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To

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Dear Jeremy:

Subject: Preliminary List of Aging Conditions and Measurement Methods to be Examined for Key Indicators of Cable Aging – Status Summary

This Pacific Northwest National Laboratory (PNNL) status summary describes progress to-date on investigating aging conditions that provide key indicators of cable aging and identifying measurement technologies that may be used as potential methods for examining these cables. It is submitted in fulfillment of deliverable “Status report listing aging conditions and measurement methods selected for assessment” (Level 4 Milestone) under project 4000114089.

The overall objective of this effort is to complete measurements of physical properties on cables subjected to a range of accelerated aging conditions, and assess results for key early indicators of cable aging. This initial assessment evaluated available literature in current advances in polymer science to determine likely measurable conditions that can serve as key indicators of cable aging. In parallel, nondestructive evaluation (NDE) measurement methods sensitive to these conditions as well as NDE methods currently being considered for cable aging assessment were identified to provide a foundation for further investigation. The literature review and assessment is continuing and the information presented in the following sections is based on literature evaluated to date. Follow-on work will continue to evaluate the potential of determining cable remaining life using the identified key indicators. To assist in this effort, we will continue to identify cables that can be (or have been) subjected to aging, measure physical properties of these aged cables using existing or possibly new NDE methods, and document results in a future technical report.

Per your request, we briefly describe our findings to-date and observations from the available information.

Background Information

In July 2012, a workshop (Simmons, et.al.) was held to lay the groundwork for a research and development roadmap to address aging cable management in nuclear power plants (NPPs). This workshop brought together subject matter experts from the U.S. Nuclear Regulatory Commission (NRC), U.S. Department of Energy (DOE) National Laboratories, The Electric Power Research Institute (EPRI), Universities, and cable manufacturers and inspectors.

The workshop focused on identifying changes in chemical structure that would be a precursor to eventual failure of an aging cable and the current state-of-the-art in NDE methods that could be applied to estimate the remaining life of the cable. These changes in chemical structure are most likely to be caused by the environment the cable is in (thermal, radiation, moisture, chemicals) and what mechanical load (both static and dynamic) is being applied. Therefore, the development of new NDE methods or development of new techniques using existing NDE methods is of significant interest. The ability to perform a nondestructive test to determine chemical, physical, mechanical, and electrical properties of the cable jackets and insulation without significant disturbance of the cables and connectors as they lay in-situ is essential.

There have been many programs and years of research to address the problems of aging cables with no single NDE method identified that can satisfy all of the requirements needed to assess life expectancy. The most common methods used are visual (looking for cracking and discoloration indicative of cable aging) and a method that indents the surface of the cable jacket (measures cable elasticity and correlates to cable aging). These are essentially the only methods currently acceptable to industry. All other current methods (such as time and frequency domain analysis, inductance and capacitance measurements, tan delta, etc.) provide flaw detection but none can predict the expected life of the cable.

The workshop identified three important areas that should be considered to assess overall cable aging:

1) Determination of the key chemical, physical and electrical indicators of cable aging
2) Advance current and develop new NDE methods to enable in-situ cable condition assessment
3) Develop models to assist in predicting remaining useful life of aging cables

The figure below succinctly illustrates the importance of using NDE to predict remaining useful life of aging cables and the individual properties that must be considered.

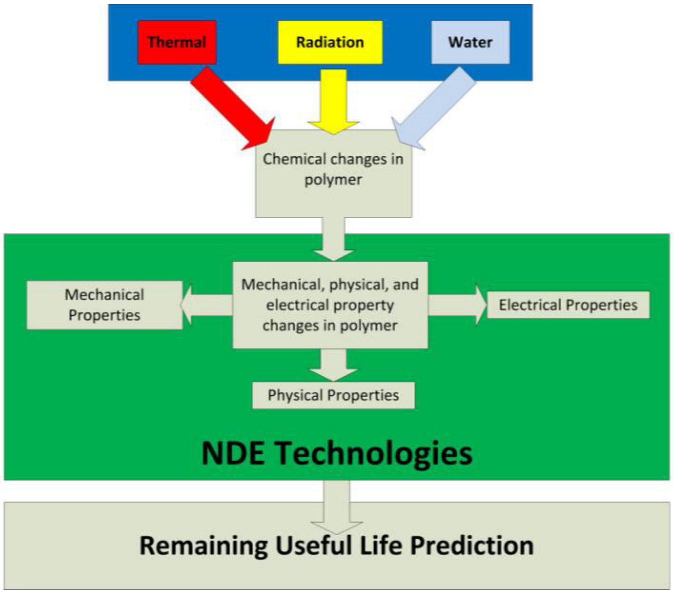

Figure 1. Overview of Research Tasks for Cable Aging Detection and Remaining Life Assessment.

