ELECTRIC POWER RESEARCH INSTITUTE

Plant Engineering: End-of-Life Guide for Medium-Voltage Cables and Accessories

2012 TECHNICAL REPORT

Plant Engineering: End-of-Life Guide for Medium-Voltage Cables and Accessories

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1025259
Final Report, October 2012

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Acknowledgments

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Plant Engineering: End-of-Life Guide for Medium-Voltage Cables and Accessories. EPRI, Palo Alto, CA: 2012. 1025259.

Abstract

While there are relatively few medium-voltage circuits in a nuclear plant, many supply a significant load or link the plant to offsite or emergency power. Therefore, if some circuits fail, a train of a safety system may be lost, a reactor trip may occur, or a limiting condition for operation may be entered. Failures of some medium-voltage cables, such as those associated with an offsite power feed, may lead to a plant shutdown. Repair and replacement of a medium-voltage cable can take a week or more and becomes complicated if spare cable, terminations and splices, and a trained installation crew and their equipment are not available.

This report describes how cables age, how they can be tested and assessed, and the logistics associated with their repair and replacement. Medium-voltage cables do not all age at the same rate, nor do they all fail at the same time. However, depending on the type of installed cable and the service conditions, some aging failures may be expected for wet cables when the plant is between 25–35 years old and beyond. Accordingly, periodic testing of underground circuits is recommended to identify degraded cables to allow repair or replacement. While dry circuits are expected to age very little if they are located in benign environments (50°C [122°F] with no oil, hydraulic fluid, or chemical exposure), terminations may dry out and age electrically for circuits in operation for very long periods. Partial discharge assessment (radio or audio assessment techniques) may be necessary when plants are near the end of their first license renewal period or have entered a second license renewal period (that is, beyond approximately 55 years of service).

Keywords
Cable replacement
Cable testing
Long-term operation
Medium voltage cable

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Section 1: Introduction

Medium-voltage cables are rated from 5 to 46 kV. In nuclear plants, most medium-voltage systems operate at discrete voltages between 4.16 and 13.8 kV, depending on the utility's preference and the age of the plant. Plants constructed before the mid-1970s tend to have 4.16 kV systems, and plants built after the mid-1970s tend to have 4.16 and 13.8 kV systems with very large motors, such as circulating water pumps powered from the 13.8 kV buses and general distribution and safety loads from the 4.16 kV systems. Some plants have 6.9 kV and 12 kV systems. Some plants have offsite feeds with site-specific voltages between 20 and 45 kV.

Medium-voltage cable systems are composed of cables and accessories along with supports and housings such as trays, conduits, and underground ducts. Accessories include terminations and splices. Although in-plant medium-voltage cable circuits rarely have splices, splices are quite common in long underground circuits because long lengths of medium-voltage cables were too large to fit on single reels for transportation. Splices, if properly made, should outlast the cable because they are designed with extra insulation thickness. However, installation errors are fairly common in splices such that deterioration over time is possible, especially under wet conditions.

Early failures (the first 5–10 years) occur due to gross manufacturing flaws or installation errors. Long-term failures (after 25–30 years) often involve a flaw or installation error coupled with a voltage stress enhancer, such as temperature or water. Longer-term failures are likely from stress enhancers and duration of service.

At the time that nuclear plants were being constructed, polymer-insulated cable design and manufacture was maturing. Some of the designs that were available used older materials (butyl rubber and black ethylene propylene rubber [EPR]) and shields (cotton or polymer tape) that were problematic or less satisfactory than later systems. Also, materials that were thought to be perfect solutions, such as cross-linked polyethylene, were found to age more rapidly due to manufacturing flaws and contaminated feed stock. With time, butyl rubber was supplanted by black EPR, which in turn was supplanted by pink EPR. Semi-conducting tape shields were supplanted by extruded polymer shields. Multiple step applications of semi-conducting shields and insulation were supplanted by single-pass extrusion processes. Each of these steps led to cables with improved longevity.

There are two specialty medium-voltage cable designs used in the industry: One that has long life expectations and one that has experienced a significant number of early failures. One manufacturer, Kerite, employs an insulation that is discharge-resistant as opposed to discharge-free that other manufacturers use. The insulation is brown and has had no wet aging-related failures to date in nuclear service.

The other specialty design is a compact cable that has thinner EPR insulation and a semi-conducting jacket that also functions as the insulation shield. The overall diameter is similar to that of a cross-linked polyethylene cable. Six corrugated drain wires are located in the jacket. A number of failures have occurred under wet conditions. Some were associated with corrosion of the drain wires that led to partial discharge.

Recent research indicates that the water-related failures are likely from swelling of the semi-conducting jacket and semi-conducting shield. The carbon fill of the semi-conducting jacket and the semi-conducting shield causes them to be hydrophilic. They swell when they take on water. The circumference and inner radius of the semi-conducting layer increase, which results in delamination of the insulation-to-jacket interface causing high stresses at the surface of the insulation with moisture to support deterioration of the insulation and ultimate failure. This compact design is the only cable type in nuclear use that has a semi-conducting jacket bonded to a semi-conducting shield and, therefore, is the only design that this failure mechanism applies to.

Table 1-1 summarizes the types of cables in use and provides a rough indication of their prevalence. Plant records indicate the style of cable used. Most plants have a single supplier for their original medium-voltage cable; however, most plants have both shielded and non-shielded cable. The shielded cable is generally used in non-safety applications, but may be used for safety applications as well. Many plant designers used non-shielded cables with thicker layers of insulation (133% or 177% of standard thickness) for safety systems. Those safety systems were designed to operate with a single line-to-ground fault under accident conditions. This ability did not cause an immediate loss of a safety function train if a cable failed during accident service. However, if such a failure occurs under normal service, continued operation is not recommended because a line-to-ground fault can convert to a phase-to-phase fault that causes very high currents to flow and can lead to extensive damage to connected equipment.

