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Light Water Reactor Sustainability Program

Assessment of Cable Aging Equipment, Status of Acquired Materials, and Experimental Matrix at the Pacific Northwest National Laboratory

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Approved by:

Steve Schlahta — Date
Director, Nuclear Science Project Management Office

SUMMARY

Despite the significant progress that has been made in recent years in the understanding of aging and degradation mechanisms of polymeric cable materials in nuclear power plants, there is further need to quantify and reduce uncertainty in condition-based cable remaining useful life prediction. Investigation of inhomogeneous aging, material microstructure evolution with aging, and correlation of mechanical, electrical and chemical changes with material aging will enable improved material aging models and support cable replacement decisions.

The most significant long-term aging and degradation mechanisms for polymer cable materials are based on exposure to elevated temperatures and to gamma radiation. Pacific Northwest National Laboratory (PNNL) has established capabilities for thermal aging of polymer samples using standard methods with control of temperature stability, sample isolation, and air recirculation. Cable materials are aged as intact cable segments and as isolated specimens of insulation and jacket materials. PNNL has also established unique “in-situ method” accelerated aging capabilities in which cable and material properties are continuously monitored directly during exposure. The combined effects of thermal and gamma radiation exposure on cable material degradation are being investigated both at PNNL and in partnership with Oak Ridge National Laboratory. Short- and long-term exposure capabilities are being established that allow for exploration of the effects of dose rate, total dose, and temperature on sample degradation.

Selections of the highest priority nuclear cable materials including cross-linked polyethylene and ethylene-propylene rubber in their modern formulations have been obtained with guidance directly from cable suppliers including RSCC Wire & Cable and The Okonite Company. Vintage cable samples that have not been put into service have been obtained from the Electrical Power Research Institute. Plans are in place to receive prioritized fielded cable samples from retired nuclear power plants including Zion and Crystal River. Aging, analysis, and prediction techniques being established on readily available contemporary cables will be extended and applied to the limited supply vintage cables to establish improved lifetime prediction capability for in-service cables. Analysis of harvested cables will provide verification and refinement of established models.

PNNL is aging materials under different conditions and relating the measurable changes in cable properties with exposure, using multiple samples and measurements to generate each data point of condition versus age toward relation of cable material condition with remaining useful life. Quantification of uncertainty in the measurements and scatter in the results will enable assignment of confidence levels in lifetime prediction based on condition information. Ethylene-propylene rubber is being thermally aged at a series of temperatures from 100^{o}C to 140^{o}C. Aging is being carried out on multiple forms of the material, including intact cable and isolated rubber specimens, to assist in understanding of the effect of material form on aging and to facilitate various characterization techniques.

The combined effects of thermal and radiation stress on nuclear cable materials represent one of the major knowledge gaps important for condition-based lifetime prediction. Prioritized experiments at PNNL aim to increase understanding of synergistic effects, in which the degradation due to concurrent heat and radiation is greater than that of the two applied sequentially, and inverse temperature effects, in which radiation damage is actually greater at lower temperatures than it is at higher temperatures. Cross-linked polyethylene is being aged both as intact cable component and separated from the cable. The effects of the sequence of gamma irradiation exposure and thermal exposure of cross-linked polyethylene at temperatures up to 135^{o}C and dose rates up to 5.5k rad/h are being determined.

The anticipated outcomes of this program are: improved understanding of appropriate accelerated aging conditions, improved knowledge of correlation between observable aging indicators and cable condition in support of advanced non-destructive evaluation methods, and practical knowledge of condition-based cable lifetime prediction.

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ACRONYMS AND NOMENCLATURE

AMS	Analysis and Measurement Services Corporation
ASTM	International standards organization
CPE	chlorinated polyethylene
Crystal River	Crystal River 3 Nuclear Power Plant, Florida
CSPE	chlorosulfonated polyethylene synthetic rubber
DMA	dynamic mechanical analysis
DOE	U.S. Department of Energy
EAB	elongation at break
EMDA	Expanded Materials Degradation Assessment
EPDM	cross-linkable ethylene-propylene rubber
EPR	ethylene-propylene rubber
EPRI	Electric Power Research Institute
FTIR	Fourier transform infrared spectroscopy
GIF	Gamma Irradiation Facility
HEF	High Exposure Facility
HFIR	High Flux Isotope Reactor
IAEA	International Atomic Energy Agency
NDE	nondestructive evaluation
NRC	National Regulatory Commission
ORNL	Oak Ridge National Laboratory
PIRT	Phenomena Identification and Ranking Technique
PNNL	Pacific Northwest National Laboratory
RPL	Radiological Processing Laboratory
SEM	scanning electron microscopy
SiR	silicone rubber
TGA	thermal gravimetric analysis
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin
Zion	Zion Nuclear Power Station, Illinois