Key Indicators

The stressors in fielded polymers, such as heat, radiation, and moisture, modify polymer chemistry and result in changes in material performance: mechanical, physical and electrical. The nuclear industry uses a variety of polymers and elastomers for insulators and jacketing materials with several of these materials used in combination. The industry has accepted as a key indicator the correlation of indentation modulus to the elongation at break (EAB). EPRI Technical Report 1008211, "Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets," develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers. The report describes 50% EAB as a conservative practical end-of-life threshold for cables that may be stressed during maintenance or subjected to LOCA exposure. The report also discusses the basis for cautious continued use of cables beyond the 50% EAB threshold.

The key to success in utilizing NDE methods for this project will be to determine what chemical changes occur that affect the properties of the insulator or jacketing materials that could lead to determining the remaining useful life based on these chemical changes. The EPRI document TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report -- Revision 1" provides a technical basis for license renewal for low-voltage environmentally-qualified cable. Specifically, the evaluation discusses age-related degradation mechanisms, the effects of age-related degradation on functionality of equipment, and aging management options. The nuclear power industry has looked at age-related degradation mechanisms, but it appears there has been no correlation using NDE methods.

It is important to first understand the aging mechanisms chemically. Based on the polymer system being investigated, it is important to determine the composition of the materials. Are there polymer additives present that were included to aid in processing or to limit thermal degradation? Are there plasticizers for flexibility? How do they affect the properties for aging? Is the basic backbone of the polymer the key indicator to material property changes with aging? What NDE methods can be utilized to indicate polymer changes independent of whether the polymer is amorphous or semi-crystalline?

Chemical Properties as Indicators

The mechanical properties of polymers are largely dictated by the molecular structure of the backbone. The super-molecular structures of polymers used in cables and jackets can be either amorphous or semi-crystalline. Semi-crystalline polymers have randomly oriented crystalline regions with amorphous regions linking them together. It is not uncommon for such polymers systems to have antioxidants, plasticizers, inorganic fillers, and various other additives added to them to enhance the properties of the neat polymer.

The chemical properties of polymer systems, including material composition, are directly related to polymer mechanical, physical, and electrical properties. Any changes to the material composition have a related effect on these other properties. The most common change to the polymer backbone from environmental degradation is chain scission. Polymer chain damage can occur in three different ways 1) chain scission at the ends of the polymer backbone, 2) chain scission randomly along the chain, and 3) chain scission of side pendants from the main backbone. Chain scission decreases polymer molecular weight and also affects various other properties such as mechanical (strength and/or modulus), physical (density, glass transition temperature), and electrical (dielectric) properties. The chain scission can induce free radicals that can cross-link and alter the properties of the material as well.

Gillen et al. have shown that during radiation aging, reactive species such as radicals are generated uniformly throughout both crystalline and amorphous regions. At temperatures well below the crystalline melting point, these species are trapped in the crystalline regions and are unable to react to form oxidative products because of low chain mobility and low oxygen diffusion rate. Degradation then proceeds primarily through oxidative scission reactions in the amorphous regions, where both chain mobility and oxygen diffusion rates are higher. Since the amorphous regions bind together the crystalline blocks, chain scission in these regions has a marked effect on the mechanical properties of the system.

If the radiation aging occurs at slightly higher temperatures, nearer the melting region for the crystalline portion, then chain mobility is high enough for the trapped species to react to form chemical cross-links rather than chain scission. In addition, the enhanced mobility enables some recrystallization to occur which can reform molecular bonds that were broken by oxidative scission in the amorphous regions. The combination of these effects is to effectively ‘heal’ some of the damage that was created by the radiation aging. The overall macroscopic effect is a reduced rate of radiation degradation at higher temperatures.