Table 1-1
Cable insulations and configurations

Insulation	Metal Shield	Semi-Conducting Insulation Shield	Frequency of Use	Period of Installation
Cross-linked polyethylene (XLPE)	Metal tape shields	Cotton or polymer tape (very early 1970s); extruded thereafter	Limited number of plants	
Butyl	Metal tape shields	Cotton or polymer tape	Limited number of plants	Late 1969s, early 1970s
Black EPR	Metal tape shields	Cotton or polymer tape	Many early plants	Early to mid-1970s plants
Brown EPR - discharge-resistant	Metal tape shields	Cotton or polymer tape (very early 1970s); extruded thereafter	Some plants	Early 1970s to mid-1980s; available until ~2008
Pink EPR	Metal tape shields	Extruded polymer	Many later plants	Mid- to late 1970s to present
Black EPR - UniShield compact design	Six drain wires	Extruded polymer (two layers; no outer jacket)	Some plants	To mid-1970s
Pink EPR - UniShield compact design	Six drain wires	Extruded polymer (two layers; no outer jacket)	Some plants	Late 1970s to present
Black EPR	Non-shielded	None	Many early plants (safety systems)	Early to mid-1970s plants
Brown EPR - discharge-resistant	Non-shielded	None	Many early plants (safety systems)	Early 1970s to mid-1980s; available until ~2008
Pink EPR	Non-shielded	None	Many later plants (safety systems)	Mid- to late 1970s to present
Paper-insulated lead-covered	Not applicable	Not applicable	Rare (one plant as 4 kV cables) Some plants (offsite feeds)	Late 1960s (Note: These cables have been in use in non-nuclear applications since the early 1900s.)
XLPE or EPR	Concentric neutrals	Cotton or polymer tape (very early 1970s); extruded thereafter	Some plants (offsite feeds)	Mostly prior to startup

Table 1-1 lists two distinct types of cables: non-shielded and those with an insulation shield. Shielding on a medium-voltage cable serves many purposes:

- The insulation system is at an equal potential circumferentially and longitudinally.
- The insulation shield eliminates surface discharge between the insulation and surrounding materials.
- The insulation system can be tested electrically between the shield and conductor.
- If the shield is properly grounded, the surface of the cable is a ground potential, improving personnel safety.
- Electrical noise is reduced.

Even though insulation shields have a number of benefits, many plant designs used non-shielded cable for safety-related circuits. The designers purposely chose a non-shielded system to allow continued operation under accident conditions should a phase become grounded. Operating with a grounded phase is not appropriate under normal conditions because if a second phase fails to ground, very large fault currents will flow that can cause severe damage to the connected equipment. However, under accident conditions, being able to function with a single fault is worth the risk and allows time for rearranging the electrical system.

Non-shielded cables have 33%–77% thicker walls to cope with higher voltages across the insulation walls of the non-failed phases under fault conditions. This additional wall also reduces voltage stress in the insulation and may slow aging under wet conditions.

End of Life Cable Considerations

Little aging occurs in medium-voltage cables that are operated within their ampacity in dry, benign environments. Benign environments are essentially ≤40°C (≤104°F) with no chemical, oil, or hydraulic fluid exposure. Cables that are limited to 80% or less of their rated ampacity should experience little thermal damage from ohmic heating. Failures of these dry circuits from aging are unlikely. A rare failure associated with a manufacturing flaw is possible. Improperly prepared terminations may fail after a significant period of operation as well. In-plant low- and medium-voltage cables rarely have splices, so splice failures do not occur. Cable circuits subjected to adverse conditions such as high temperature and/or radiant heat, oils, hydraulic fluid, or chemicals can age prematurely. High-resistance terminations can cause overheating of the conductor connection and premature aging of the termination insulation.

Submergence and wet conditions can adversely affect the longevity of medium-voltage cables and splices. Early vintage plastic- and rubber-insulated cables (late 1960s to mid- to late 1970s) are susceptible to wet aging under energized conditions. Modern rubber cable insulations (late 1970s to early 1980s through the present) are less susceptible to wet aging. Brown HTK (High-Temperature

Kerite) has not had wet failures to date from its inception in the 1970s, although failures have occurred in splices in Kerite circuits. Pink EPR in standard design cables (metal tape shields) has not suffered wet aging failures, but one failure from a manufacturing flaw has been identified. The compact cable design seems particularly sensitive to wet aging, apparently from swelling of the jacket/shield system that leads to the disruption of the insulation shield-to-insulation interface. These compact cables in which the jacket doubles as the semi-conduction insulation shield can suffer separation of the shield from the insulation during installation or corrosion of the neutral wires that leads to partial discharge failure. Failures of the compact design have been observed after 10–20 years.

Although the early medium-voltage cable insulations are more susceptible to wet-energized aging, this does not mean that all medium-voltage cables will reach a certain age and then fail. The failure distribution (that is, cables aged to the point where they must be replaced or they will fail in service) is expected to be quite broad. The width of the distribution is likely due to variations in environmental conditions and variations in the rate of degradation in the insulation itself. Failures, even at 25–30 years of operation, often are associated with manufacturing defects coupled with wet aging rather than wet aging alone. So even with the first failure in a medium-voltage cable population at 30–35 years, the last failure in that population may not occur until 60 or more years of service. Accordingly, periodic testing of medium-voltage cables that have insulation shields is appropriate to identify those cables that are in the early portion of the failure distribution so they can be replaced and the cable system integrity can be maintained. The recommended periodic tests are described in Section 2.

There is no body of evidence indicating that a generic failure mechanism exists for wet aging of *low-voltage* cable. However, prudence dictates that testing, at least on a sampling basis, is appropriate for wet low-voltage power, control, and instrumentation cable until such time as proof can be shown that circuits are or are not experiencing degradation from wet service.

Industry Commitment to Cable Aging Management

In September 2010, the U.S. nuclear industry committed to implementation of cable aging management via a letter from J. M. Rinkel of the Nuclear Energy Institute to T. J. McGinty, Director, Division of Policy and Rulemaking, U.S. Nuclear Regulatory Commission [9]. The letter committed the industry to implementing aging management for medium-voltage cable systems in accordance with the EPRI cable aging management guidance [2].

Section 2: Aging and End of Life for Medium-Voltage Cable Systems

Medium-voltage cables (cables with ratings 5–46 kV) age differently depending on their design, vintage, environments, and service conditions. The following subsections cover these conditions. While variations in aging between manufacturing vintages for EPR cables do exist, with older insulation systems being more susceptible to aging, implementation of cable aging management is recommended for all vintages of medium-voltage cables until sufficient evidence is available that more modern cables (manufactured after ~1978) age sufficiently slowly. Modern EPR cables have extruded shields and silane-treated clay fillers. The insulations are most often pink or brown, but some may have been dyed black or gray. Manufacturers continued to make improvements including triple extrusion and improvements to cleanliness of materials and ionic impurity-free carbon black for semi-conducting shields.

Medium-Voltage Cable Subject to Wet Conditions

Cables subjected to wet or submerged conditions can suffer water-related degradation under energized conditions. Submergence does not have to affect the entire length of the cable. Full or partial submergence of a short section of a circuit for an extended period can lead to insulation degradation. The degradation is known as *water treeing* in crosslinked polyethylene (XLPE) insulation.

In EPR insulation, the nature of water-related degradation is harder to understand due to the opacity of the material; however, recent research indicates that water tree–like structures exist in aged black EPR. The aged black EPR cables have small diameter channels through the insulation from the outer surface to the conductor shield that exhibit low insulation resistance by comparison to the surrounding insulation [3].

