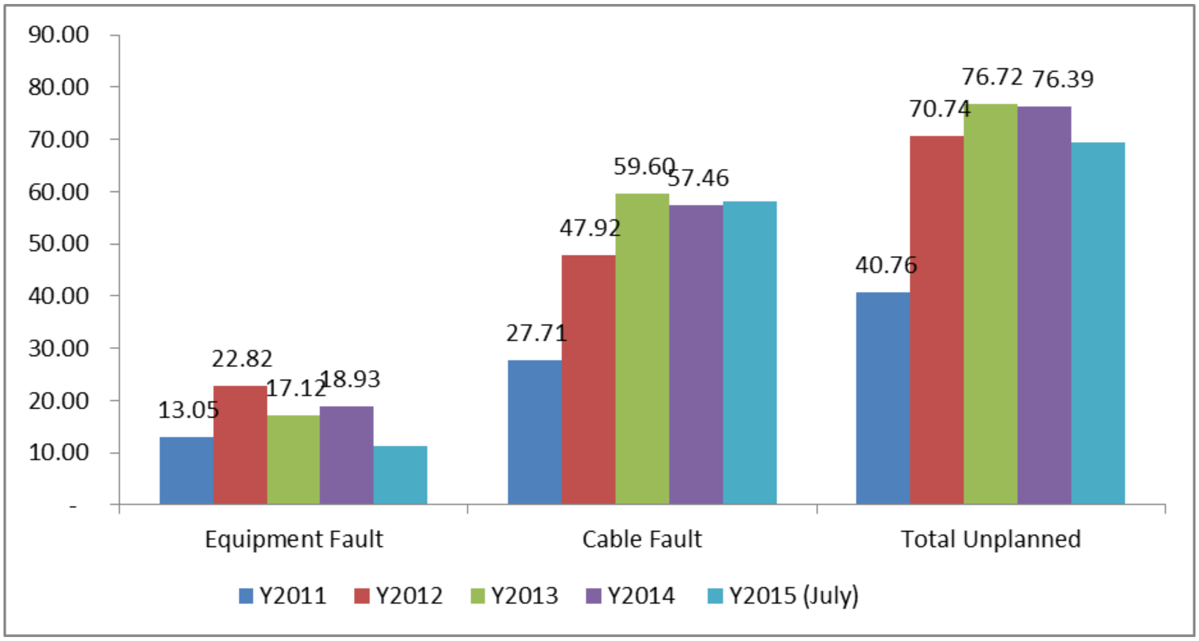

Figure 1: Figure 1: Unplanned Outage Duration Years 2011-2014

This document summarizes the RCM based management strategy for Medium Voltage Cross-Linked Polyethylene Cables (XLPE) nominally rated 15 kV and 35 kV operated by the utility. While this maintenance strategy is targeted at XLPE cables, with a little work, it can be adapted to Polyethylene Cables with Tree Retardant (TR-XLPE). Successful implementation of this maintenance strategy will result in an effective XLPE Cable assessment and maintenance program that contributes to the following goals:

- Safely maximizes the life of the utility's XLPE Cables.
- Optimizes cable ratings.
- Takes advantage of new technology that will provide valuable efficiencies
- Reduces risk.
- Satisfies the needs of Stakeholders and Customers.
- Serves as a basis for an optimal maintenance and replacement plan.

This maintenance plan is based upon:

- Industry best practices
- Manufacture recommendations
- Technical seminar and documentation provided by Kent Brown a cable specialist and independent consultant
- The utility Engineering and Operations Experience
- Cigré technical brochures

The maintenance plan for XLPE Cables is intended to be a living document. Revisions may be based on one or more of the following:

- Changes in the utility's business practices
- New or revised rules and regulations that apply to medium voltage cables
- Changes in industry best management practices
- Market forces (e.g., new materials, unavailability of products)
- Changes in the cable’s risk profile.