Assessment of Cable Aging Equipment, Status of Acquired Materials, and Experimental Matrix at the Pacific Northwest National Laboratory

1. INTRODUCTION

Continued operation of nuclear power plants beyond their current license periods will require improved understanding of the longevity of safety-related plant components including electrical cables and connectors. Polymeric materials used for cable insulation and jacketing are susceptible to performance degradation over time with exposure to environmental stresses such as heat and radiation. Understanding of cable material degradation under realistic plant conditions enables development of effective condition monitoring techniques and informed prediction of cable remaining useful life. Identifying and reducing uncertainty in condition-based cable lifetime prediction will help to reduce costs while maintaining safety in effective operator aging management plans.

The most important polymer cable materials in U.S. nuclear plants with respect to aging management are cross-linked poly olefins (including cross-linked polyethylene-XLPE), ethylene-propylene based rubbers (including EPR and EPDM), and silicone rubbers. Modern XLPE materials are similar to those used historically in nuclear power plants and to currently-installed vintage materials. EPR formulations, in contrast, have undergone more changes in the history of the nuclear industry in the United States.

Standard accelerated aging methods to effect degradation in electrical cable polymer materials are based on the assumption that more extreme conditions, such as higher temperature or radiation, produce the same aging and degradation in a shorter period of time as less extreme conditions do in a shorter period of time. In this way, the degradation of many decades of exposure can be predicted by practically pursued experiments lasting months or weeks. However, for some conditions relevant to those present in operating nuclear power plants, this proportional exposure assumption is not valid. Complications to the simplistic proportional aging paradigm include inhomogeneous aging (including diffusion-limited oxidation), accelerated aging from the simultaneous presence of thermal and radiation stress (synergistic effects), and the non-intuitive relationship between sample temperature and radiation damage experienced by some materials (inverse temperature effect). These variations from the simple proportional model of aging arise from differences in the mechanisms of material degradation experienced under different combinations of exposure stress.

Increased understanding of the nature and relative importance of degradation mechanisms in polymer cable materials relevant to those currently installed in operating nuclear power plants will enable improved condition-based prediction of cable remaining useful life. Accelerated aging experiments investigating the combined effects of stresses can be performed on achievable time scales from a few weeks to a few years in duration to improve understanding of details of competing degradation mechanisms. Correlation of mechanical, electrical, and chemical changes in polymer material aged under these conditions, as well of the variation and uncertainty in these measurements, will aid in development of useful predictive models.

2. RESEARCH PRIORITIES

The magnitude of electrical cable types and potential for adverse cable environments in the one hundred or so operating nuclear power plants in the United States and the limits to their current licensed operational periods gives urgency to the need to employ limited research resources to the highest priority knowledge gaps. Representing the U.S. Department of Energy (DOE), Pacific Northwest National Laboratory (PNNL) participates in a working group of cable aging research stakeholders that includes representatives from the U.S. Nuclear Regulatory Commission (NRC), and the Electric Power Research Institute (EPRI). Led by Andrew Mantey, Senior Technical Leader at EPRI, the group maintains a multi-year cable research roadmap to assist in coordination of independent research efforts. Priorities identified by the group, particularly those not currently being addressed, provide an input for materials and conditions on which to focus.

Another prime source of information for priority setting is the NRC *Expanded Materials Degradation Assessment (EMDA), Volume 5: Aging of Cables and Cable Systems* document (Bernstein et al. 2014). This document includes a Phenomena Identification and Ranking Technique (PIRT) analysis in which a panel of government and industry subject matter experts categorized polymer materials and thermal/radiation exposure combinations based on susceptibility of the materials to degradation and extent of community knowledge of their degradation behavior. For instance, this document identifies silicone rubber (SiR), cross-linked polyolefin (XLPO), and ethylene-propylene rubber (EPR) under plant conditions of up to 45–55°C and 1–100 rad/h gamma exposure as combinations with relatively high susceptibility and relatively low knowledge—opportunities for prioritized research. Knowledge gaps identified in the EMDA document include activation energies for material degradation, dose rate effects, inverse temperature effects, and understanding of actual nuclear power plant environments (in comparison to laboratory aging environments) (Bernstein et al. 2014).