In XLPE, the water trees are not the direct breakdown method. Water trees can essentially run through the full thickness of the insulation without failure. However, a water tree causes increased voltage stress in the surrounding material, making it sensitive to voltage surges that convert the water trees to electrical trees in which partial discharging will cut through the insulation in a relatively short period, which leads to electrical breakdown. Water trees in XLPE are believed to grow through repetitions of small increments of electrochemical degradation followed by electromechanical failure of the polymer when water is forced through the electrochemically degraded area by electromotive force. Tree-like patterns are observed in the translucent XLPE.

In EPR and butyl rubber insulations, it is not clear that the mechanism is the same as in classical water treeing observed in XLPE. However, the mechanism does appear to reduce the local strength of the EPRs that do not have silane-treated clay and butyl rubber such that pockets of higher water absorption and fissures develop that have lower insulation resistance than surrounding areas [1]. EPRI report 1024894, *Medium-Voltage Cable Failure Mechanism Research, Update 4* [3], suggests that the ultimate failure mechanism of the black EPRs and butyl rubbers is through leakage current–induced thermal runaway of a low-resistance channel in the insulation that formed from energized wet aging.

Cables with Insulation Shields

Detection of the onset of water-related degradation in XLPE and rubber-insulated cables in nuclear plants depends on the use of electrical testing, which requires an insulation shield as a ground plane. The insulation shield allows the test voltage to be applied across the insulation between the shield and the conductor. The dominant metallic component of nuclear plant shields is a helically wrapped metal tape that is generally copper, but sometimes zinc.

The metal shield grounds the semi-conducting layer that is bonded to the insulation surface to prevent partial discharging. While metal tape shields allow electrical testing, they also limit the types of tests that can be applied because slight tarnishing causes the overlaps to be insulated from one another. This causes the helically wrapped tape to act like a long coil (inductor) rather than a copper tube leading to the attenuation of high-frequency signals. Partial discharges emit high-frequency signals that are severely, if not completely, attenuated by the time the signals reach the cable terminals, often making partial discharge testing impractical. Accordingly, tests that do not rely on detection of high-frequency signals must be used.

Two such tests are dissipation factor (tan δ) and dielectric spectroscopy. Current research indicates that partial discharge may not occur at the time of failure of the black rubber insulation and that thermal runaway is the likely means of ultimate failure [3]. This conclusion would further indicate that tan δ and dielectric spectroscopy are the appropriate aging management tests for wet service cables rather than partial discharge testing. However, for assessment of terminations and splices in dry areas and offsite feed cables that have concentric neutrals, partial discharge testing is an important method.

In tan δ testing, elevated ac voltage is applied to the cable while measuring resistive leakage though the insulation and capacitive current across the insulation. The ratio of the resistive current to capacitive current is the tan δ. To make the test set portable, very low frequency (VLF) (generally 0.1 Hz) is used. Testing is performed at approximately 0.5 line-to-ground voltage (V_0), 1 V_0, 1.5 V_0, and 2 V_0. Interpretation of the results are based on the absolute value of tan δ, the difference in tan δ values at 1 and 2 V_0, and the standard deviation at each voltage hold. Low, stable tan δ with a very low standard deviation during voltage holds is desirable. Specific recommendations for acceptance criteria are contained in EPRI report 1020805 [2].

Dielectric spectroscopy is a more sophisticated form of tan δ in which both voltage and frequency are varied to assess insulation deterioration. While VLF tan δ can be performed by station personnel, dielectric spectroscopy requires a specialized test set and skilled interpretation that most often requires expert application and analysis by a service provider.

Both VLF tan δ and dielectric spectroscopy require the cable circuit to be out of service, disconnected from its load and the application of elevated voltages. If the load were to remain connected, the cable result would be masked by the load result. If an XLPE cable section is spliced to an EPR section, they must be separated, or the EPR section result will mask the XLPE result. When testing XLPE cables, it may be necessary to disconnect them from the breaker cubical back plane to get satisfactory results.

While VLF tan δ and dielectric spectroscopy will detect degradation, they provide no location information and do not discriminate between widely spread lower levels of degradation and a localized severe condition. VLF withstand testing is a means of providing an indication of which condition exists. The withstand test will tend to break down a severe local degradation. Cables with widespread low-level degradation will not break down during a VLF withstand test and may be returned to service because they have useful remaining service life. Once identified as having low-level distributed degradation, these cables should be tested more frequently to determine when they should be removed from service.

Insulation resistance testing is not considered an adequate aging management test for medium-voltage cable. Although insulation resistance testing can identify severely degraded cable that should immediately be removed from service, it cannot detect significant levels of aging that are necessary to provide a warning of the impending need to replace or repair cables [3].

Some plants have one cable circuit that has distribution cable with concentric neutrals as an offsite feed. Cables with concentric neutrals, especially XLPE insulated cables, do not exhibit high-frequency signal attenuation. Use of partial discharge testing is appropriate for such cables. Partial discharge testing can identify insulation and splice problems in these longer circuits.

Non-Shielded Cables

General

Electrical standards and codes allow 5-kV rated rubber-insulated cables to be produced without insulation shields for use in power plants. Nuclear plant designers often chose non-shielded cables for safety-related applications. The design premise was that under accident conditions, a non-shielded system could run with a single phase-to-ground fault to allow operators time to cope with the accident and the cable fault. Under operation with a single phase grounded, there is a risk of the fault burning into a phase-to-phase fault. Phase-to-phase faults result in high fault currents that could severely damage connected equipment. Removing the cable from service as soon as possible is desirable under normal conditions. Under accident conditions, having the option of continuing to use the circuit balances the risk of a phase-to-phase fault.

Wet-Service

The thickness of the insulation is increased to 177% of the thickness in a non-shielded cable if the cable is allowed to operate for an indefinite period with a single ground. Due to the extra insulation thickness, the voltage stress in the insulation where the cable touches a grounded metal structure is much lower than in a shielded cable. Accordingly, water-related degradation would occur more slowly and have a greater thickness of insulation that would have to degrade before the insulation became sensitive to voltage surges that could cause the initiation of a breakdown mechanism. To date, there is no indication that lack of a shield causes non-shielded cables to be more prone to aging. Logic and experience to date indicate that they should provide good service longer than shielded cable.

Dry-Service

In a non-shielded medium-voltage cable, the voltage drop between phase conductors or between a phase conductor to ground distributes across the two layers of insulation and jacket and the air gap (if any) between the conductors or across the insulation and jacket and the air gap to ground. The distribution is capacitive, making the largest voltage drop occur across the lowest capacitance, which is generally the air gap. Accordingly, nearly full line voltage is available at the surface of non-shielded cables. This represents a personnel hazard, and caution must be taken in the vicinity of non-shielded cables.

With respect to aging, non-shielded cables can be subject to partial discharge (corona) where the surfaces of two phases are close together. The partial discharge leads to erosion of the jackets and eventually the insulation and can lead to failure. Figure 2-1 shows evidence of partial discharge erosion (corona attack). The white powder in the vicinity of the area where the cables come near to contact indicates that partial discharge damage is occurring. Figure 2-2 shows partial discharge between a phase and a ground.