List of Acronyms:

The following acronyms are used in this document:

Cigré- Conseil International des Grands Réseaux Électriques
DF-Dissipation Factor
IR-Infrared
kV-kilo Volts
PF-Power Factor
PI- Polarization Index
RCA-Root Cause Analysis
RCM-Reliability Center Maintenance
SAIDI-System Average Incident Duration Index
SAIFI-System Average Incident Frequency Index
SME-Subject Matter Expert
TR-XLPE-Tree Retardant Crossed Linked Polyethylene
XLPE-Crossed Linked Polyethylene

Asset Description:

Second generation XLPE cables were manufactured in the 1980's. While similar to today's medium voltage cable, their design and manufacturing process were much less refined thus not meeting life expectations. Major differences between second generation cables and the current generation (see Figure 2) are:

- Lower quality (dirty) base material used by manufacturers
- Poorer extrusion process
- Higher susceptibility to water treeing
- Insulation shields or screen were not super smooth

Most of the utility's cables are installed in duct and while they are radially fed, with minimal switching, they can be removed from service without impacting the customer.

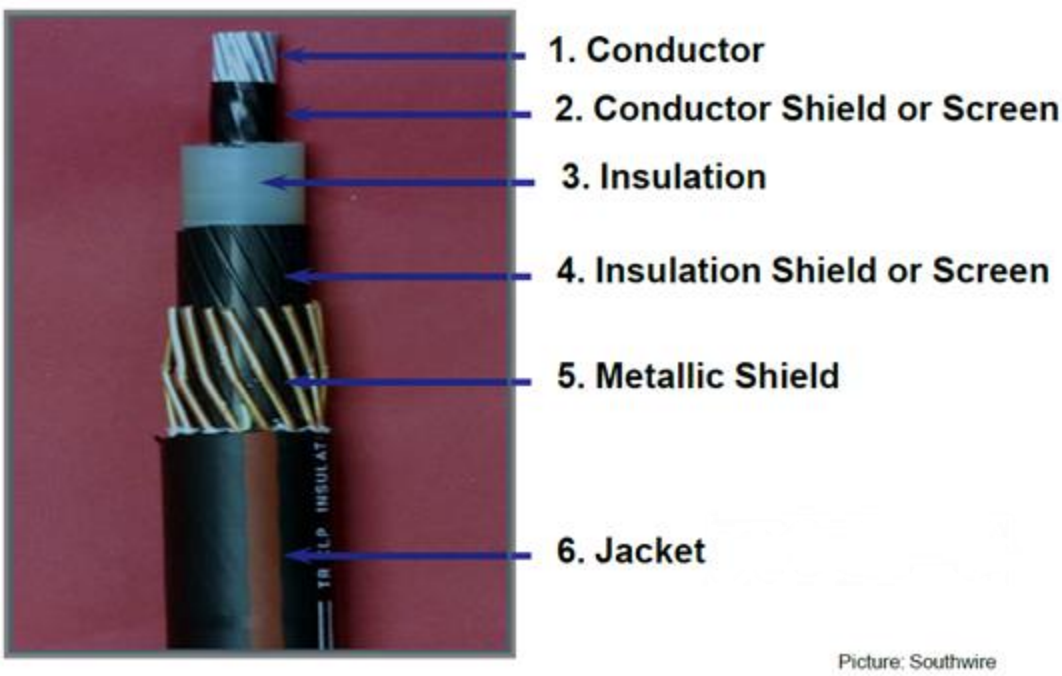

Figure 2: Typical Third Generation XLPE Cable

Electrical Description:

Most of the utility's XLPE cables were installed during a three (3) year period at the utility are of similar design. The average length of each segment is 200 meters. General characteristics of these cables are:

- Operating Voltage: 13.8 kV and 34.5 kV
- Populations:
  - 6,225 (15 kV system)
  - 1,014 (35 kV system)
- BIL: 110 kV (15 kV system)
  200 kV (35 kV system)

- Manufacturers: Sumitomo
  Kabel & Draht
- Years of Installation: 1980-1982 (Majority)
- Copper conductor Size:
  70 mm^2
  95 mm^2
  120 mm^2
  150 mm^2
  185 mm^2
  300 mm^2
- Conductor Screen: Semicon
- Insulation: Cross-Linked Polyethylene
- Insulation Screen: Semicon
- Metallic cable shield
- Jacket/Oversheath Material: PVC

Failure History:

Initially, medium voltage XLPE cables provided the utility with good performance having very low annual failure rates for their first 15 to 20 years of operation. At approximately 15 to 20 years of age, failure rates began to rise (see Figure 3 and Figure 4 below).

