PNNL-30402

# Light Water Reactor Sustainability Program

# Potential Life Extension Strategies for In-Service Degraded Cables

September 2020

U.S. Department of Energy

Office of Nuclear Energy

PNNL-30402

# Potential Life Extension Strategies for In-Service Degraded Cables

**Satish K. Nune, Mychal P. Spencer, and Leonard S. Fifield**

**September 2020**

**Prepared for the**
**U.S. Department of Energy**
**Office of Nuclear Energy**

# SUMMARY

Electrical cable systems are integral to the safe and efficient operation of nuclear power plants. As cable materials age over time in service, the performance and reliability of cables decrease and can fall to unacceptable levels. Effective techniques for assessing cable health and monitoring their condition are essential for determining cable status, predicting remaining useful life, and informing operators of the need for additional monitoring or replacement. The need for accurate cable status information is important both for maintaining safety and maximizing up time, but also to avoid unnecessary replacement of satisfactorily-performing cables. Unnecessary cable replacement is to be avoided as it can draw time and limited resources away from other operational and maintenance issues. Replacement of cable lines can introduce new workmanship-related defects or failure points at splices and connections, extend schedules for outages, and be especially difficult for not-easily-accessed cables such as those that are buried, in concrete walls, or that would require shutdown or removal of unrelated equipment to access.

An alternative to replacement of cables that are experiencing aging in service is to treat the cables in place to extend their operational lifetime. Treatment to restore cable performance and return cables to an effectively ‘younger’ state is sometimes referred to as cable rejuvenation. Rejuvenation has been used to extend the life of millions of feet of moisture-degraded underground residential cable. Though a common practice outside of nuclear, rejuvenation has not yet widely been used in the U.S. nuclear fleet perhaps due to questions regarding the reliability of rejuvenated versus new replacement cables.

Commercial cable rejuvenation technologies focus on mitigating moisture-related cable degradation. Mitigating cable aging via other environmental stress mechanisms such as elevated temperature or radiation will likely involve treatments and formulations that differ from those currently in use. It is likely that increased use of rejuvenation technologies to extend the life of aging cables in nuclear power generation will require additional validation of methods to confirm the reliability of treated cables to perform their intended function not only in routine service, but also, for safety-related cables, in the course of design basis events.

This report discusses current rejuvenation technology used commercially for treatment of moisture-related degradation and proposed chemical strategies that may enable mitigation of cable insulation aging in nuclear power plants due to thermal or radiation exposure. Future work could involve demonstration of these options for recovering degraded cable mechanical or dielectric performance and determination of the resilience of treated cables to design basis event conditions, such as those experienced during a loss of coolant accident.

# ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, for the Light Water Reactor Sustainability (LWRS) Program Materials Research Pathway. The authors extend their appreciation to Pathway Lead Dr. Thomas Rosseel for LWRS programmatic support. This work was performed at the Pacific Northwest National Laboratory (PNNL). PNNL is operated by Battelle for the U.S. Department of Energy under contract DE-AC05-76RL01830.

# CONTENTS

# FIGURES

# TABLES

# ACRONYMS

| | |
|---|---|
| AC | Alternating current |
| ATR | Attenuated total reflection |
| CFR | Code of Federal Regulations |
| DPDMS | Diphenyldimethoxysilane |
| EMDA | Expanded Material Degradation Assessment |
| EPR | Ethylene propylene rubber |
| EPRI | Electric Power Research Institute |
| FTIR | Fourier transform infrared spectroscopy |
| LDH | Layered double hydroxides |
| MDOS | Dimethyloctylsilane |
| NPP | Nuclear power plant |
| NRC | Nuclear Regulatory Commission |
| PE | Polyethylene |
| PMDMS | Phenylmethyldimethoxysilane |
| PNNL | Pacific Northwest National Laboratory |
| PSA | Poly(sodium acrylate) |
| PVA | Polyvinyl alcohol |
| RF | Rejuvenation fluid |
| SEM | Scanning electron microscopy |
| SPR | Sustained pressure rejuvenation |
| TIPT | Titanium isopropoxide |
| TMMS | Trimethylmethoxysilane |
| UPR | Unsustained pressure rejuvenation |
| URD | Underground residential distribution |
| UV | Ultraviolet |
| VPE | 1-(4-vinyloxy) phenylethenone |
| WBT | Water blocking tapes |
| XLPE | Cross-linked polyethylene |
| XLPVA | Cross-linked polyvinyl alcohol |

# 1. INTRODUCTION

Nuclear power plants (NPPs) produce approximately 20% of the power in the United States [1]. The minimum operational lifetime of NPPs was originally established as 40-years [2,3]. Twenty year extensions to the original operational basis of NPPs is allowed per Title 10 of the Code of Federal Regulations, Part 54 (10 CFR 54) and as described in the foreword of the U.S. Nuclear Regulatory Commissions (NRC's) Expanded Materials Degradation Assessment (EMDA) Volume 5: Aging of Cables and Cable System [4]. With the approval of license extensions up to 60-years for most of the U.S. NPP fleet, a second or subsequent renewal to 80-years of operational lifetime has been approved for two NPPs and is currently being evaluated by multiple nuclear utilities [5]. To ensure reliability of cable systems in NPPs over these license extensions, much focus has been given to electrical cable aging-related issues and their knowledge gaps [6], such as synergistic effects [7,8], diffusion limited oxidation [9,10], inverse temperature effects [11], and dose-rate effects [12]. Understanding leading indicators for cable aging behavior enables development of technology to monitor cable condition and assess cable remaining useful life [13]. The ability to foresee imminent cable demise through accurate non-destructive evaluation provides the opportunity to plan for cable repair or replacement, or to accept the risk of cable failure with clear information. In addition to safety concerns, unexpected cable failure can be extremely costly if it results in an unplanned power generation outage or forces redirection of resources during a busy outage schedule. With foreknowledge, costs associated with cable repair or replacement can be minimized. However, even with prior knowledge and an adequate planning period, many cables in an NPP are difficult to replace due their complex routing or inaccessible location. Operating experience has shown that many cable defects or failures are related not to cable material aging issues, but to workmanship issues related to application of terminations, splices, etc. Cable rejuvenation is the concept of treating a degraded cable to return it to new or like-new condition. If condition monitoring identifies degradation in NPPs cables, rejuvenation may be a way to eliminate or significantly postpone the need for cable replacement.

Cable rejuvenation has been widely and successfully applied to millions of miles of underground commercial electrical cables to extend cable insulation lifetimes by 20 years or more. The use of rejuvenation fluids has been shown to reverse the effects of water and electrical treeing, restore dielectric properties to their original response, and prevent partial discharge [14]. Initial work has focused on investigating the applicability of rejuvenation fluids to extending NPP cable lifetimes. For example, the Electric Power Research Institute (EPRI) investigated the effects of common rejuvenation fluids on aged medium voltage ethylene propylene rubber (EPR) insulated cables and found a large improvement in breakdown voltages [15,16]. Exploratory work conducted at PNNL found that directly soaking degraded EPR specimens in plasticizer reduced their material stiffness, while soaking in antioxidant did not produce a notable effect on their elongation at break [17]. However, much still remains unknown, such as how rejuvenated cables respond to a design basis event, how long rejuvenated cables retain their improved properties when exposed to thermal and/or radiation stressors, how rejuvenated cables would meet the original license design basis performance requirements, and the appropriate compositions of the rejuvenation fluid for common NPP cables.