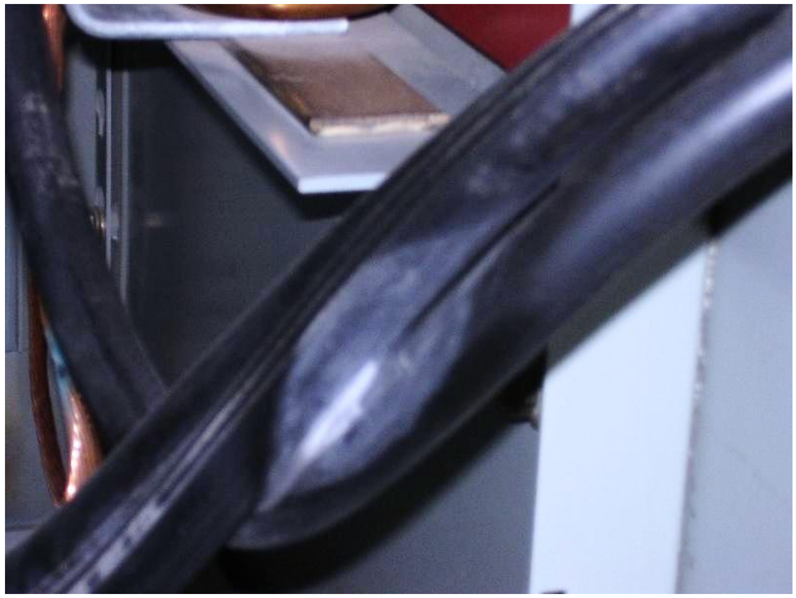

Figure 2-1
Partial discharge (corona) between two non-shielded medium-voltage phase conductors

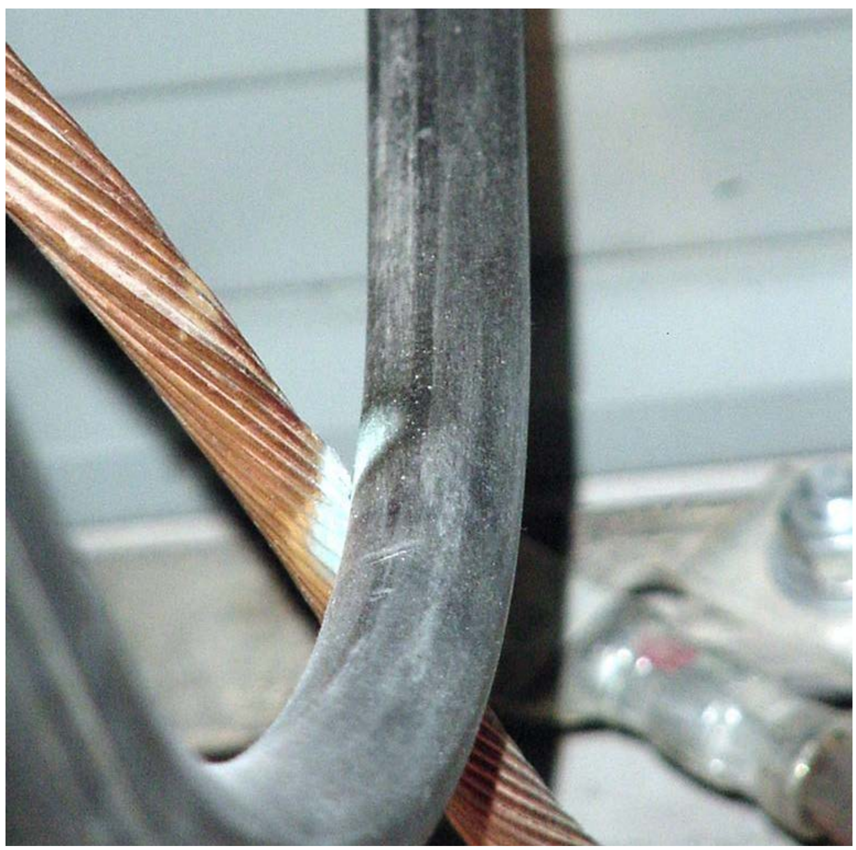

Figure 2-2
Partial discharges between a non-shielded medium-voltage phase and ground

If such conditions are identified, the circuit should be de-energized, and the damage site inspected. Repairs should be made as appropriate, and the cables separated from each other or ground. The process of corona erosion is relatively slow, but it can cause failure in a decade or so if not corrected.

Testability of Non-Shielded Cables

Unlike cables with an insulation shield, there is no electrical plane at the surface of the insulation for the application of voltage. If voltage is applied between the conductor of a non-shielded cable and ground, the voltage across the insulation is highly variable depending on whether the surface of the conductor jacket/insulation is touching ground or is surrounded by air. Figures 2-3a and 2-3b show that the voltage across the insulation of a non-shielded cable is highly variable depending on whether the surface is in contact with ground or separated by an air gap.

The fact that there is no consistent ground plane at the surface of the insulation makes electrical testing very difficult or impossible. If an elevated voltage is applied across the insulation, the stress in the insulation is randomly distributed along and around the cable. Leakage currents would be randomly distributed in accordance with the condition of the insulation and the voltage stress at each point. Measurements with tan δ would provide elevated results that are likely to not be repeatable or be consistent between phases because of the low capacitance of the non-shielded insulation and random nature of the ground plane. Results could not be interpreted. If a withstand test were applied, severe stresses might or might not result, depending on the voltage distributions.

If a flaw or severe degradation did exist, it is not likely to be detected, especially if the environments in the ducts are less severe than at other times during operation. For example, if the water has been drained from the ducts, the stress in the insulation system would likely be very low by comparison to periods when water was in the ducts. Insulation resistance testing could be applied between a conductor and the other conductors grounded; however, the results should be believed only if the insulation resistance is low (that is, less than a few 100 megohms-1000 feet (less than 30 megohms-km)).

In that case, there is a significant degradation in the insulation system. High values are desirable, but they do not necessarily indicate that the cable insulation is healthy because the jacket and surrounding air may be supporting the high insulation resistance value, and the result is not fully indicative of the quality of the insulation.