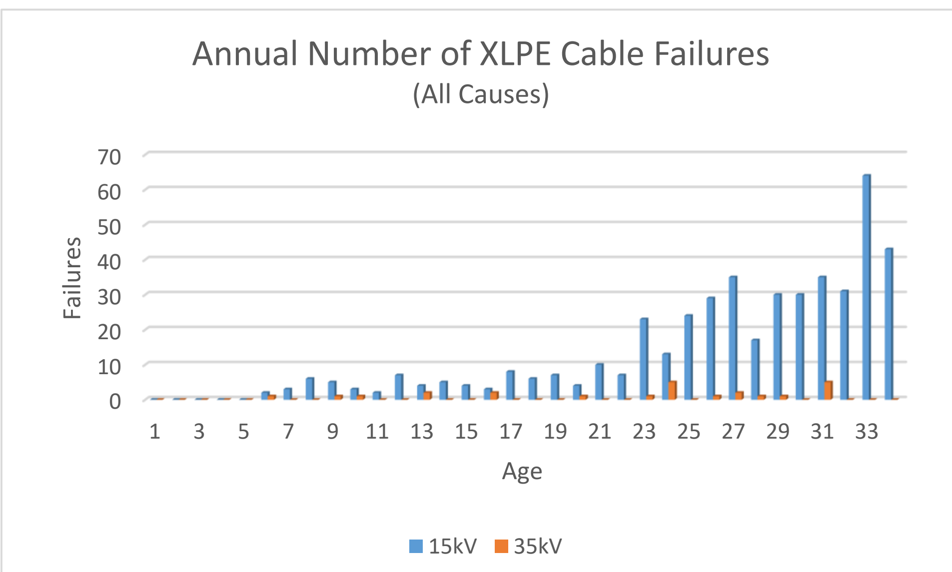

Figure 3: Annual Number of Failures for MV XLPE Cables as a Function of Age

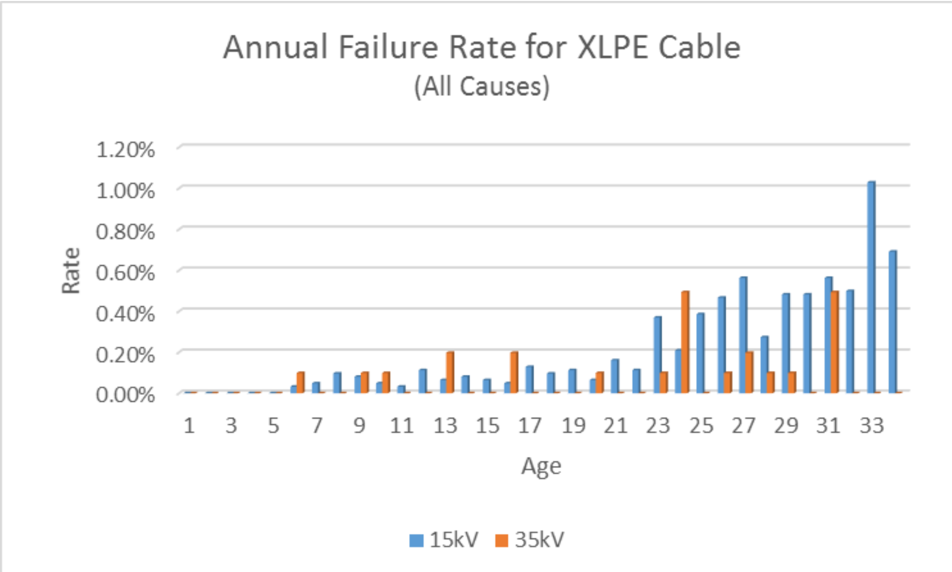

Figure 4: Annual Failure Rates for MV XLPE Cables at the utility

Application of RCM to MV XLPE Cables:

The goal of an RCM (Reliability Centered Maintenance) plan is ensure critical asset functions are highly reliable and available to operations. To meet this goal, a maintenance program must be identified that is both technically and economically effective. RCM based maintenance programs have four general task types:

Condition Assessment:
The condition of a function is determined either continuously or periodically, when significant deterioration has taken place, a condition directed task occurs that returns the function to a "like new" condition. Condition directed tasks can include:

- Overhaul or rebuilding
- Replacement of worn components
- Upgrading or modernization
- Retirement of the asset and full replacement

Condition assessment generally allows for maximum utilization of an asset at the lowest maintenance cost.