In this report, an overview of common cable rejuvenation techniques employed in commercial operations are reviewed with the purpose of noting rejuvenation fluid compositions which may be applicable for NPP electrical cable rejuvenation. First, in Section 2, the background of degradation mechanisms of electrical cables is discussed. Then, in Section 3, the history and state-of-the art in cable rejuvenation techniques is reviewed. In Section 4, challenges and opportunities for developing a cable rejuvenation fluid are presented. Section 5 concludes the report with a discussion of potential future work.

# 2. ELECTRICAL CABLE DEGRADATION

## 2.1 Wet Cable Degradation

Durable and reliable polymeric dielectrics play a critical role in power transmission and instrumentation and control cables. Cables used in underground residential distribution (URD) face significant challenges over time because of environmental factors that can weaken cable insulation [18,19]. Degradation due to moisture and electrical stress can result in a gradual decrease of the dielectric properties of the polymeric insulation, ultimately leading to complete degradation and failure. Stress leading to chemical degradation of polymers is generally promoted by initially formed voids, defects, and chemical impurities. Formed cavities will gradually propagate through the polymer insulation and grow into shapes resembling the branches of a tree. Humidity, in combination with an AC electric field at ambient conditions typical of underground cable installations, can result in the expansion of water trees (see Figure 1) [20,21]. When growing water trees can no longer contain the voltage stress, an electric tree will form [22]. Time dependent growth and expansion of water trees can significantly reduce the useful life of underground cables.

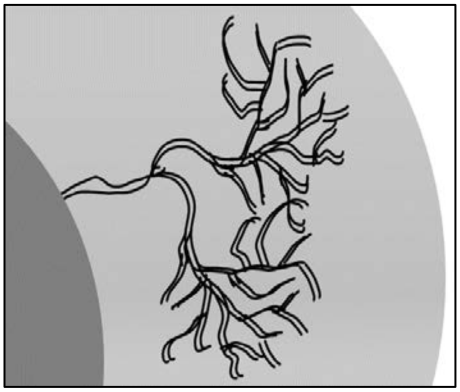


Figure 1. The formation of water trees due to electrical stress.

To avoid cable failure through water tree formation, various approaches have been investigated. One approach is to incorporate nanofiller additives to enhance the dielectric properties of the insulation to reduce the likelihood of electrical treeing (see Section 3.2). Another approach is the addition of voltage stabilizers. A stabilizer is a chemical compound that inhibits or delays the inception of water treeing. Previous work has hypothesized that voltage stabilizers capture high energy electrons and dissipate their energy in the form of heat. In the absence of such stabilizers, electrons degrade the dielectric through ionization. A library of different classes of organic voltage stabilizers have been proposed and developed [23]. These stabilizers include (i) hydrophobic alcohols [24], (ii) polycyclic hydrocarbons [25], aromatic dyes [23], siloxanes with aromatic side chains, and ferrocene/siloxane mixtures [23]. Aromatic and aliphatic ketones and diketones, such as acetophenone and benzophenone, can trap electrons and are therefore effective voltage stabilizers [26]. However, the poor compatibility of ketones with polymers, in particular their ability to cross-link, has hindered adaptation. To improve compatibility, novel polymers containing 1-(4-vinyloxy) phenylethenone (VPE) have been developed. VPE can be grafted onto common dielectrics, such as cross-linked polyethylene (XLPE), during the cross-linking process which promotes stability (Figure 2) [26]. Other voltage stabilizers, such as thioxanthones (Figure 3), exhibit promising voltage stabilizing properties because of their similarity in structural elements and in electronic properties at the molecular level [23].

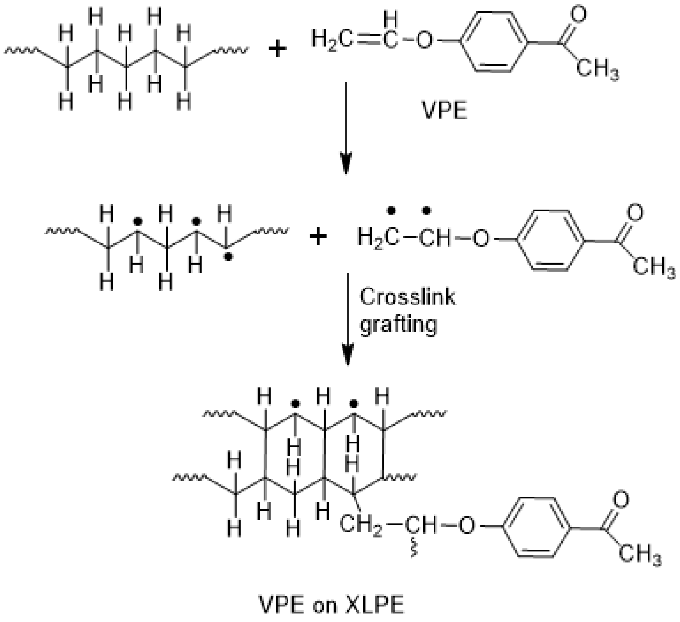


Figure 2. The cross-linking of a VPE stabilizer onto XLPE.

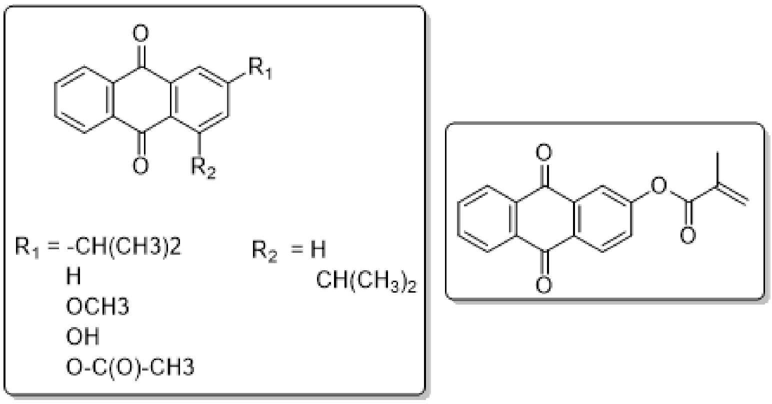


Figure 3. Illustration of thioxanthone-based stabilizers.

## 2.2 Oxidation Degradation of Cable Insulation

Water and electrical treeing are not the only factors responsible for failure of polymeric insulation in electrical cables. Failure can occur through a combination of complex mechanisms as shown in Figure 4. Radiation and thermal stress can lead to oxidation of the dielectric, and mechanical stress can lead to crack propagation through the dielectric due to embrittlement caused by oxidation. Oxidation in polymers is initiated and sustained through the generation of radical species. Chain scission due to thermal vibrations or high energy photons produce free radicals which then react with oxygen leading to high energy activated moieties. These radicals then react with another molecule to lower their energy state and the auto-oxidation process is repeated. The usage of antioxidants, such as bulky phenols or hindered amines, in dielectrics is known to limit the auto-oxidation process (see Figure 5) as the antioxidant consumes free radicals as they are generated. Replenishing antioxidants and other additives through cable rejuvenation may inhibit free radical formation and reduce the risk of cable failure by decreasing the rate of polymer degradation [27]. Antioxidants used with commercially available silane-based rejuvenation fluids (described below), for example, should have the following properties: (i) good miscibility with the primary rejuvenation fluid (silanes), (ii) reactivity with monomers that are formed after the primary rejuvenation fluid reacts with water, and (iii) the ability to provide good dielectric properties at the ambient temperatures and conditions of the cable to be rejuvenated [27]. An example of such an antioxidant is 4-[(dimethoxymethylsilyl) propyl]-2,6-di-tertbutylphenol [27].