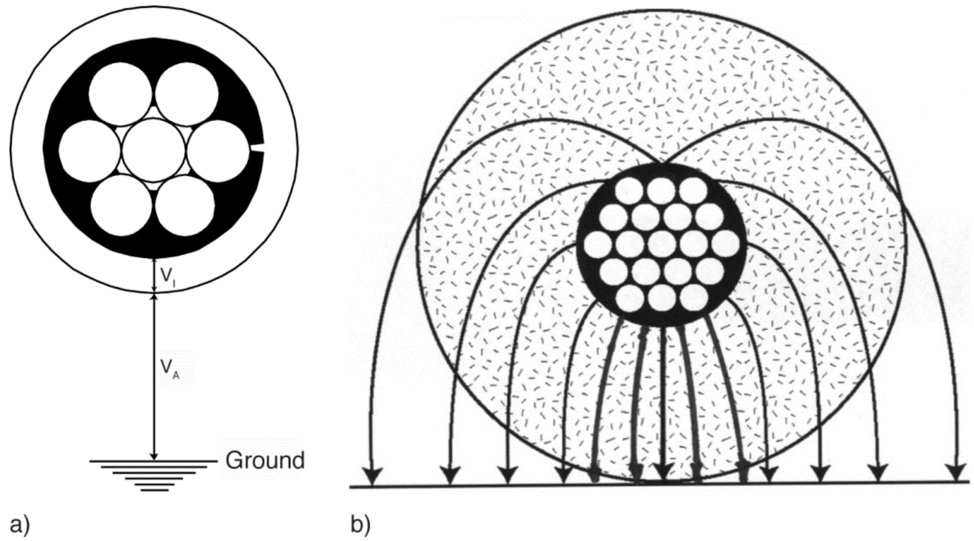

Figure 2-3
Voltage distribution in non-shielded medium-voltage cables

In Figure 2-3a, the insulation surface is separated from ground by air. Most of the voltage drop will be across the air. In Figure 2-3b, the insulation is touching ground. The voltage stress in the cable is highly distorted around the circumference of the insulation, with the highest voltage between the conductor and ground.

Because these cables are not electrically testable in a manner that would provide a direct indication of their health, contingency plans for the replacement should a cable fail are recommended. Cable, splices, and terminations should be readily available (on site or in a corporate or industry warehouse), and skilled installers and installation procedures should be available. If a failure occurs, the plant should be committed to performing a formal forensics study to determine if age-related degradation was the cause. If so, actions should be taken to address aging in non-shielded cables subject to similar environmental and service conditions.

Medium-Voltage Cables Subject to Dry Conditions

Dry medium-voltage cables can be damaged by elevated temperature and radiant energy conditions. High temperatures cause the jacket and insulation system to oxidize and harden. Such damage is generally a long, slow process unless thermal insulation has been left off a high-temperature pipe that is adjacent to the medium-voltage cable, in which case the degradation could occur in a few years. Most medium-voltage cables subject to dry conditions are in relatively cool areas and are not adjacent to high-temperature piping. Some exceptions include reactor coolant and recirculation pump motors in containment and cables connected to residual heat removal pumps. These cables may run near piping with elevated temperatures or through areas with elevated temperatures.

Given that most medium-voltage cables do not run through areas with temperatures greater than 40°C (104°F), thermal aging of the insulation is not a great concern. Failures of such circuits are rare and are generally associated with a manufacturing flaw, an installation error, or inadvertent damage from an external condition. These are all random failures and are not indicative of an age-related phenomenon at work. At present, there is no difference in the types of failures experienced in early vintage butyl rubber and EPR cables (those manufactured prior to approximately 1978) and later vintage EPR cable with silane-treated clays. Dry XLPE cables also have experienced only random failures that are rare. Some failures in all types of cables have been attributed to errors in making terminations with the exception of non-shielded cables that have very simple terminations that are not prone to insulation failures.

Splices and Terminations

Nuclear plant medium-voltage cable terminations are generally in dry locations in switchgear, motors, and transformer compartments; however, some plants have outdoor terminations on some of their cables that terminate in switchyards or at outdoor transformers. While in-plant splices are rare, long runs of cable that are underground almost always have splices. These splices are located in manholes and vaults, but never in ducts. The manholes and vaults may be wet or dry. The splices may be taped designs or heatshrink designs from original plant construction. Coldshrink designs are available for non-safety circuits for replacement work.

Splices and terminations in non-shielded medium-voltage cables are the same as they are for low-voltage power cables. However, for shielded cable, the voltage stress at the end of the shield is very high, and special termination and splice designs are necessary to prevent splice or termination failure. A number of designs exist to reduce the voltage stress at the point where the shield ends at a termination or splice. These methods are described in splice manufacturers' literature.

Figures 4-28 and 4-29 in EPRI report EL-5036, *Power Plant Electrical Reference Series, Volume 4, Wire and Cable* [4], show the stress levels and how a taped splice is formed to overcome the stresses. A properly made splice or termination should outlive a cable insulation system because it has thicker insulation layers than the cable itself. However, splicing errors did and do occur, from not following the manufacturer's directions for thicknesses and overlaps, as a result of cuts in the insulation or air pockets from not taping correctly, or improper heating for heat-shrinkable coverings. A small but significant percentage of splices in medium-voltage circuits have either failed or have been identified as defective during off-line electrical testing. In one case, (see Figure 2-4) a newly made splice was subjected to a tan δ test followed by a withstand test. The cable failed 17 minutes into the withstand test. Dissection of the splice determined that the splicer had accidentally made a through cut in the insulation while removing the shield from the cable. Feedback from the initial set of medium-voltage testing by the industry indicated that 9 of the 24 problems identified in 177 tests were splice related or about 37% of the issues identified by testing [5].

Figure 2-4
Damage to a newly installed cable splice that was identified by a withstand test. The black spot on the cable is where the technician accidentally cut through the insulation when removing the semiconductor shield.

Termination failures are relatively rare, but are more frequent in outdoor applications where water entry and contamination can occur. Some pothead-type terminations used for cable risers from underground to aerial cables have failed in service or were the cause of high tan δ test results.

Some failures have occurred in motor termination boxes where temperatures are higher than local ambient temperatures. The motor termination is heated by direct conduction from the winding leads, and heat is transferred from the winding through the frame to the termination box. Depending on the motor lead to termination design, significant heating of the termination is possible that will raise the termination box temperature by 10–20°C (18–36°F) leading to thermal aging of the termination and possibly leading to failure in 30 or more years. Failures have also occurred when high-resistance connections occurred, either from installation errors or relaxation of compression in the conductor connections. Control of high-resistance connections is possible through periodic visual inspection of the termination or infrared thermography. Some plants have installed infrared thermography ports or infrared windows in motor termination boxes to allow assessment without opening the motor termination box.

Failure Behavior in Medium-Voltage Cable Populations

The failure distribution for all medium-voltage cables in a power plant would be very broad and would extend for decades following the first cable failure, which for most plants is after 25–30 years or more of wet service and generally much longer in dry service. The first failure in a plant with XLPE-insulated cables in wet service is generally after 25 years of service. For butyl and black EPR-insulated cables in wet service, the first failure tends to occur after 30–33 years of service. Because the cables in a medium-voltage system are subject to a broad range of conditions with few cables having minor defects and some circuits having a splice or termination installation error, the range of time to failure if all cables were allowed to run to failure could range from 65 to 80 years. The period from the first failure to the last failure in the population could be 40–50 years from the first failure. The long period is related to whether a flaw is in a wet or dry section of cable and the other service and temperature conditions surrounding the cables. The cables with no flaws or installation errors will have very long lives. Flaws—if they exist in a wet length of a cable—will tend to cause the earliest failures. Gross flaws or installation errors will cause failures in dry cables. Flaws that could be a problem under wet service may cause no shortening of life in dry service.