Periodic Renewal Maintenance:
Maintenance renew or replacement tasks that are performed on a fixed interval with no condition assessment. The failure mechanism is generally well known and very predictable, renew or replacement tasks occur well before functional failure.

Hidden Failure Finding:
The function is normally extremely reliable and its failure mechanism is not readily observable by operations. The function is tested on a "go/no-go" basis. Failure of the functional test results in immediate corrective action.

Corrective Maintenance:
Functional failure can occur with only a minor impact on operations. The cost of corrective maintenance is less than the cost of prevention.

RCM Analysis:

A complete FMEA (Failure Mode and Effect Analysis) with RCM task selection was performed in June and July 2015 for Medium Voltage XLPE High Voltage Cable Systems and documented in an Excel RCM Workbook. Included in the system analysis was:

- MV XLPE 15 and 35 kV Cable
- Cable Corridor
- Joints/Splices
- Terminations
- Manholes

The analysis identified five (5) critical functions that were to be of the highest reliability with the recommended maintenance program designed to prevent functional failure:

- Conduct rated current
- Maintain boundary integrity
- Provide cable testing provision
- Provide electrical earthing connectivity
- Provide rated dielectric/insulation

Key Findings:

The dominant mode of medium voltage cable failure experienced by both the utility industry and the utility is:

"Fails to provide rated dielectric strength/insulation integrity"

The dominant mode of other parts of the cable system (manholes) experienced by the utility is:

"Fails to maintain boundary integrity-water ingress"

Application of RCM techniques to manage this mode of failure resulted in challenges including:

- Condition assessment tasks are not fully effective in identifying incipient insulation failures.
- Insulation renewal tasks are not economical.
- Failures are readily observable so hidden failure finding tasks are not applicable.
- Run-to-failure/corrective maintenance is unacceptable to operations and customers.

Modern medium voltage cable systems are designed to have a life of 40 or more years, consistent with most other T&D equipment. Previous generations of medium cable systems had significantly shorter lives due to the inherent design and manufacturing of the cable insulation system. While the dielectric aging and failure mechanism of MV XLPE cable is well understood by the industry, it is difficult to economically reverse or slow down. Techniques like silicone injection have proven to be technically feasible, their economic feasibility is limited to direct buried installations where cable replacement cost are quite sizable.

Understanding the amount of aging that has occurred to these systems over the past 35 years provides a basis for predicting remaining life and is an ongoing challenge to the utility and thus an important element of this RCM study. Unfortunately, because of their long length and inaccessibility, direct electrical and visual condition assessment is extremely challenging. A microscopic section of contaminated insulation or localized water trees are masked by all the good insulation, very difficult to detect and yet can result in dielectric breakdown.

Fortunately, because the utility's cable population is large and fairly homogenous, a statistical approach to life management is possible.

Asset Life:

The utility industry does not have standardized/exact definition of the expected life of an asset should be, instead it leaves it up to the specific utility to determine when end-of-life occurs. Most utilities will agree that asset life is the lowest expected life for a selected asset given its operating environment where that life is derived from a determination of the most imminent trigger among the five asset life triggers

- Service level life-period of time an asset will be in service.
- Capacity life- the period of time before the demand placed on an asset exceeds its design capability.
- Physical life – the time before an asset is physically non-functioning or failed, this is generally the longest of all five triggers.
- Economic life – the period in which the asset returns more value to the utility than it costs to own, operate, and maintain.
- **Depreciable life** - the time period over which an asset can lawfully be depreciated.

For XLPE cables, service level life is generally used to describe the expected life of the cable, the operating time the cable can meet customer's reliability expectations. Service life is significantly less than the cable's physical life.