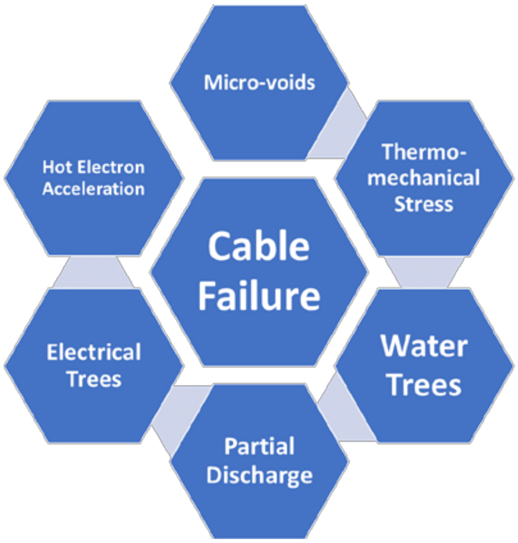


Figure 4. Possible mechanisms leading to the moisture-related failure of electrical cable insulation.

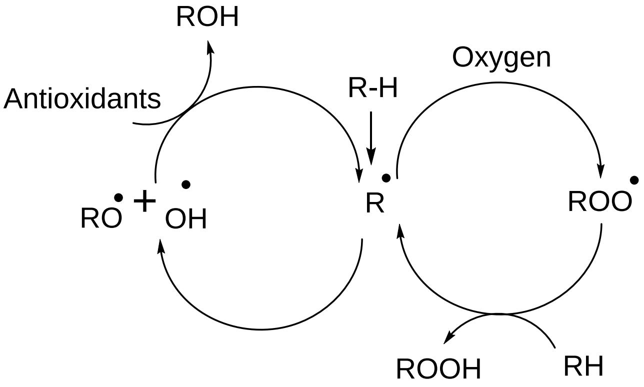


Figure 5. The polymer oxidation cycle and the role of antioxidants.

# 3. ELECTRICAL CABLE REJUVENATION

For the last few decades cable rejuvenation has been considered the modern go-to option for extending the life of electrical cables in power production and electric utilities [20]. In the last 30 years over 80 million feet of medium voltage power cables have been rejuvenated. Replacing degraded electrical cables is a challenging task as it comes with a large economic risk, including the potential for extended plant downtime. The cost for rejuvenation is advertised to be much less than the cost of replacement. It may also be faster to implement and less disruptive to plant operations and as well to the environment. In the past, cable rejuvenation has been primarily focused upon injecting silicone-based fluids into strands of aging medium voltage power cables; the injected fluids migrate through the cable to locations of water treeing, react with water, and enhance the dielectric properties of the insulation.

## 3.1 History and Status of Silane Injection Technology

In early 1970, in an aim to address the issue of water treeing in dielectrics, researchers investigated the use of dry gas technology to enhance insulation cross-linking with partial success. An alternate approach was undertaken in the mid-1980s whereby acetophenone, a known plasticizer and byproduct of XLPE, was injected into degraded electrical cables. It was assumed that acetophenone would migrate to the location of the water trees and fill the formed voids thereby reducing the likelihood of electrical treeing. However, large-scale adaptation was hindered due to the poor chemical compatibility of acetophenone, a regular maintenance cycle which required re-supplying the acetophenone, and a relatively high freezing point (approximately 20°C) making injection of acetophenone difficult. To address these issues, acetophenone was mixed (at least 50%) with propylene carbonate to enable injection over a wide range of temperatures. However, the action of this mixture was not sustained enough to provide a lasting benefit. To avoid the above issues, a new silicone-based injectable cable rejuvenation fluid was developed in 1989 that extended the life of electrical cables for decades [14,28–32]. A summary of common silicone-based rejuvenation fluids (RFs) is shown in Table 1. Since their inception, millions of feet of electrical cable have been successfully treated using silane (silicone-based) injection technology as shown in Figure 6 [33].

Table 1. Development of rejuvenation fluids in the past.

| **Rejuvenation Fluid** | **Composition of Rejuvenation Fluid (wt. %)** | | | |
|---|---|---|---|---|
| | **-** | **RF1** | **RF2** | **RF3** |
| Acetophenone | 100 | - | - | - |
| $PhMeSi(OMe)_2$ (PMDMS) | - | 99.8 | 70.0 | 95.0 |
| $Ti(OCH(CH_3)_3)$ (TIPT) | - | 0.2 | 0.2 | 0.2 |
| $Me_3SiOMe$ (TMMS) | - | - | 28.8 | 4.8 |

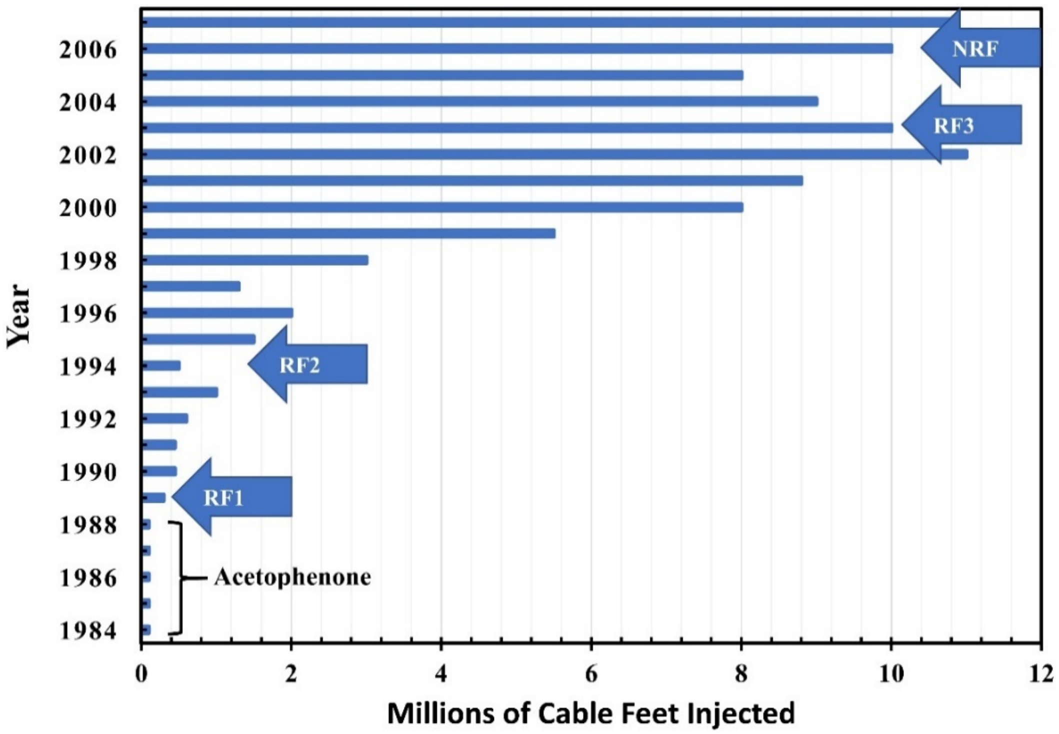


Figure 6. Development of cable rejuvenation fluids and corresponding millions of feet of cable injected.