Figure 2-5 is a hypothetical case showing the effects of separating the failure distributions into subsets by stress levels such as dry versus wet circuits. The width of the age-related distribution of the highly stressed population is narrower than that for the moderately stressed population. These curves show two things: the dry population will degrade much more slowly than the wet population due to the lack of electro-chemical stresses, and both distributions are expected to be broad, although the distribution for the more highly stressed wet population will be narrower. Recent research indicates that below 65% humidity, water-induced degradation does not occur [3]. So in some environments, significant failure mechanisms related to conditions, such as wetting, cease to exist when the stress level is low. In the case of the black butyl and EPR cables, the first age-related failures that have been observed have occurred in the 30–35 year range for wetted cables [1, 6].

In Figure 2-5, these first failures would mark the beginning of the gradual increase in slope on the red curve, which is marked "a." Figure 2-5 indicates that if all wet portions of the cable system were replaced on the basis of the first observed failure, a large amount of available service life in the original system would be lost. This would be conservative and might be justifiable in critical safety systems, but in general would be very costly.

The alternative for shielded cables is condition-based replacement. Performance of tan δ or dielectric spectroscopy tests [2] will indicate whether the cables and any splices have degraded from wet service or if they remain in acceptable condition. EPRI report 1020805, *Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants* [2], provides criteria for good, further study required, and action required conditions. Good cables continue to be tested on a six-year schedule, further study required cables are evaluated for conditions that could cause elevated measurements and/or are tested at each outage, and action required cables are replaced as soon as possible. Replacement based on condition may require only a few replacements over a decade or more. The need to replace the remainder of the system is a decision to be made based on the failure rate, the number of cables to be replaced, and the effects on work management schedules and staff loadings. Replacement of all wet cables at a plant is likely to take several years to complete, given the time required to remove cables from ducts and the time to install, terminate, and test the new cable.

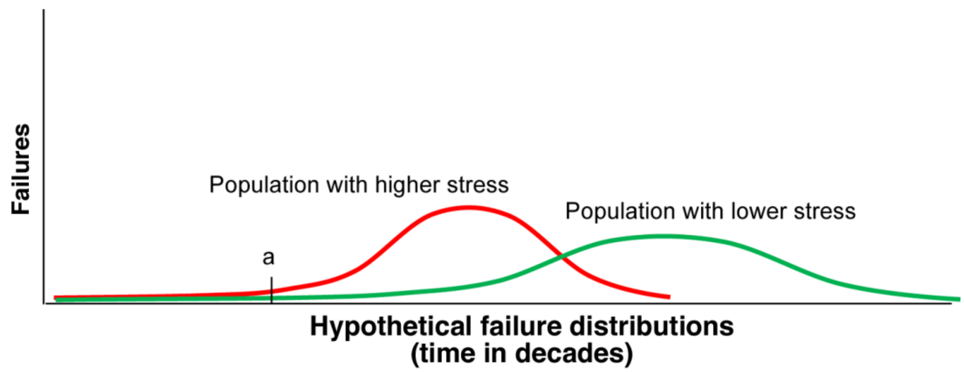

Figure 2-5
Failure distributions for two cable populations with different stress levels

Summary of Medium-Voltage Cable System Conclusions

Shielded Cables

Table 2-1 summarizes the expected onset of first failures for various types and vintages of shielded, medium-voltage cables in wet or underground service. Periodic testing at intervals of approximately six years is recommended for plants with cables that are 20 years old or older. Testing recommendations and assessment criteria are contained in EPRI report 1020805, *Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants* [2]. Completely dry cables are not expected to be subject to age-related failures unless serious manufacturing defects or installation errors exist. Condition monitoring of dry cables is not recommended unless operating experience indicates an issue with a particular cable type or application.

Non-Shielded Cables

A one-time visual inspection is recommended for termination cubicles and housings to determine if partial discharge erosion (corona damage) for non-shielded cables is occurring. Careful inspection of phase cable surfaces where they are adjacent to each other or ground for signs of white powder is recommended. **Warning: The cables must be de-energized when performing these inspections. Lethal voltages may be present at the surface on non-shielded cables when they are energized.**

With regard to wet or potentially wet services cables, because these cables cannot be electrically tested, contingency plans should be in place to allow replacement should they fail. Cable, terminations, and pull procedures should be available, and a skilled installation team should be identified. Any cable that fails should be subjected to a full forensics evaluation to determine if the cause of failure is age related.

Note: Currently, there is no indication that non-shielded cables are experiencing early failures. By design, these cables have thicker insulation walls and should not fail earlier than related shielded cables.

Splices and Terminations

Shielded splices and terminations are part of the shielded cable circuit and are tested with the cables. The recommendations in Table 2-1 apply.

Table 2-1
Summary of medium-voltage cable system recommendations for cables with insulation shields subject to wet conditions

Cable Type	Manufacturing Period	Observed Onset of First Failures under Wet Service Conditions	Failure Mechanism under Wet Aging	Recommended Test
Butyl rubber	Late 1960s to early 1970s	~35 years	Deterioration of insulation quality with small localized channels in the insulation with very low resistance. Ultimately, failure results from thermal runaway of a channel.	Dissipation factor or dielectric spectroscopy
Black EPR	1970 to 1978–1980	~30–33 years	Same as butyl rubber.	Dissipation factor or dielectric spectroscopy
Brown EPR (Kerite HTK)	Early 1970s to approximately 2005	None known (40-year-old nuclear installations exist)	Very long life expected; no end-of-life mechanism observed to date.	Dissipation factor or dielectric spectroscopy
Pink EPR	Late 1970s through the present	None known (30 plus years of service to date in some cases)	Long life expected; no end-of-life mechanism observed to date.	Dissipation factor or dielectric spectroscopy
Compact design, pink EPR (semi-conducting jacket and semi-conducting shield with 6 strand wires)	Late 1970s through the present	10–25 years	Disruption of insulation to shield interface due to swelling of semi-conducting shield/jacket system.	Dissipation factor or dielectric spectroscopy
XLPE	Early 1970s through mid-1980s	~25 years	Water treeing.	Dissipation factor, dielectric spectroscopy, or partial discharge
TR-XLPE	Current design	Not known (limited service to life)	Water treeing but at a greatly reduced rate; expected end of life greater than 40 years.	Dissipation factor, dielectric spectroscopy, or partial discharge

Section 3: Test Methodology for Medium-Voltage Cable Systems

Although a number of medium-voltage cable test systems exist, many of them were developed for use on XLPE distribution system cables with concentric neutrals. While some XLPE cables are used in nuclear plants, their design generally employs metal tape shields rather than the heavy concentric neutrals of distribution cable. The tape shields allow the cables to be more flexible, which is a requirement for power plant cable installation. Further flexibility is provided when rubber-insulated cables are used, and rubber is the dominant type of insulation used in nuclear plants.