Weibull Failure Model:

The Weibull distribution is widely used for life analysis. The Weibull probability distribution was first developed in 1951 and since that time has been used widely by equipment manufactures to predict failure rates, warrantee replacements and to identify unique modes and causes of failures. The Weibull Wear model is based on the assets physical life. Predicting an asset's physical allows one to better manage both the assets service and economic life.

The Weibull model can answer two critical questions routinely asked by utility executives and asset managers:

1. "How many failures do I expect during a specific period of time?"
2. "Is the rate of failure increasing, decreasing or staying steady?"

The Weibull Equation

The Weibull cumulative probability function has an explicit equation:

$$F(t) = 1 - e^{-(t/\eta)^{\beta}}$$

Where: F(t) = fraction of the population failing
t = failure time
η =characteristic life
β = slope or shape parameter

When will Physical End-of-Life Occur?
Most assets, including cables, don't fail at the same time, some fail soon after installation (infant mortality), others operate for a very long time and the rest of the asset population fails at some time in-between. For a large population of assets, the Weibull model will predict when an accumulated percentage of the population will have failed, typically asset managers are interested in the time it takes for accumulation of 1% to 2% of the asset population to reach their physical end-of-life.

Will Assets Fail Faster than They Can Be Replaced?
It is understood that even with the best design, manufacturing, installation and operating efforts, assets will eventually fail. Some failure can be prevented through maintenance or planned retirement. Unplanned replacement of an asset is challenging to manage, especially if the rate of failure is increasing. The Weibull failure model predicts how failure rates change as the asset population ages. Knowing future failure rates allows asset management to ensure they have a proper mix of resources to repair and replace cables.

Weibull Software:

Weibull Smith™ software developed by Fulton Findings was used in this analysis. The software allowed for the easy loading of data. Two general types of data were entered for each cable subpopulation:

- Failures-For the specific mode of failure, dielectric/insulation failure, the age of each failed cable was imported into the analytic tool.
- Suspension-The age of every cable that had not failed was imported into the tool. The age was based on the cable installation date (1980-1982)

The WeibullSmith™ software was used to both to create Weibull plots and compute the above parameters. The plots provide an easy visualization of the reliability of the asset. Three critical concepts to understand to when looking at the results/graphs generated by the WeibullSmith™ software are:

- When the data on a Weibull forms a straight line, one cause of failure is generally dominant, if the plot has a "dog leg" more than one cause of failure is occurring.
- η or the characteristic life is the time at which 63% of the population of modules under analysis are expected to have failed.
- β or the shape parameter describes the rate of failure (see Figure 5 below):
    - β < 1 indicates failures are decreasing with time
    - β = 1 indicates the failure rate is constant and failures are random
    - β > 1 indicates the failure rate is increasing with time

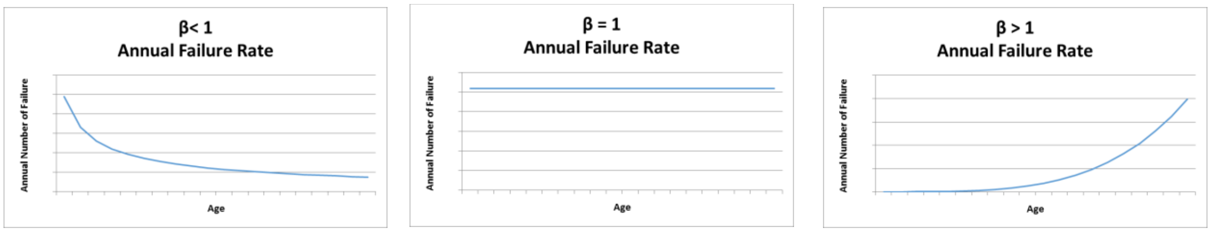

Figure 5: Annual Failure Rates for Different Weibull Shape Parameters (β)

MV XLPE Aging Model:

The utility has done an excellent job of recording cable and joint failures and separating the major causes of failure:

- Cable insulation failures
- Cross phasing
- Dig-ins
- Fallen Concrete
- Joint failures
- Terminations