Conventionally injected rejuvenation fluids inhibit or stop water tree formation by consuming water in the electrical cable. The injected fluids reacts with water to form a polymer analogue with a dielectric constant significantly higher than water or air [34]. Phenylmethyl dimethoxysilane (PMDMS) was the first silicone-based injectable rejuvenation fluid due to its high reactivity with water. In addition to PMDMS, titanium isopropoxide (TIPT) was used as a catalyst at low weight fractions during the condensation step to enable cross-linking of the injectable fluid [28]. TIPT also reacts with water to form $TiO_2$ nanoparticles which have excellent dielectric properties and act as a nanofiller, replacing water within voids created by water trees. The reactive groups ($OCH_3$) of the injected silanes form methanol and short polymer segments (monomer) when exposed to water. After the first hydrolysis reaction, the methoxy groups on the injected silane are converted to hydroxy groups [33]. The formation of hydroxyl groups is a spontaneous reaction and will be formed with or without TIPT. However, with TIPT a second hydroxyl reaction will occur to produce an oligomer with two monomer units. It has been assumed that because of the density difference, methanol will diffuse out of the insulation [35]. The reaction continues until all the reactive methoxy groups in the injected fluid are consumed leading to longer oligomers. When the newly formed oligomers become at least 5-8 units long, their viscosity slowly increases to the point where they become immobile, producing a protective layer around the damaged insulation. Silane activity, chain length, rate of rejuvenation, and penetrability play a critical role for these silane-based fluids.

While the above first-generation rejuvenation fluid was successful in extending the life of electrical cables, the difficulty of injecting the fluid into cables and slow reaction rate led to an inhomogeneous distribution of the fluid. To increase the reaction rate of the rejuvenation process, a new rejuvenation fluid mixture was developed. The newly developed fluid comprised PMDMS, TIPT, and trimethylmethoxysilane (TMMS) (see Table 1 and Figure 7). While TMMS is also a silane, it penetrates polymeric dielectrics about 25 times faster than PMDMS [14,36]. This formulation was noted to contribute to corrosion of aluminum conductor strands. With reductions of the concentration of TMMS to approximately 5%, corrosion was addressed while the improved penetration potential of the injection fluid was retained. Diphenyl-dimethoxysilane (DPDMS) is another silane that was heavily studied due to its ability to penetrate dielectrics faster and easier as it has more methyl groups than PMDMS. While earlier generation rejuvenation fluids (such as those shown in Table 1) were initially successful, long-term reliability was limited due to migration of the fluid out of the electrical cable. To enhance long-term reliability, new rejuvenation fluids were developed. The newly developed rejuvenation fluids (for example, U732 by Novinium) contain chemical components that provide voltage stabilization to reduce water treeing, UV-stabilization, and antioxidants to limit oxidation.

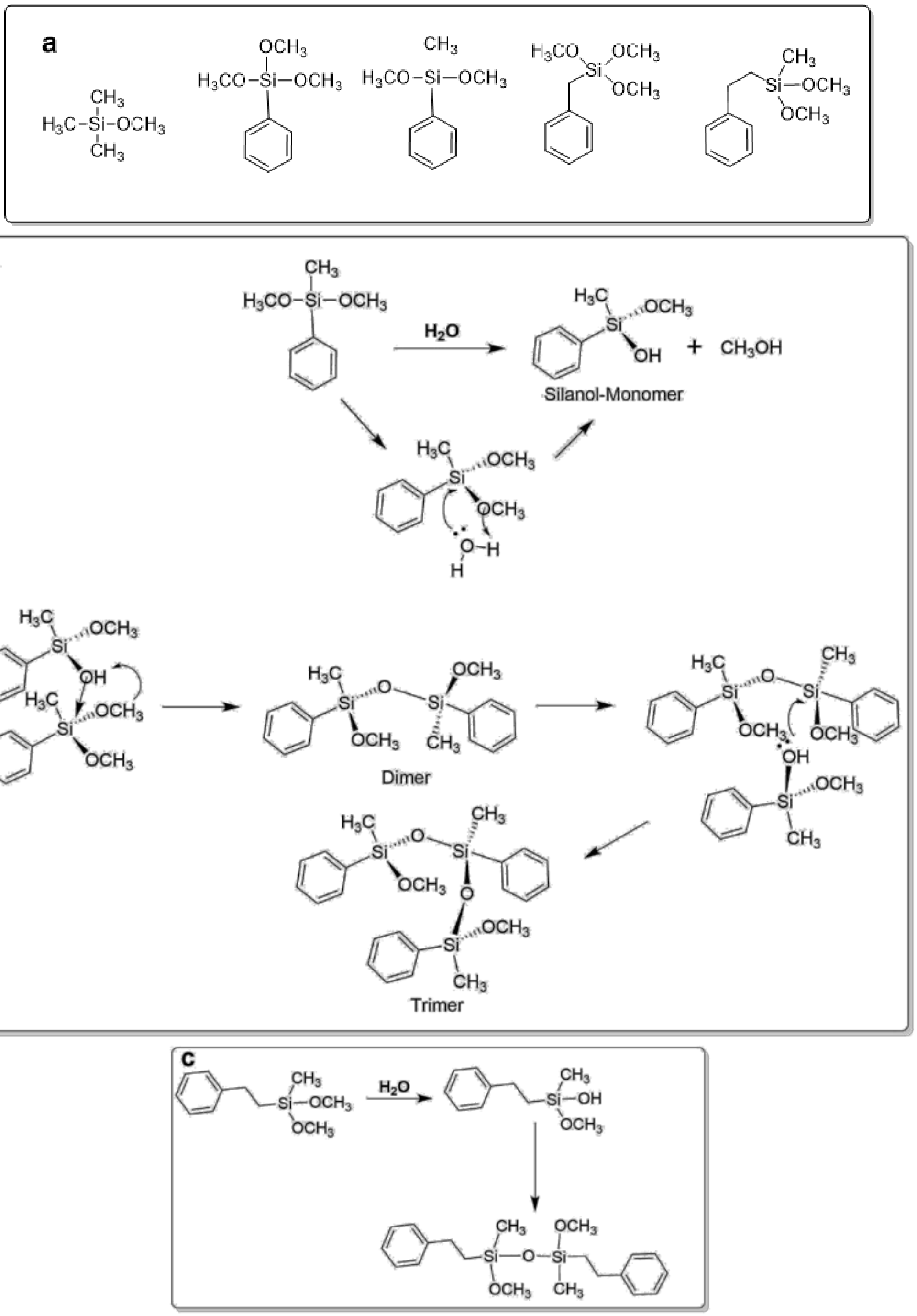


Figure 7. (a) Common injectable silanes used for the lifetime extension of cables and (b & c) illustration of the rejuvenation process.

Besides the chemistry of the rejuvenation fluid, the success of the rejuvenation approach relies on the injection method. Historically, fluid injection has been conducted using several techniques. Unsustained pressure rejuvenation (UPR) uses low pressures (10 to 15 psi) to inject fluids into cable strands through injection elbows or connection ports. Before the fluid is injected, an air test is performed to ensure that there is a flow path for the injection fluid. As the pressure is low, it takes time for the injection fluid to flow from the injection point to the end of the cable. For example, it can take between 48 to 72 hours for the injection fluid to flow through a 300-foot cable segment and the dielectric strength of the rejuvenated cable will be restored in about 24 months or at rate of 0.5% per day. As the viscosity of the rejuvenation fluid and the reaction and cross-linking rate are dependent upon temperature, it is expected that elevated temperature conditions would accelerate the rejuvenation process. Furthermore, cable segments with underlying conditions, such as strand corrosion, may need additional time. To address this issue, a sustained pressure rejuvenation (SPR) process was developed in which the rejuvenation fluid is injected into cable strands at moderate pressure (100 to 300 psi) [37]. Because of the higher pressures, the SPR approach is relatively fast and the dielectric strength of SPR rejuvenated cables can be restored in approximately 7 days with minimal operational impact. SPR is the current state-of-the-art that is used to inject rejuvenation fluids (with tailored catalyst and oxidants) that has been shown to extend the life of cables by 40 years [37]. In non-nuclear case studies, cable rejuvenation has been calculated to yield an approximate savings of 40 percent over total cable replacement. As the cable rejuvenation process is relatively simple, there is a minimum ecological impact with no new pollution or extra resources consumed. Correspondingly, cable rejuvenation provides at least a 3000-metric ton reduction in environmental $CO_2$ for every 10 miles of cable not replaced and, for each meter of rejuvenated cable, saves approximately 195 grams of aluminum, 484 grams of copper and 963 grams of plastic [38]. Perhaps the most important aspect of cable rejuvenation is that it often results in fewer outages as fluid injection is a faster process than complete cable replacement.