The use of rubber insulation with tape shields reduces the field of possible tests by essentially eliminating partial discharge testing. Rubber insulation attenuates high-frequency signals significantly in comparison to XLPE. Tape shields tarnish slightly, especially in wet applications, as they age. The tarnish acts as an insulator between the turns of the tape, converting it from the equivalent of a metal tube when new to a long coil when aged. The coil acts as an inductor and further attenuates high-frequency signals. Partial discharges emit high-frequency signals, and if they exist, they would likely not be detectable in field testing. Further, recent research [3] has determined that the likely final transition to failure is thermal runaway that does not produce partial discharges.

The recommended tests that will identify age-related degradation for cables with insulation shields are dissipation factor (tan δ) and dielectric spectroscopy, both of which are performed off-line and with elevated voltage. The dissipation factor is the tangent of the angle between the real and capacitive currents. In field testing, the voltage source generally operates at 0.1 Hz, and measurements are taken at ½ V_0 (line-to-ground voltage), 1 V_0, 1.5 V_0, and 2 V_0. The results are based on the absolute value of the measurement, the difference between 1 V_0 and 2 V_0, and the standard deviation of the values at each test voltage. EPRI report 1020805, *Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants* [2], provides assessment criteria by insulation type.

Dielectric spectroscopy assesses the insulation permittivity and dissipation factor with respect to voltage and frequency. At each applied voltage, a frequency sweep is performed, and the permittivity and tan δ parameters are evaluated. New, aged, and highly aged insulations have specific behaviors. At voltage-dependent permittivity, the onset of aging is recognized with the transition to leakage current, which indicates more severe aging, and leakage current behavior, which indicates that the cable should be replaced. The test requires special test equipment and interpretive skills and generally requires a vendor's services.

Neither tan δ nor dielectric spectroscopy provides an indication of the location of the degradation. Tan δ tests do not discriminate between a severe localized degradation and more widespread lower-level degradation. If the tan δ indicates degradation, a 0.1 Hz withstand test can be applied to a cable to determine if the degradation is severe and localized or if it is a more widespread lower level degradation. Elevated voltage is applied for 30–60 minutes at the IEEE Std 400.2 [10] recommended value. If no failure occurs, the degradation is not a localized severe condition. If a cable fails under test or in service, EPRI report 1023060, *Underground Cable Fault Location Reference and Application Guide* [7], describes methods and tools for locating the fault along the cable length.

Testing of Offsite Feed Cables

Some plants have polymer-insulated offsite feed cables that have voltages between 33 and 45 kV. These circuits often have typical distribution cables with XLPE insulation and concentric neutrals. The circuits are also long enough to require multiple splices. Although tan δ and dielectric spectroscopy tests will work for these cables, partial discharge testing can be particularly useful to assess electrical degradation of the splices. While a well-made splice should outlast the life of the cable, installation errors or damage to splices may result in shorter lives. XLPE distribution cables with concentric neutrals can be assessed with partial discharge techniques because of their low attenuation factors for high-frequency signals.

Section 4: Logistics

Manufacturing lead times for medium-voltage cable are on the order of 16 weeks with minimum order requirements. While a common medium-voltage cable specification has been developed by EPRI for ordering new cable [8], the wide range of cable sizes and specialty configurations prevents manufacturers from stocking cable for nuclear industry use. Cable sizes range from 2/0 AWG to 2000 kcmil (67.4–1014 mm^2) with the largest size weighing 8 lbs/ft (12 kg/m) with most of the weight being the copper conductor. Many utilities have no spare cable to cover potential replacement needs. Some utilities are members of the Pooled Inventory Management System (PIMS)[1] for cables, which stores common sizes of medium-voltage cable for its members. If a failure occurs, the following will likely be needed in addition to cable:

- Termination kits
- Splice kits (necessary for long lengths or connections of new sections to old sections)
- Fault locating equipment
- Pulling sheaves and pulling force dynamometer
- Cable removal procedure
- Cable installation procedure
- Cable tension and sidewall bearing pressure calculations
- Compatible pulling lubricant
- Skilled splicing crew and supervision
- Post-installation test procedure (for example, very low frequency (VLF) tan δ and withstand test)

Removal and replacement of medium-voltage cables are not trivial activities. Many nuclear plants have not experienced medium-voltage cable installations since prior to plant startup, and electricians experienced in splice and termination procedures are not available on staff. In addition, plants with operation dates before 1979 are likely to have older style medium-voltage cables that have cloth or polymer tape insulation shields. Certified technicians may not be familiar with such old cable designs and may require additional training if new cables will be

[1] PIMS is a service of Southern Company Services Inc, Memphis, Tennessee.

spliced to cloth or polymer tape shield original designs. When splicing and terminating medium-voltage cable, installation crews must carefully follow the splice or termination manufacturer's installation procedure to prevent installation errors that can lead to early failures.

In addition, use of insulation shield removal tools—rather than using a knife to remove the insulation shield—is highly recommended. If a knife is used to remove the insulation shield, there is a significant probability that the installer will cut into the insulation while removing the semi-conducting polymer shield. Such cuts, if not detected, lead to early termination and splice failure. A shield removal tool cuts only partially through the semi-conducting shield layer, thereby preventing a cut into the insulation layer, which would cause a very high electrical stress in the remaining insulation and would likely become a site for partial discharge or wet electrical degradation should wet conditions occur. If a post-installation VLF withstand test is performed, such an installation error is likely to cause a test failure, further extending the outage. A post-installation VLF tan δ and withstand test is highly recommended to preclude failures within the first few years of operation of the replaced or repaired circuit.

Circuit Outage Durations

Fault location and replacement activities are likely to take at least a week for a simple cable circuit. However, circuits with heavy loads often have multiple conductors per phase and startup transformer, and auxiliary transformer 4 kV circuits often have five or six cables per phase. Underground and in-plant paths for these cables can be quite complex. Underground ducts can be long and have multiple turns requiring multiple pull points to avoid excess sidewall bearing pressure that will damage cable during pulling. A side wall bearing pressure that is too high can disrupt the shield-to-insulation interface, leading to high electrical stresses and early failure.

If multiple cables per phase must be replaced, circuit outages take a few weeks for underground sections. If the cable within the plant must be replaced, long multiconductors-per-phase cables may require months to replace because multiple fire breaks will need to be removed and the cable tray system may have to be dismantled to allow removal and replacement of the large conductor cables.

Although replacements of some circuits will not require plant outages, replacements of offsite feed, auxiliary feeds, and most safety circuits will cause most plants to enter limiting conditions for operation conditions requiring shutdowns 24 hours after their failure. A lack of spare cable, accessories (splices and terminations), and pulling crews can lead to significant delays and further exacerbate lost generation costs.