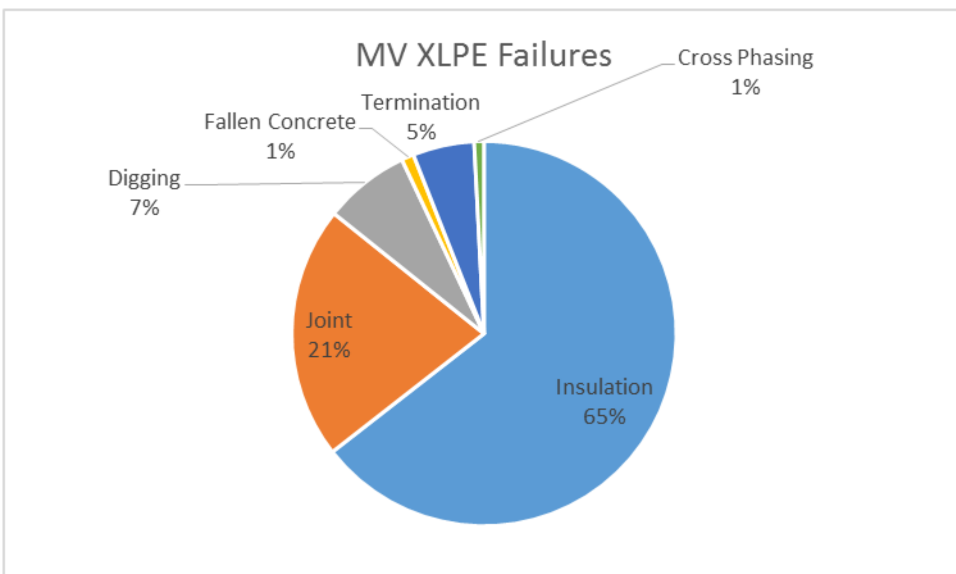

Figure 6: Failure Cause Distribution for 15 and 35 kV MV XLPE Cable

For each of the above causes of failure, failure data for 15 kV and 35 kV XLPE cable was provided by the utility's Power Transmission & Distribution Technical Support Department. Data for the dominant cause of cable failure - insulation failure (see Figure 6 above) was analyzed using WeibullSmith Software and the results are graphed below in Figure 7 below.