3. MATERIALS

The most common polymer cable materials in nuclear power plants, representing four out of five cables, are XLPO/XLPE, EPR/EPDM and SiR (Bernstein et al. 2014). Nine in ten plants report XLPO/XLPE and seven in ten report EPR/EPDM as polymer cable materials present in-containment where radiation exposure can be of concern. SiR and CSPE (trade name Hypalon®) were reported to be found in-containment in less than 30% of plants, with other materials less than 20% (EPRI 1994).

The materials deemed to have the highest combination of 1) susceptibility to significant degradation and 2) need for deeper understanding of damage from thermal and irradiative stress, include SiR, EPR, XLPO and CSPE (Bernstein et al. 2014).

To address these knowledge gaps beginning with the highest priority materials, we are therefore focusing on EPR/EPDM, XLPO/XLPE, SiR, and also CSPE. Unfortunately, stock of un-aged examples of many materials of interest currently in place in operating nuclear power plants is in short supply. Where vintage un-aged materials are not available, effort has been made to procure contemporary cables containing insulation and jacketing material with the highest relevance to cables in the field. Small amounts of un-aged cable materials that are available have been sourced as possible, and are intended for confirmatory use following data established on more readily available materials. Actual field-aged cable that has been pulled from operating plants or sourced from retired nuclear power plants is also being procured as possible. This material is invaluable, especially if exposure data for the material is available, for confirming our understanding of aging in the natural environment and for subsequent incremental aging experiments.

Modern formulation of nuclear-grade pink EPR/EPDM has been procured from The Okonite Company in three representative forms. One is medium-voltage, 15kV shielded power cable (Okoguard ®-Okolon® TS-CPE Type MV-105, Catalog number 115-23-2131), with 5.59-mm thick EPR/EPDM insulation and a 2.0-mm thick TS-CPE jacket (TS-CPE is an EPR/CPE composite). Another is medium-voltage, unshielded Okoguard® Aerial Jumper Cable (15kV, 90C rating, Catalog number 303-21-1944), with 5.33-mm thick EPR/EPDM and no jacket. The third form of nuclear-grade pink EPR/EPDM graciously provided to us by Carl Zuidema, Director of Polymer Research of The Okonite Company, is a series of nominally 6-in. × 8-in. × 0.0600-in. press-cured plaques of Okoguard® medium-voltage insulation compound convenient for fabrication of aging and test specimens. Though pink EPR/EPDM is a modern formulation and varies from brown and black EPR formulations employed in the early decades of nuclear power plant construction, is it relevant to pink EPR cables that have been installed in plants in more recent times.

Five hundred feet of modern construction nuclear-grade cable containing XLPE has been graciously provided by Eric Rasmussen, Director of Engineering of RSCC. This cable is Firewall® III Instrumentation Cable, Multi-Conductor Shielded (XLPE/CSPE) (Product Code I46-0021). It consists of a twisted pair of conductors with 0.64-mm thick XLPE insulation surrounded by a shielding layer and 1.1-mm thick CSPE jacket. Firewall ® III XLPE is fire-retardant and the XLPE used in this cable example is reported to be of comparable formulation to that used in the various constructions of modern Firewall ® III cable and to the XLPE used historically in nuclear power plants.

Unused samples of cables used in the construction and operation of decades old nuclear power plants are in relatively short supply. Around 50 feet each of vintage cables from Brand-Rex, The Okonite Company, Rockbestos, and Boston Insulated Wire were graciously supplied by Andrew Mantey, Senior Technical Leader of EPRI. These include EPR/EPDM, XLPE/XLPO, and CSPE materials representing examples of these materials that are decades old, but have not experienced thermal or irradiative stress.

Examples of fielded-cable samples available include an approximately 20-foot length of mildly aged cable with EPR/EPDM insulation and CSPE jacket removed from service at the Fermi II Nuclear Station because of high recorded indenter modulus values in a localized portion of the cable. Fielded cables of a range of priority materials and constructions, and including some lifetime exposure information, is also expected to be received during fiscal year 2015 from the closed Zion nuclear power plant and Crystal River 3 nuclear power plant.