## 3.2 Inclusion of Nanoparticles

Research has shown that the addition of nanoparticles such as $SiO_2$, $Al_2O_3$ or $TiO_2$, to cable insulation can improve dielectric and mechanical properties. Due to their high surface-to-volume ratio, and correspondingly high surface energy, interfacial interactions between the nanofiller and the polymer matrix can produce composites with desirable and tailored properties. For example, the addition of only 1 wt. % $SiO_2$ (specific surface area 380 $m^2/g$ and particle diameter range 3–15 nm) to XLPE improved the dielectric strength by 65%, the tensile strength by 6%, and the elongation by 47% as shown in Figure 8 [39]. However, compatibility between the nanofiller and polymer matrix is very important to ensure such property enhancements. Commonly, compatibility is controlled by functionalizing the surface of the nanofiller to bond to the polymer matrix (see Figure 9). Surface functionality can also limit agglomeration which can reduce mechanical strength and dielectric performance. In a recent study, $TiO_2$ surface-functionalized with dimethyloctylsilane (MDOS) was shown to enhance the volume resistivity and dispersion (reduced agglomeration) in XLPE [40].

The use of inorganic nanofillers has been a recent trend in silicone-based rejuvenation fluids. By adjusting the chemistry of the rejuvenation fluid, coupling between the nanofiller and insulation can be controlled. Furthermore, due to the size of the nanofiller, it can occupy and cover water trees uniformly. Gamma-phase alumina [41] is a common nanofiller in rejuvenation fluids due to its high melting point (2054°C) which provides stability during electrical discharge. This filler also imparts mechanical strength, cracking resistance, and desirable thermal properties. For nanofillers with hydroxyl groups (-OH), coupling with the insulation is a straight-forward process: (1) methoxy groups of PMDMS react with water to form silanol, (2) silanol reacts with hydroxy groups on the nanofillers to form siloxane, and (3) micro voids in the insulation containing both oxygen and carboxyl groups react with silanes or other groups in the rejuvenating fluid resulting in nanoparticle attachment to the polymer matrix. The long-term stability created by oxidation of the resulting nanocomposite may be reduced due to the adsorption of antioxidants on the nanofiller surface and possible transfer of catalytic impurities from the nanofillers to the polymer matrix.

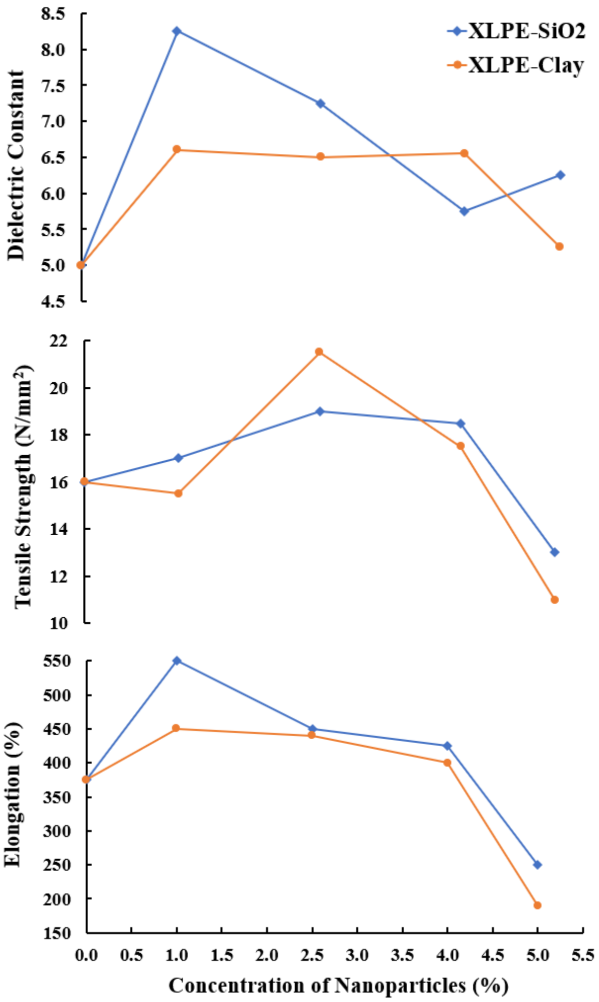


Figure 8. Enhancement of dielectric strength, tensile strength, and elongation of XLPE modified with $SiO_2$ and clay nanoparticles.

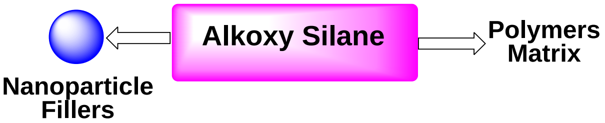


Figure 9. Coupling between nanofillers and the polymer matrix using silanes.

## 3.3 Self-Healing Approaches

Self-healing materials that can restore insulation properties to a pre-damaged state could play an important role in the electrical cable industry (see Figure 10) [42–44], especially in conditions where electrical cables are not easily accessible. While many types of self-healing materials have been developed, they are broadly classified based on their ‘extrinsic’ or ‘intrinsic’ processing mechanisms. In the case of an extrinsic mechanism, self-healing relies on the availability of healing agents which are dispersed throughout the insulation in various forms or networks. When the insulation is damaged, the healing agents undergo changes in their chemistry, such as a coupling reaction with the polymer to repair the damaged region. Conversely, the intrinsic mechanism incorporates labile bonds within the structure itself. When the insulation is damaged, the self-healing material immediately cross-links with the insulation to prevent further damage. Each of these approaches has advantages and disadvantages that need to be evaluated based upon the application. For example, extrinsic self-healing materials often result in materials that are mechanically and chemically dissimilar to that of undamaged material, while intrinsic materials can only activate a limited number of times and a resupply of healing agents is needed for continuous repair.

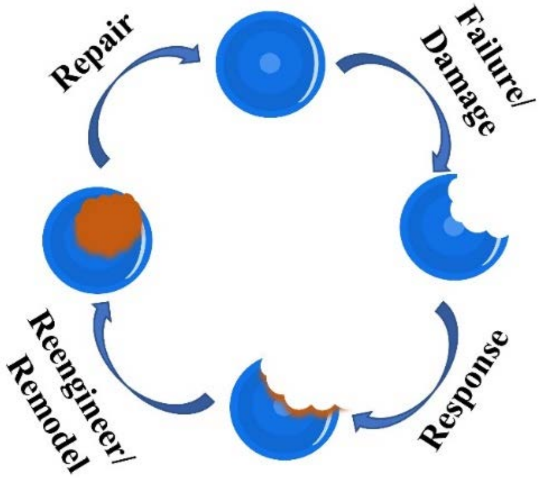


Figure 10. The repair cycle of self-healing insulation material.