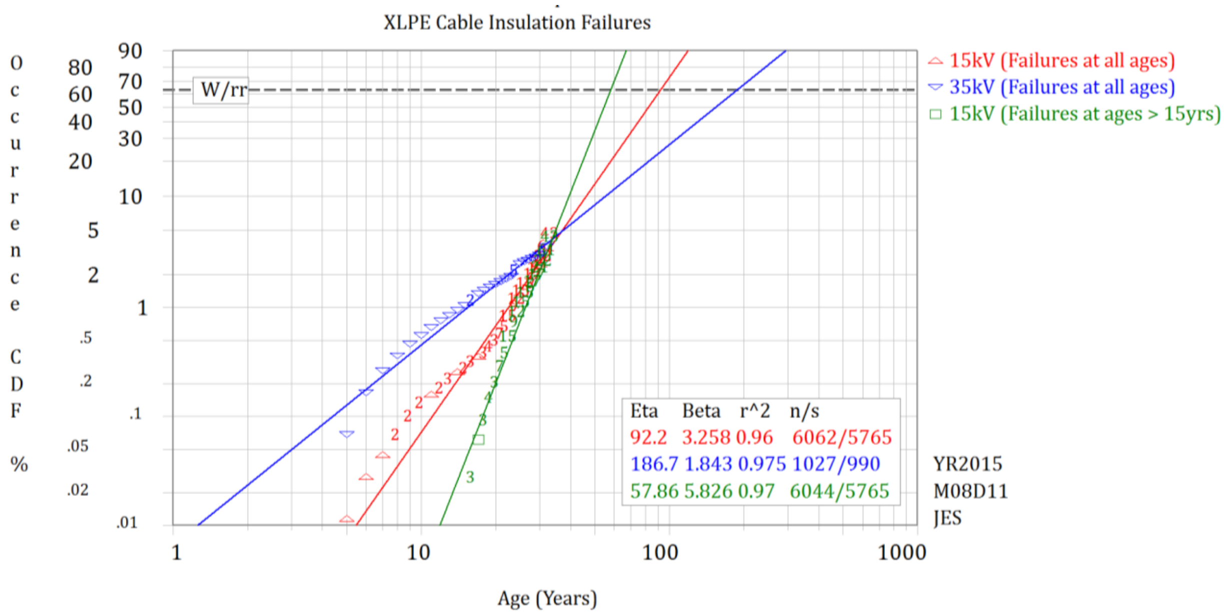

Figure 7: Plot of Weibull Cumulative Density Function for Second Generation MV XLPE Cables

The results of the Weibull analysis of second generation XLPE cable insulation failures revealed:

- XLPE insulation fails at a predictable rate.
- 35 kV cable insulation performs better than 15 kV cable insulation (the Eta for 35 kV cable is twice that of 15 kV Cable).
- The insulation failure rate of both 15 kV and 35 kV increase with age, 15 kV insulation failures have a very pronounced aging characteristic (large beta).
- It appears that two insulation failure mechanisms are occurring on 15 kV cable, the first at age 15 years and less and the second at ages older than 15 years.
- The Weibull model correlates very well with the insulation failure data, failure data correctly distinguished dominant failure modes.

Future Failure XLPE Failure Rates

The Weibull model predicts increasing failure rates for both the utility's 35 kV and 15 kV cables. The increase in failure rates for 15 kV cables will be substantially more dramatic. Failure rates for 15 kV are cables are expected to increase (see Figure 8 below) and can only be managed by a replacement program.

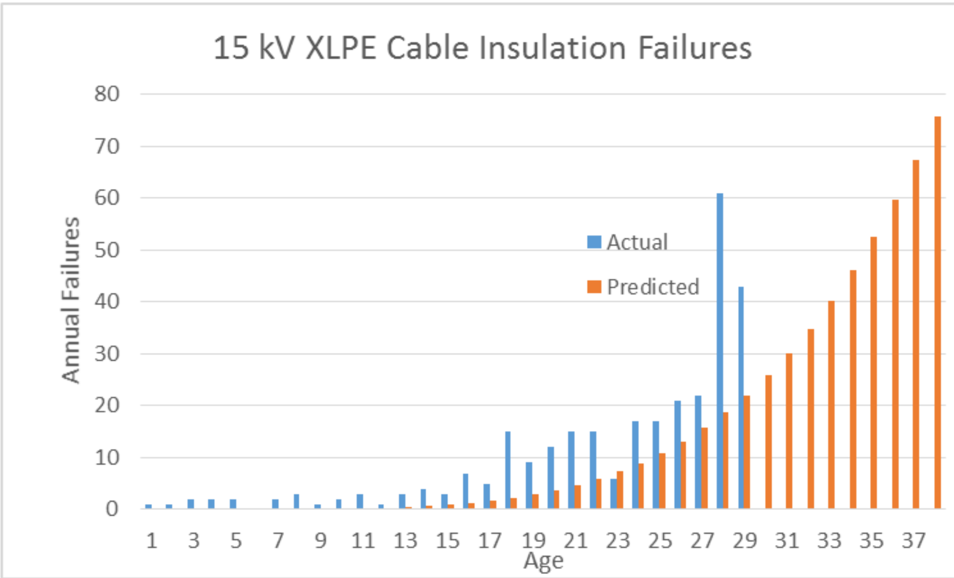

Figure 8: Comparison of Predicted 15kV Insulation Failures to Actual

Summary of RCM Based Maintenance Recommendations:

Both historical failure experience and Weibull analysis support setting a life limit on all medium voltage XLPE cable. Replacement of this cable population should be planned and prioritized based on risk. Those cables most likely to fail and having the greatest failure consequence should be replaced first.

While most XLPE cables were installed in a three-year time span, replacement will probably take place over a longer time period. To optimize expenditures, manage budgets, control quality and minimize failure impacts on customers, cable replacement must be thoughtful and planned.