4. ACCELERATED AGING

The nature of polymer cable material changes with aging and degradation in nuclear power plant operation over 40, 60, 80, or more years is important to understand when making decisions about cable replacement, cable safety, and cable continued operations. However, controlled laboratory aging experiments might reasonably last a few years at most. Accelerated conditions are therefore pursued to induce aging and degradation in the cable materials in a manageable period of time between a few weeks and a few years. Understanding and accounting for the differences between field aging and accelerated aging is an important aspect of this work. In general, the closer to field conditions that can be achieved in a laboratory test including lower temperature and lower dose rate, the closer the correlation with field aging that can be expected.

The most common adverse environment experienced by polymer insulated/jacketed electrical cables in the nuclear power plant is elevated temperature. Accelerated thermal aging of cable segments and cable materials at PNNL is performed in temperature-controlled, forced-air ovens equipped with multiple thermocouples for temperature data monitoring and recording. Current aging ovens include benchtop and floor model Thermo Scientific Heratherm mechanical convection ovens, Blue M Mechanical Convection Ovens, and a Tenney Jr. Compact Environmental Chamber.

The irradiative aging and degradation of polymer cable materials in nuclear power plants of primary concern is due to gamma radiation exposure. Cable may experience long-term exposures from zero to 100 rad/h. Laboratory experiments to investigate the combined effects of thermal and radiation exposure, including synergistic effects and inverse temperature effects, involve short- and long-term exposure of samples to controlled temperature and controlled gamma dose rate. Capabilities to perform these experiments include both those available through Robert Duckworth and colleagues at Oak Ridge National Laboratory (ORNL) and capabilities resident at PNNL.

The High Flux Isotope Reactor Gamma Irradiation Facility (HFIR GIF) at ORNL has the ability to age samples at temperatures between 40°C and 100°C with dose rates between 25k rad/h and 10M rad/h. A ^{60}Co irradiator resource at ORNL has an additional available dose rate of 1.4k rad/h (Duckworth 2015).

PNNL gamma irradiation capabilities include those housed at the High Exposure Facility (HEF) and in the Radiological Processing Laboratory (RPL). RPL has the capability to accept radiologically active and/or contaminated samples and provides a vast suite of instrumentation such as scanning electron microscopes and thermal gravimetric analysis (TGA) for sample characterization. Hot cells in RPL may be equipped with gamma sources for designed exposure experiments. The HEF in PNNL Building 318 includes options for table-top exposure and down-well exposure to gamma sources. In the first of these cases, sample specimens are placed at set distances from an exposure window and the source is pneumatically raised from below the floor up in to the window. Dose rates up to 6k rad/h at 30 cm from the source are achievable. Sample temperature may be controlled by housing the samples inside a circulating air laboratory oven during the gamma exposure. In the second, down well, exposure scenario sample specimens are lowered into a long cylindrical chamber in the floor in which a ^{60}Co source is stored. Distance from the source provides control over dose rate and small cylindrical heaters around samples can provide controlled temperature.

Both thermal-only aging and combined thermal/radiation aging samples are prepared and controlled during the aging to maximize uniformity of exposure. Test specimens, such as strips for dynamic mechanical analysis (DMA) and tensile specimens for elongation at break (EAB), are suspended apart from neighbor samples, oven walls, etc. in the oven during aging, as displayed in Figure 1. Mechanical convection is used throughout aging to improve temperature uniformity and to ensure that stagnant atmosphere around samples is not a limiting factor in sample aging.