Currently, to avoid the formation of water trees, water blocking tapes (WBT) are used which contain highly swellable materials such as poly(sodium acrylate) (PSA). Although a simple technique, such a method can pose issues due to the poor mechanical strength in the damaged area. However, the usage of a self-healing material might simultaneously address the issue of water tree formation and provide mechanical support. An example is hydrophilic thermoplastic elastomers which swell when reacting to water. More recently, the self-healing of electrical cable insulation against water treeing was achieved using 0.1 vol. % of superparamagnetic nanoparticles in a thermoplastic polymer [45]. The nanoparticles enabled repair of regions damaged by electrical treeing with localized heating of the insulation caused by dissipation of heat from magnetic losses associated with an AC magnetic field. Interestingly, this resulted in the regeneration of the dielectric strength over multiple cycles of tree formation and healing. Newly developed self-healing insulating materials use host-guest interactions to self-heal [46].

## 3.4 Radiation Resistant Materials

Protection of electrical cables from radiation remains an attractive strategy and new radiation resistant nanocomposites have been developed that mitigate radiation degradation mechanisms [47]. Researchers at Oak Ridge National Laboratory recently developed nanocomposite insulating materials that mitigate free radicals generated by radiolysis [48]. Different types of nanoparticles ($SiO_2$, $TiO_2$, and MgO) were used with cross-linked polyvinyl alcohol (PVA/XLPVA), XLPE, and polyimide [49]. The chemical, electrical, and mechanical performance of each polymer was evaluated as a function of radiation dose exposure and composition. In the presence of nanoparticles, the erosion radius of the insulation decreased significantly when compared to neat insulation. While improvements in the dielectric strength were observed to depend primarily on the nanoparticle concentration, degradation due to moisture was also observed. It was concluded that the overall dielectric strength performance of nanocomposites depends heavily on uniform dispersion and distribution of nanoparticles with no particle aggregation. Nanoparticle aggregation often resulted in loss of electrical strength, high levels of partial discharge, or shortening of insulation life [48].

# 4. CHALLENGES AND RESEARCH OPPORTUNITIES

While previous work has focused on developing cable rejuvenation fluids that contain antioxidants or nanofillers, a cohesive approach is needed to develop a cable rejuvenation fluid which contains nanofillers, antioxidants, and also offers thermal and radiation protection. There is an immediate need to develop a next generation rejuvenation fluid that is not only capable of reacting with water easily but also has the capability to trap free radicals and protect the cable from thermal and radiation damage.

The addition of nanofillers to rejuvenation fluids can enhance electrical performance and further extend cable lifetimes, but poor design of the nanofiller composition can have a negative effect [50]. In particular, nanofiller agglomerates may result in inhomogeneous accumulation in water tree voids and result in a decrease of mechanical strength and electrical breakdown strength of the polymeric insulation [50]. Furthermore, an excess concentration of nanofiller can result in poor interfacial adhesion between the nanofiller and insulation, which may lead to reduced electrical performance of rejuvenated cables. The high surface-to-volume ratio of nanofiller can also result in adsorption and compromise antioxidants in the rejuvenation fluids, which may have an impact on the long-term stability of rejuvenated cables. Suitable functionalization of nanofillers could inhibit agglomeration and at the same time improve interfacial adhesion with the cable insulation. Besides inorganic nanoparticles, such as $SiO_2$, $TiO_2$, MgO and gamma-alumina, reconstructed layered double hydroxides (LDH), which are known for their oxygen and water barrier properties, could play critical role in cable rejuvenation [49]. High aspect ratio nanosheets of LDH are important to achieve tortuous pathways as illustrated in Figure 11. This is a well-recognized concept for gas barrier [51], moisture barrier [50], and insulation and flame retardant materials. Another potential solution to the issue of nanoparticle agglomeration is the usage of ‘hedgehog’ particles [52] that use topological rather than chemical surface effects to control interparticle attraction.

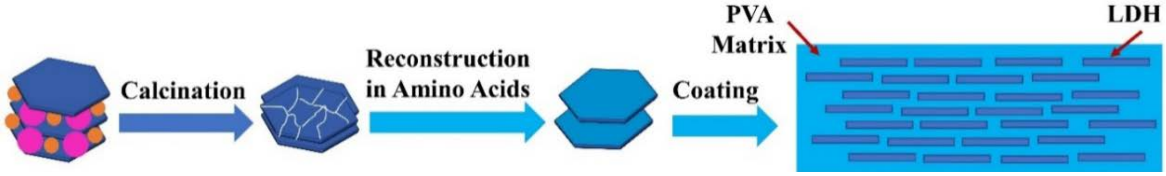


Figure 11. (a) LDH reconstruction and cross-sectional view of oxygen barrier coatings containing LDH nanosheets.

Antioxidants can impart improved radiation and thermal resistance to rejuvenated cables. Antioxidants are currently used in cable rejuvenation to trap or stabilize generated radicals and to decompose peroxide into alcohol. The use of multiple antioxidants is cumbersome, and control of their properties becomes difficult at scale. Furthermore, additional antioxidants may need to be injected into the rejuvenated cable over time to mitigate against thermal or radiation stress. An alternate approach is to develop a novel self-renewing antioxidant that can scavenge high energy hydroxyl free radicals. An example of such an antioxidant is cerium oxide (Figure 12) [53,54]. Demonstrating good biocompatibility, and a unique redox process, the antioxidant activity of cerium oxide ($CeO_2$) relies upon the availability of $Ce^{+3}$ at the particle surface, which makes the overall process size-dependent [53,54]. Due to this, cerium oxide has the unique property that it is self-regulative and self-regenerative and there is no need to renew the antioxidant over time.

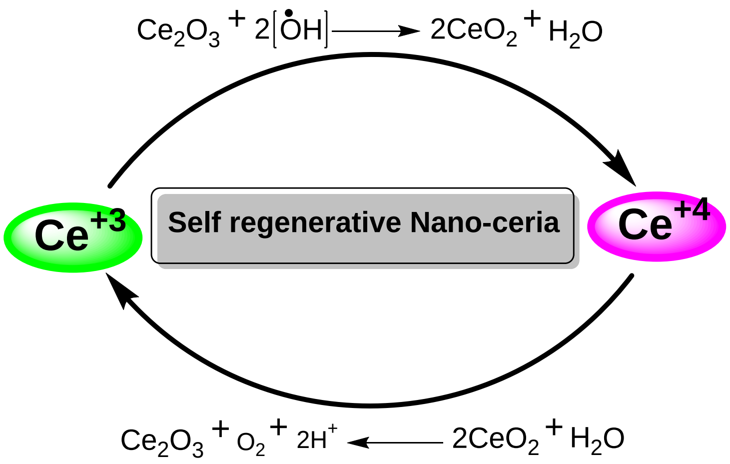
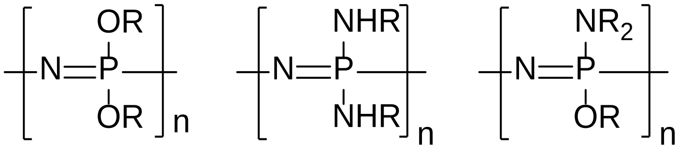


Figure 12. The free radical scavenging property of cerium oxide.