Periodic Condition Assessment and Maintenance:

Historical failure data, practical engineering experience and the Weibull model are all in agreement and predict that the condition of XLPE cables will continue to deteriorate. The utility has performed condition assessment on in-service XLPE cables on sample basis. This assessment provides a good relative indication of each cable and is an essential element of risk-replacement decision activity. Additional assessment of cable condition, while probably interesting, will add little to the utility's overall XLPE cable knowledge.

Routine cable assessment activities recommended below are for replacement cable only, assessment of some existing 2nd generation XLPE cable is recommended to take place when opportunities are available. The "opportunity based" program is meant to:

- Keep technician skills at a high level
- Provide actual validation of the failure model as engineers should be able to track insulation deterioration.

Continuous Monitoring:
There currently are no significant continuous monitoring activities taking place on medium voltage cables. Monitoring feeder loads will prevent the overloading of cables exiting the station but does not give detailed insight into the loading of downstream cables.

Periodic Documented Condition Assessment:
On-line Condition Assessment Tasks-6 Months:
- Perform Infrared inspection of station terminations

On-line Condition Assessment Tasks-12 Months:
- Survey inspection of cable vaults and manholes

Off-line Condition Assessment Tasks-24 Months (Random Sampling of Replacement Cables):
- Tan Delta Measurement
- Cable Polarization Index
- Sheath Insulation Resistance

On-Condition Diagnostics and Maintenance:

On-condition or corrective maintenance will occur when:
- A defect is identified during routine inspection
- Condition Assessment task has identified severe deterioration of a function, i.e.:
  - Hot spot
  - High Tan Delta
- Detailed inspection of deteriorated/failing cable vaults and manholes identified by survey inspection.
- Corrective maintenance of cable vaults and manholes problems found through detailed inspection.

Design Improvements

Traditionally, underground networks works were believed to be protected from lighting and thus the installation of lightning arresters was thought to be unnecessary. It has been found that destructive voltage surges are generated in the network as the result of switching and cable faults. These surges, over time have an accumulative effect and contribute to cable, splice, termination and transformer failure. Mitigation of these surges can occur with the installation of surge arresters at key network nodes. It is recommended that a transient analysis be performed on a sample portion of the utility Distribution Network to determine:

- The technical and operational value of installing underground surge arresters
- Typical installation locations where underground surge arresters will have the greatest effect,

End-of-Life Determination:

A cable and its accessories will be identified as being at end of life and thus replaced when:

- Age exceeds a life limit set by the utility based on allowable failure rates.
- In-service insulation failure occurs
- Condition assessment shows excessive deterioration:

- High Tan Delta
- Low Polarization Index (PI)
- Low Jacket/Oversheath Insulation Resistance.

Vaults and manholes will be determined to be at end-of-life when detailed inspections reveal that their structural capabilities have deteriorated to a point where repair is technically, operationally or economically not practical.

Prioritization of Cable Assessments:

A risk assessment can be made for all cable segments. This assessment can be qualitative and make use of a Risk Matrix similar to that shown in Figure 2 below.

Likelihood			
Very Likely	Medium 2	High 3	Extreme 5
Likely	Low 1	Medium 2	High 3
Unlikely	Low 1	Low 1	Medium 2
	Minor	Moderate	Major
	Impact		

Figure 9: MV XLPE Risk Matrix

Elements used qualifying risk are:

- Likelihood
    - Condition Assessment Findings
    - Installation environment
    - Loading
- Impact
    - Load interrupted
    - Outage duration
    - Customers served

Cables ranked as extreme or high risk are to have the highest replacement priority, cables ranked as minor will have the lowest replacement priority. Cables ranked as medium risk will be replaced based on opportunity and efficiency. Medium ranked cables located in close proximity to high priority cables should be replaced along with the high priority cables to take advantage of logistic and scheduling efficiencies.

A detailed risk based replacement plan should be developed and documented after the utility management agrees an age limit is to be applied to the maintenance and replacement strategy for MV XLPE cables.

RCM Documentation:

Detailed documentation can be found in the Excel RCM Workbook for XLPE Cables.

Other RCM Opportunities:

The RCM approached used in this analysis can be also applied to distribution assets including:

- Pad-mount Transformers
- Pad-mount Switchgear