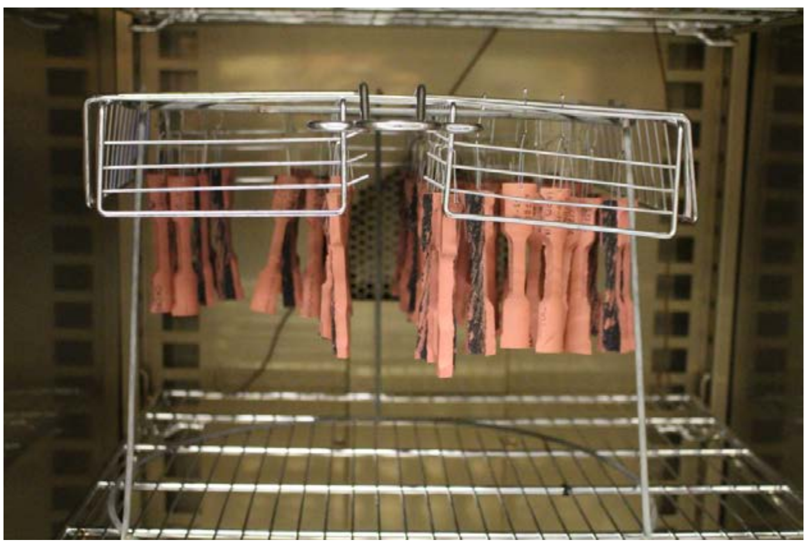

Figure 1. Image of EPR/EPDM test specimens suspended in aging oven

5. MATERIAL CHARACTERIZATION

To develop a better predictive understanding of cable materials changes with exposure to environmental stress, we are investigating key chemical, mechanical, physical, and electrical indicators of change (Simmons et al. 2015). We are relating common cable status metrics, such as EAB and indenter modulus, with observable changes in microscopic structure, changes in chemical molecular structure, and changes in nondestructive evaluation (NDE) signals to get a more complete picture of material change and methods to evaluate that change. Inhomogeneous aging of samples during aging, including diffusion-limited oxidation and point nucleation of aging, are important to understand in the context of aging mechanism of in-service cables.

Test techniques employed by the recent International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) on “Qualification, Condition Monitoring, and Management of Aging of Low Voltage Cables in Nuclear Power Plants” to assess non-conductor (non-metallic) cable materials include density, EAB, indenter modulus, and ultrasonic velocity for physical/mechanical properties, and Fourier transform infrared spectroscopy, near-infrared spectroscopy, oxidation induction time/temperature, and TGA for chemical properties.[a] Recent cable material analysis methods used at Sandia National Laboratory are similarly categorized into macroscopic/physical including tensile, permeation, elongation and dimension analysis; and molecular/chemical including ultraviolet-visible spectroscopy, surface analysis, differential scanning calorimetry, additives, molecular weight, density, x-ray, nuclear magnetic resonance, Fourier transform infrared spectroscopy, mass spectrometry, and gas permeation chromatography (Von White II et al. 2013).

The major mechanical property characterization techniques currently being used at PNNL for polymer cable material include tensile testing for EAB, modulus and strength, DMA, and surface indentation modulus. The Mechanical Test Laboratory in the Physical Sciences Facility (Building 3410) houses a series of Universal Test Stands for tensile specimen measurement. That laboratory also contains micro- and nano-indenter instrument for cable measurement including cross-sectional modulus mapping. A dynamic mechanical analyzer (DMA) (TA Instruments Q800) instrument in the Physical Sciences Laboratory on the central PNNL campus is used as a sensitive measure of polymer state, including changes to the loss modulus and the storage modulus of the material. This instrument can also be operated in in-situ mode in which accelerated aging is performed on a polymer sample while the mechanical response of the material is monitored in real time.

Physical properties of cable polymers are evaluated by measuring change in visual appearance with digital camera-equipped microscope, density using the Archimedes method, and surface structure using scanning electron microscopy (SEM). Three-dimensional structure of intact polymer material with the conductor removed can also be imaged using the x-ray microtomography capability in the Life Sciences Laboratory II building. Proof-of-concept investigation using this method has confirmed its ability to reveal material defects such as from cuts or punctures and content inhomogeneity such as inorganic filler aggregation. Velocity of sound measurements in polymer material with aging is being pursued in the 2400 Stevens building on the south PNNL campus.

Potentially most revealing for degradation mechanism information, chemical property changes such as bond breakage and formation are investigated at PNNL using Fourier transform infrared (FTIR) spectroscopy including in attenuated total reflection mode (Nicolet™ iS™10). Gel content, reflecting polymer chain scission and crosslinking changes, is determined through soxhlet extraction. Extraction combined with gel permeation chromatography enables quantification of polymer extractives. TGA may be used to determine oxidation induction time and temperature, for other investigations of degradation versus temperature, and for measurement of volatile and inorganic content with aging (Netzche STA 449). Equipment and instrumentation for measurement of chemical properties and property changes in cable materials is broadly available on the PNNL campus, including in the Physical Sciences Laboratory, the Applied Process Engineering Laboratory, the Environmental Molecular Sciences Laboratory, and the Life Sciences Laboratory II.