In addition to nanofillers and antioxidants, improvements to rejuvenated cable flame resistance is desirable to further extend cable lifetime. Phosphazene-based materials [(-P=N-)n] have been heavily studied as flame- and fire-retardant coatings due to their low flammability and low vapor pressure [55], making them attractive additives for rejuvenation fluids. Polyphosphazenes are useful as they are compatible with a wide range of functional groups, such as -OH or $-NH_2$, due to the presence of chlorine, which can be substituted via nucleophilic substitution [56]. Due to this, phosphazenes (see Figure 13) can easily be covalently cross-linked to the insulation, as well as the rejuvenation fluid. Furthermore, because of stable phosphorus-oxygen linkages (bond energy: 410 kJ/mol vs. C-O 358 kJ/mol) in the phosphazene-based materials, they are highly stable against water and have a high tolerance to extreme environments (temperature, radiation, etc.).



R = Rejuvenated fluid (Silane)

Figure 13. Schematic representation of different types of phosphazenes.

# 5. CONCLUSIONS

Efficient and effective options for cable aging management are of increasing importance to the nuclear industry. Cable rejuvenation may present an effective, cost-saving option to extend the life of installed cables with signs of age-related degradation. While commercial rejuvenation fluids have been demonstrated to extend the life of underground cable systems by more than 20 years, additional work is needed to verify performance of rejuvenated cables with respect to the original design basis of nuclear power plant electrical cables. A new generation of fluids capable of rejuvenating not just moisture-degraded cables, but also thermal or radiation degraded cables could include such features as self-regenerable nanoparticle antioxidants, thermally protecting phosphazenes, or layered double hydroxide materials for oxygen and radiation protection. Development of technological solutions to recover performance from installed, degraded cables for use in the nuclear industry will likely require confirmation of the effect of treatment on the results of current cable test methods, a justification for consideration of a treated environmentally qualified cable as qualified, and an understanding of any effects of treatment on the performance of safety-related cables in the advent of a design basis event.

# 6. REFERENCES

[1] P.L. Joskow, The Future of nuclear power in the United States: Economic and regulatory challenges, (2006).

[2] M. Subudhi, Literature Review of Environmental Qualification of Safety-Related Electric Cable, 1 (1996) 1–306. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/27/059/27059900.pdf.

[3] R.F. Gazdzinski, W.M. Denny, G.J. Toman, R.T. Butwin, SAND96-0344: Aging Managment Guideline for Commercial Nuclear Power Plants - Electrical Cble and Terminations, 2000.

[4] NRC, Expanded Materials Degradation Assessment (EMDA), Volume 5: Aging of Cables and Cable Systems, NUREG/CR-7153, 2014.

[5] Nuclear Energy Agency - Committee on the Safety of Nuclear Installations, NEA/CSNI/R(2018)8 Cable Ageing in Nuclear Power Plants, 2018.

[6] L.S. Fifield, A. Zwoster, M. Murphy, PNNL-27987: Initiation of Experimental Campaign to Address Knowledge Gaps Related to Simultaneous Thermal and Gamma Radiation Aging of Crosslinked Polyethylene and Ethylene-Propylene Rubber Cable Insulation, Richland, WA, 2018.

[7] K.T. Gillen, Importance of Synergism for Degradation of Elastomers in Combined Radiation Plus Temperature Environments, Rubber Chem. Technol. 93 (2019) 121–141. https://doi.org/10.5254/rct.19.80457.

[8] T. Seguchi, K. Tamura, T. Ohshima, A. Shimada, H. Kudoh, Degradation mechanisms of cable insulation materials during radiation-thermal ageing in radiation environment, Radiat. Phys. Chem. 80 (2011) 268–273. https://doi.org/10.1016/j.radphyschem.2010.07.045.

[9] K.T. Gillen, R.L. Clough, Rigorous experimental confirmation of a theoretical model for diffusion-limited oxidation, Polymer (Guildf). 33 (1992) 4358–4365. https://doi.org/10.1016/0032-3861(92)90280-A.

[10] L. Verardi, D. Fabiani, G.C. Montanari, Correlation of electrical and mechanical properties in accelerated aging of LV nuclear power plant cables, ICHVE 2014 - 2014 Int. Conf. High Volt. Eng. Appl. (2014) 1–4. https://doi.org/10.1109/ICHVE.2014.7035376.

[11] G. Przybytniak, J. Boguski, V. Placek, L. Verardi, D. Fabiani, E. Linde, U.W. Gedde, Inverse effect in simultaneous thermal and radiation aging of EVA insulation, Express Polym. Lett. 9 (2015) 384–393. https://doi.org/10.3144/expresspolymlett.2015.36.

[12] K.T. Gillen, R.L. Clough, Time-temperature-dose rate superposition: A methodology for extrapolating accelerated radiation aging data to low dose rate conditions, Polym. Degrad. Stab. 24 (1989) 137–168. https://doi.org/10.1016/0141-3910(89)90108-0.

[13] PNNL, Light Water Reactor Sustainability (LWRS) Program–Non-Destructive Evaluation (NDE) R&D Roadmap for Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants, PNNL-21731. (2012).

[14] G. Bertini, History and Status of Silicone Injection Technology, Novimium. (2007).

[15] B. Bernstein, Extending the Service Life of Ethylene Propylene Rubber Insulated Cables, 2002.

[16] B. Fryszczyn, Plant Engineering: Results of Cable Rejuvenation of Severely Degraded Black Ethylene Propylene Rubber Medium-Voltage Cables, 2013.

[17] L.S. Fifield, T.D. Smurthwaite, J.A.S. Robers, B.J. Tarasevich, M.P. Westman, A.J. Zwoster, Progress at PNNL on New Technologies for Repairing Aging Cables in Nuclear Power Plants, 2015.

[18] Y. Del Valle, N. Hampton, J. Perkel, C. Riley, Underground Cable Systems underground cable systems, in: Encycl. Sustain. Sci. Technol., Springer New York, New York, NY, 2012: pp. 11158–11187. https://doi.org/10.1007/978-1-4419-0851-3_758.

[19] M. Acedo, I. Radu, F. Frutos, J.C. Filippini, P. Notingher, Water treeing in underground power cables: modelling of the trees and calculation of the electric field perturbation, J. Electrostat. 53 (2001) 267–294.

[20] W. Shu, S.A. Boggs, Effect of Cable Restoration Fluid on Inhibiting Water Tree Initiation, Ieee