One potential cause of a cable failure outage is a jammed cable either during removal or installation. While rare, such a problem occurred at one plant causing the duct on the multi-cables-per-phase installation to be abandoned and the circuit to be re-engineered to allow use of fewer ducts. In this case, the cable jammed during removal. When removing a cable, having a pull rope on both ends is recommended to allow the cable to be pulled back if it begins to jam. Jamming can occur due to configuration alone or if the duct system has sustained damage since the time of installation.

In addition to jamming issues, some early plants installed fiber ducts rather than steel or PVC. These fiber ducts, such as "Orangeburg," were composed of fiber and tar that degrade by swelling and delamination. The result is that the ducts may not be reusable, leading to the need to replace the entire duct system, which is a high-cost, time-consuming activity.

Replacement/Repair Issues

Fitness for Return to Service

Insulation resistance should not be used as an indicator of fitness for service for medium-voltage cables. Whereas a very low insulation resistance (that is, less than 100 megohms-1000 ft (30 megohms-km) is indicative of a severely deteriorated cable, seemingly good insulation resistances, such as a gigohm-1000 ft (300 megohms-km), does not necessarily indicate a sound cable that will function for a significant period. Unacceptable insulation condition that is obvious from tan δ or dielectric spectroscopy testing cannot be identified with insulation resistance testing until the cable is very near or at the point of failure.

Under no circumstances should an acceptance of 1 megohm per kV plus a megohm be used for medium-voltage cable. Cable with such a low insulation resistance is failed. If returned to service, the failure could burn into a phase-to-phase fault with currents that could damage transformers and other connected equipment. EPRI report 1022968, *Plant Engineering: Cable Aging Management Program Implementation Guidance,* provides further discussions of insulation resistance in relation to medium-voltage cable.

If a cable falls into the "Action Required" category when tan δ testing [2], then the cable should be returned to service only if it passes a VLF withstand test lasting 30 minutes or more. If it passes the VLF withstand test, the condition is likely caused by lesser distributed degradation rather than one significant severely degraded local condition, and return to service for a reasonable period to allow a scheduled replacement is possible. Failure of the VLF withstand test will occur only if the cable is highly degraded. Such a withstand test will not cause failure of a "good" cable.

Duct Cleaning and Condition

Once the medium-voltage cables have been removed from a duct, the duct should be cleaned and proven to be in good condition. This may be done by pulling wire brushes through the duct and then pulling a mandrel through the duct to prove that it is not collapsed anywhere along its length.

Compatibility of Pulling Compounds

When pulling a new cable, using a pulling compound (lubricant) that is compatible with the cable jacket and using a dynamometer to limit pulling tension are required. If the lubricant is not compatible with the jacket, the jacket and subsequently the shield and insulation may fail shortly after installation. Changes in the jacket materials of medium-voltage cables have occurred in the last decade due to the shutdown of Hypalon-producing facilities and changes to environmental regulations that have reduced the number of polymers available for both jacketing and insulation systems. The cable manufacturer should be asked if they know of specific pulling compounds that are compatible with their cable system that also meet site chemical control guidelines.

Splice Problems

Not all test or in-service failures are related to cable failures. Long, underground cables have splices because of allowable reel sizes. About one-third of failures to meet test acceptance criteria are related to splice degradation for older circuits and failures on circuits with modern insulation are most often associated with splice degradation. Cable insulation failures to date on modern cables have been associated with manufacturing flaws. Most splice failures are associated with errors during installation rather than age-related degradation alone. Accordingly, when splices are being installed, keen attention to the capability/qualification of the installer, use of proper tooling, and manufacturer's instructions and details are important.

Zinc Tape Shields

A few plants have helically wrapped zinc tape shields rather than copper tape shields. Two problems have been identified with this type of shield:

- In long vertical runs, proper support is necessary. If inadequate vertical support is employed, the jacket and zinc metal shield can slip with respect to the insulation and conductor bunching the zinc shield above the support and extending and cracking it below the support. Arcing and elevated stress that lead to cable failure can occur across the break in the zinc tape.
- If water enters the zinc shield, which could occur at a poorly made underground splice, or if an underground jacket were breached, corrosion can lead to powdering and loss of the metallic tape for an extended distance, preventing the zinc shield from being restored during circuit repairs.

Identifying the metallic shield component in use at a plant before cable problems are identified will help ensure that rapid restoration of circuits is possible.

Section 5: Conclusions

Medium-voltage cable will age if exposed to elevated temperature, high electrical stress, or wet-energized conditions. Many cables are located in benign environments (dry, cool, contaminant free). Cables subjected to elevated temperatures or located in areas that could be wet must be controlled by an aging management program. The electrical stress in shielded cable is controlled. For non-shielded cables, care must be taken to control corona discharge to surrounding ground surfaces or between cable phases.

Off-line electrical testing is an appropriate means of assessing aging of shielded medium-voltage cable subject to wet conditions. Long medium-voltage cables generally have splices that will also be assessed by the off-line tests. The recommended tests for the medium-voltage cable designs used in nuclear plants are very low frequency (VLF) tan δ and VLF withstand or dielectric spectroscopy. Acceptance criteria have been established for VLF tan δ results that allow cable circuits to be ranked as "good," "further study required," and "action required" [2]. Older style butyl rubber–, black EPR–, and XLPE-insulated cable populations are known to have their first failures between 25 and 35 years of service, depending on the material type. The failure distribution is expected to be very broad with some of the cables in the distributions having expected lives as long as 70–80 years. More modern cable designs based on brown and pink EPR have not yet experienced water-related failures in nuclear plant service. The exception is a unique compact design that has failure mechanisms unrelated to the insulation material.

No condition monitoring electrical test exists for non-shielded medium-voltage cable insulation. Accordingly, plants with non-shielded cable must remain abreast of industry operating experience related to their cable type (manufacturer and insulation specific) and must commit to the performance of detailed forensics if a cable fails in order to determine if aging was the cause. If so, appropriate corrective actions must be taken for similar applications.

The electrical stresses in terminations and splices on shielded cables are very high, and preparing terminations and splices in accordance with manufacturers' instruction is critical to having a long life on replacements. The terminations on non-shielded cables are very similar to those in low-voltage cable. Because of the lack of an insulation shield on non-shielded cables, the stresses at the termination are not elevated, and no voltage stress relief layers are necessary.

The replacement of a medium-voltage cable is not a trivial exercise. In addition to replacement cable, terminations and splices must be available. Lead time for replacement cable can be 16 weeks or more. Qualified installation personnel, pulling procedures, and pulling equipment (dynamometer, sheaves, etc.) are also necessary. For multi-cables-per-phase circuits, circuit outage durations may be weeks for underground segments, but could be months for in-plant cable.

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