In conjunction with the LWRS Cable Nondestructive Evaluation project at PNNL, electrical property changes of polymer cable materials with aging including dielectric constant, resistance/conductivity, and breakdown voltage are ongoing. Most of the equipment for these techniques is located in the

[a] H. Hashemian, personal communication.

2400 Stevens building on the south PNNL campus and in the Engineering Development Laboratory on the central campus.

6. EXPERIMENTAL PLAN

The focus for cable aging research at PNNL is informed and guided by current consensus needs and understanding gaps (see Research Priorities, Section 2 above), such as the knowledge gaps identified in the EMDA (Bernstein et al. 2014) and the priorities identified in the EPRI/DOE/NRC Cable Working Group roadmap. In addition to these guiding documents, we are coordinating our research efforts with other research groups to leverage our programs and to keep our efforts focused on the most important problems. Information exchange regarding parallel and complementary research is maintained with Andrew Mantey at EPRI and Sheila Ray and Darrell Murdock at the NRC. Direct collaborators include Professor Nicola Bowler at the Iowa State University, Gary Harmon at Analysis and Measurement Services Corporation (AMS), and Robert Duckworth at ORNL.

Toward relation of cable material condition with remaining useful life, we are aging materials under different conditions and relating the measurable changes in cable properties with exposure, using multiple samples and measurements to generate each data point of condition versus age. Quantification of uncertainty in the measurements and scatter in the results will enable assignment of confidence levels in lifetime prediction based on condition information. For example, nuclear-grade, pink EPR/EPDM, the most important cable insulation material for thermal aging and degradation of cables in U.S. nuclear power plants, is being aged at multiple rates to generate lifetime performance curves using multiple age indicators. Example EPR/EPDM aging temperatures are listed in Table 3. EPR/EDM insulated cables are being aged as intact segments, in the same form as a cable would experience exposure in the field, as insulation specimens sampled from cables, and as test specimens of the material itself. Images of EPR/EPDM cables are presented in Figure 2. The complication of diffusion-limited oxidation is considered for cable aged at higher temperatures, such as above 140°C, especially for thicker samples. Some samples are aged at temperatures at which inhomogeneous aging is expected in order to understand this accelerated aging phenomenon. Forms of EPR/EPDM studied are listed in Table 1. Exposure temperatures are listed in Table 2 along with approximate anticipated exposure periods for each temperature before specimen EAB values will be less than 50% absolute, a conservative measure for cable end of useful life (IEC/IEEE 62582-3, 2012). Primary methods to characterize EPR/EPDM aging are listed in Table 3.

Figure 2. Images of EPR/EPDM Cables

Table 1. EPR/EPDM Specimen Forms and Example Characterization Methods for Each

Form of Okonite Okoguard® EPR/EPDM	Example Characterization
Intact aerial jumper cable segments containing conductor	Indenter
Intact medium voltage power cable segments with metal shielding and TS-CPE jacket	Indenter
Dumbbell shaped tensile specimens cut from cable	EAB
Dumbbell shaped tensile specimens stamped from sheet	EAB
Long, thin strips cut from EPR/EPDM sheet	DMA
Square cut from EPR/EPDM sheet	Acoustic

Table 2. EPR/EPDM Thermal-Only Aging Conditions

Temperature (°C)	Approximate Exposure Duration (days)
100	800
125	150
130	100
135	75
140	50

Table 3. Cable Material Characterization Techniques

Category	Examples
Mechanical	EAB, Indenter, Sound Velocity, DMA
Physical	Density, Color, Surface Structure, SEM
Chemical	FTIR, Gel Content, Extractives, TGA