Trans. Power Deliv. 26 (2011) 97–100.
[21] W. Shu, J. Guo, S.A. Boggs, Water Treeing in Low Voltage Cables, Ieee Electr. Insul. Mag. 29 (2013) 63–68.
[22] R. Patsch, J. Jung, Water trees in cables: generation and detection, Iee Proceedings-Science Meas. Technol. 146 (1999) 253–259.
[23] H. Wutzel, M. Jarvid, J.M. Bjuggren, A. Johansson, V. Englund, S. Gubanski, M.R. Andersson, Thioxanthone derivatives as stabilizers against electrical breakdown in cross-linked polyethylene for high voltage cable applications, Polym. Degrad. Stab. 112 (2015) 63–69.
[24] E. McMahon, Polyethylene insulation containing a tree growth-inhibiting alcohol, US 4206260 A. (1980).
[25] Hjertberg T, V. Englund, Polyolefin composition for Medium/High/Extra high voltage cables with Improved Electrical Breakdown Strength., US20100263903 A1. (2010).
[26] W. Dong, X. Wang, B. Tian, Y.G. Liu, Z.X. Jiang, Z.G. Li, W. Zhou, Use of Grafted Voltage Stabilizer to Enhance Dielectric Strength of Cross-Linked Polyethylene, Polymers (Basel). 11 (2019).
[27] G. Bertini, D. Busby, R. Varjian, Anti-oxidant additive for underground cable rejuvenation fluidsPublisher: IEEE, 2015 IEEE Electr. Insul. Conf. 10.1109/IC (205AD).
[28] K. Zhou, X. Tao, X. Wang, W. Zhao, W. Tao, Insight into the new role of titanium isopropoxide catalyst on rejuvenation for water tree aged cables, IEEE Trans. Dielectr. Electr. Insul. 22 (2015) 611–618. https://doi.org/10.1109/TDEI.2014.004065.
[29] S. Pelissou, C. Dang, S. St-Antoine, Underground Medium-Voltage Cable Rejuvenation-Part III: Influence of Operating and Emergency Conditions, Ieee Trans. Power Deliv. 27 (2012) 214–223.
[30] S. Pelissou, G. Lessard, Underground Medium-Voltage Cable Rejuvenation-Part I: Laboratory Tests on Cables, Ieee Trans. Power Deliv. 26 (2011) 2324–2332.
[31] S. Pelissou, S. St-Antoine, Underground Medium-Voltage Cable Rejuvenation-Part II: Pilot Projects in the Field, Ieee Trans. Power Deliv. 26 (2011) 2605–2612.
[32] Y. Xie, Y.F. Zhao, S.Z. Bao, P.Y. Wang, J.S. Huang, G. Liu, Y.P. Hao, L.C. Li, Rejuvenation of Retired Power Cables by Heat Treatment: Experimental Simulation in Lab, Ieee Access. 8 (2020) 5635–5643.
[33] G. Bertini, Rejuvenation Reformulated, Novinium. (2007).
[34] A.H.M. Shirazi, S.M.H. Hosseini, Comparison of aged XLPE power cables restoration by injecting two various anti-failure nanofluids, Eng. Fail. Anal. 90 (2018) 262–276.
[35] G. Bertini, D. Busby, R. Varjian, Anti-Oxidant additive for underground cable rejuvenation fluids, 33rd Electr. Insul. Conf. EIC 2015. (2014) 317–320. https://doi.org/10.1109/ICACACT.2014.7223562.
[36] G. Bertini, G.A. Vincent, Cable Rejuvenation Mechanisms: Update, Novinium. (2006).
[37] R.K. Brinton, Cable Rejuvenation, IEEE PES. Novinium (2010).
[38] R.K. Brinton, G.J. Bertini, Extending Power Cable Life an Additional 40 YearsRichard, Novimium. (2007).
[39] S. ESA, O. ES, E. M, W. El-Kattan, Modified Cable Insulation Characteristics Using Nano Composites for the Nuclear Power Plant, J Electr Electron Syst. 8 (2019) 1000298. https://doi.org/10.4172/2332-0796.1000298.
[40] Y.Y. Wang, K. Xiao, C. Wang, L.J. Yang, F.P. Wang, Effect of Nanoparticle Surface Modification and Filling Concentration on Space Charge Characteristics in TiO2/XLPE Nanocomposites, J. Nanomater. 2016 (2016).
[41] A.H.M. Shirazi, S.M.H. Hosseini, Comparing the Performance of gamma-Alumina Nanofiller and Titanium Tetraisopropoxide Catalyst in the Rejuvenation of Water Tree Degraded XLPE Cables, J. Electron. Mater. 48 (2019) 6240–6252.
[42] Y. Murakami, M. Nagao, M. Kosaki, Electrical Insulation Performance of Paper-Ice Composite Insulation System at Cryogenic Temperature, Ieej Trans. Electr. Electron. Eng. 4 (2009) 640–644.
[43] M.S. Lin, L. Peng, S. Zhang, L. Li, Q. Fu, J.B. Hou, Preparation and Functions of Self-healing

Light-shielding Paints for Cable Cover, Chem. J. Chinese Univ. 40 (2019) 1766–1774.
[44] Y.Y. Wang, Y.D. Li, Z.X. Zhang, Y.F. Zhang, Effect of Doping Microcapsules on Typical Electrical Performances of Self-Healing Polyethylene Insulating Composite, Appl. Sci. 9 (2019).
[45] Y. Yang, J. He, Q. Li, L. Gao, J. Hu, R. Zeng, J. Qin, S.X. Wang, Q. Wang, Self-healing of electrical damage in polymers using superparamagnetic nanoparticles, Nat. Nanotechnol. 14 (2019) 151–155. https://doi.org/10.1038/s41565-018-0327-4.
[46] L. Peng, M.J. Zhang, M.S. Lin, Q. Fu, A novel self-healing power cable insulating material based on host-guest interactions, Rsc Adv. 8 (2018) 25313–25318.
[47] Y. Nakamura, M. Sorimachi, H. Kimura, S. MATSUYAMA, RADIATION RESISTANT COMPOSITION, WIRE AND CABLE, US 8,076.408 B2. (2009).
[48] R. Duckworth, T. Aytug, P. Paranthaman, G. Polizos, K. Leonard, Radiation-Resistant Electrical InsulationMaterials for Nuclear Reactors: Final Report, ORNL/SPR-2 (2018).
[49] J. Yu, K. Ruengkajorn, D.G. Crivoi, C. Chen, J.C. Buffet, D. O'Hare, High gas barrier coating using non-toxic nanosheet dispersions for flexible food packaging film, Nat. Commun. 10 (2019) 1–8. https://doi.org/10.1038/s41467-019-10362-2.
[50] F.C. Ding, J.J. Liu, S.S. Zeng, Y. Xia, K.M. Wells, M.P. Nieh, L.Y. Sun, Biomimetic nanocoatings with exceptional mechanical, barrier, and flame-retardant properties from large-scale one-step coassembly, Sci. Adv. 3 (2017).
[51] R.R. Nair, H.A. Wu, P.N. Jayaram, I. V Grigorieva, A.K. Geim, Unimpeded Permeation of Water Through Helium-Leak-Tight Graphene-Based Membranes, Science (80-. ). 335 (2012) 442–444.
[52] J.H. Bahng, B. Yeom, Y. Wang, S.O. Tung, J.D. Hoff, N. Kotov, Anomalous dispersions of "hedgehog" particles, Nature. 517 (2015) 596–599. https://doi.org/10.1038/nature14092.
[53] S. Schlick, M. Danilczuk, A.R. Drews, R.S. Kukreja, Scavenging of Hydroxyl Radicals by Ceria Nanoparticles: Effect of Particle Size and Concentration, J. Phys. Chem. C. 120 (2016) 6885–6890.
[54] G. Vinothkumar, P. Arunkumar, A. Mahesh, A. Dhayalan, K.S. Babu, Size- and defect-controlled anti-oxidant enzyme mimetic and radical scavenging properties of cerium oxide nanoparticles, New J. Chem. 42 (2018) 18810–18823.
[55] V.M. Rangaraj, S. Singh, S. Devaraju, V.S. Wadi, S. Alhassan, D.H. Anjum, V. Mittal, Polypropylene/phosphazene nanotube nanocomposites: Thermal, mechanical, and flame retardation studies, J. Appl. Polym. Sci. (2020).
[56] D. Mathew, C.P.R. Nair, K.N. Ninan, Phosphazene-triazine cyclomatrix network polymers: some aspects of synthesis, thermal- and flame-retardant characteristics, Polym. Int. 49 (2000) 48–56.