The most common polymer material found in-containment in U.S. nuclear power plants is cross-linked polyolefin/polyethylene. XLPO/XLPE has been observed to be very resistant to chemical and thermal degradation. Significant questions remain, however, regarding the effects of gamma irradiation on XLPO/XLPE and the combined effects of thermal exposure and gamma radiation exposure including synergistic effects and inverse temperature effects. To address these knowledge gaps and develop predictive understanding of the aging and degradation of nuclear-grade XLPO/XLPE, we are correlating exposure with performance for Firewall® III XLPE cables from RSCC. We intend to age intact cable segments (product code I46-0021), including CSPE jacket, shielding, drain wire, and XLPE-insulated multi-strand conductors. We also plan to age XLPE insulated conductors separated from the cable assembly and XLPE insulation with the conductor removed. Forms of XLPE to be investigated are listed in Table 4. Thermal-only aging is carried out similar to as described for EPR/EPDM samples, by hanging XLPE specimens in mechanical convection ovens and sampling multiple specimens periodically to obtain information on scatter and uncertainty of measured property change with aging. XLPE is very thermally stable and statistical changes in properties with thermal-only aging are expected to require at least 10k hours at temperatures of 135°C or below. Irradiation aging of XLPE samples will be carried out in the HEF with samples held at ambient temperature and flowing air. The effect of thermal vs. radiation order on sequential aging will be investigated. Initial combined thermal and radiative aging will be carried out in the HEF by loading samples into a mechanical convection oven and placing the oven within the gamma exposure zone. Ion gauge characterization at sample locations before the exposure and dosimetry monitoring during exposure will confirm actual dose rates and doses experienced by the polymer specimens. The experimental plan will compare XLPE properties with exposure at high dose rate/low dose rate, high temperature/low temperature, and at common total dose. Exposure conditions for XLPE are listed in Table 5. Primary methods to characterize changes in XLPE with exposure are similar to those used for EPR/EPMD and are listed in Table 3.

Figure 3. Image of Firewall® III Cable (product code I46-0021)

Table 4. XLPE Forms for Exposure and Characterization

Intact Cables	XLPE insulated conductor, inside shield and CSPE jacket
Insulated Wires	XLPE insulation around copper conductor
Isolated Insulations	XLPE insulation with conductor removed

Table 5. XLPE Experimental Matrix

	RT	85°C	135°C	0 rad/h	10k rad/h	50k rad/h
Thermal only – lower temp		x		x		
Thermal only – higher temp			x	x		
Radiation only – lower rate	x				x	
Radiation only – higher rate	x					x
Concurrent			x			x
		x				x
		x			x	
			x		x	
Consecutive – thermal 1st			x			x
Consecutive – gamma 1st			x			x

7. CONCLUSION

Important knowledge gaps remain in answering life expectancy questions for electrical cable polymer components in existing nuclear power plants. Building on the decades of existing valuable work and lessons learned in material behavior and aging phenomena, this program seeks to address outstanding knowledge gaps to help enable U.S. nuclear operators to make educated continued cable use decisions.

Research priorities are informed by subject matter consensus sources including the EMDA (Bernstein et al. 2014), the IAEA CRP, and the EPRI/NRC/DOE cable working group. EPR/EPDM, XLPO/XLPE, and SiR are major material targets for understanding based on the preponderance of their usage in installed nuclear power plant cables. Adequate guidance exists from the academic literature and from reports and standards published by the NRC, DOE, Institute of Electrical and Electronics Engineers

(IEEE), ASTM International, EPRI, International Electrotechnical Commission (IEC), and IAEA to inform cable aging and characterization practices, material targets, and relevant exposure conditions. Equipment and capabilities to perform all of the major published characterization techniques to assess cable material aging exist at PNNL and are available to this program. Thermal aging capabilities exist and are straightforward to expand. Capabilities do exist at PNNL for gamma irradiation aging experiments in HEF and RPL, for a defined range of dose rates and total dose. These capabilities may be expanded with, for instance, the purchase of higher activity sources in the future. This program will leverage gamma radiation exposure capabilities with collaborative partners including the HFIR and other facilities at Oak Ridge National Laboratory.

Existing U.S. nuclear power plant-relevant, high-priority cables materials are available for PNNL studies including modern pink EPR/EPDM from Okonite and XLPO/XLPE from RSCC. Small amounts of vintage cables that have not been placed in service have been received from EPRI, with additional samples potentially available in the future including from other partners such as AMS. Valuable field-aged cable samples are expected to be available from retired nuclear power plants including Zion and Crystal River Unit 3.

Thermal-only aging experiments are underway and radiation experiment planning is nearing completion. Experimental plans and progress will be reviewed on an ongoing basis for input by LWRS program managers and by independent subject matter experts such as contacts at EPRI, NRC, and the nuclear cable industry to assure that the right information is being targeted in the most efficient way.

The anticipated outcomes of this program are:

- Improved understanding of appropriate accelerated aging conditions
- Improved knowledge of correlation between observable aging indicators and cable condition in support of advanced NDE methods
- Practical knowledge of condition-based cable lifetime prediction.

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