Exposure to environmental stressors can lead to changes in polymer chemical properties including loss of molecular weight, cross-linking (or gelling), release of volatiles (including additives and plasticizers), functional group transformation (such as carbonyl formation), and polymer backbone conjugation (Scheirs 2000)

Physical Properties as Indicators of Chemical Change

Polymer chains are broadly classified into four key structures: 1) linear, 2) branched, 3) cross-linked, and 4) networked. These chemical structural characteristics directly correlate to many properties of the polymer, most notably the mechanical and electrical properties. The ability of chain segments to rotate is influenced by the applied stresses or thermal vibrations that influence the mechanical and thermal characteristics of the polymer. The outcome of these properties can be influenced by any damage to the structure that can change the property relationship. The structure can change the molecular weight, cross-link density, the degree of crystallinity, the chemical resistance, and the electrical properties.

Initial literature searches have revealed physical property changes in polymers that indicate chemical change and may be correlated to cable and jacket functional life status. Molecular weight is one of the most influential factors of polymer properties. Reduction or increase in effective molecular weight of a polymer system directly affects the energy required to break and form non-covalent bonds between polymer molecules. Thus the transition between polymer phases is a strong function of polymer chain length. Changes in the melting, the glass transition, and the gel temperatures of a polymer are measures of scission or cross-linking of the polymer chains. Alteration of polymer average chain length, chain length distribution and chemical side-group connectivity affect the free volume within the polymer system. Consequently the macroscopic density of the polymer sample and properties such as gas permeation and liquid (e.g. oil) uptake can be correlated with polymer aging. Other measureable physical property changes as a function of polymer environmental degradation include discoloration, change in refractive index and change in sound velocity within the material.

Mechanical Properties as Indicators

The large number of chemical and structural characteristics of polymeric materials over time influences the properties and behavior of the materials. The density, stiffness, strength, and ductility are influenced by the degree of crystallinity in semi-crystalline polymers. The stiffness in rubbers and cross-linked polymers is related to the degree of cross-linking. The melting point and glass transition temperatures are also related to the polymer chemical state.

The macro-polymer chain structure significantly varies from polymer to polymer; however, the chain arrangement has a large influence on the mechanical properties. Chains that are coiled or have a large amount of kinks in them have a tendency to have more flexibility or have high elongation. The long chain structures with their kinks, coils, and bending will entangle and intertwine with themselves and other chains in the bulk. This molecular entanglement is an important characteristic of polymers and elastomers and is a key contributor to high elongation, moduli, and strength, such as those found in rubbers. Likewise with semi-crystalline polymers, highly ordered structures pack themselves into organized units with amorphous linking material between them.

Key indicators of these changes are noticed in current state-of-the-art technologies such as the indenter modulus that is correlated to the elongation at break. All of these properties are related to changes in polymer structure. Other influenced mechanical properties are creep, and recovery and relaxation time that are related to how much the stressed polymer will recover over time. Mechanical property modifiers such as plasticizers, processing aids and other additives can be altered by loss or consumption of these additives over time. For example, a small loss of plasticizer can significantly alter the elongation and modulus of the material.

Electrical Properties as Indicators

As electrical conductivity is proportional to the product of charge mobility and charge carrier concentration, the conductivity of polymers used in cable and jacket insulation varies with change in charge carrier density in the material. As cables age, multiple processes combine to increase the number of carriers in the polymer insulation material, thereby increasing the conduction and ultimately leading to dielectric breakdown. Increase in the ionic (charge-bearing) content of polymer material over time may result from ingress of moisture or other impurities, departure of additives initially present in the material, creation of charged moieties through bond scission due to oxidation or photo-cleavage, or infiltration of surface charges within the material. In addition, change in spatial distribution of heterogeneities in additives, plasticizers and fillers, and rearrangement of polymer structure such as evolution of crystalline phases over time can alter material electrical properties. Dielectric strength (breakdown voltage divided by thickness), insulation resistance (applied voltage divided by leakage current over a given period of time) and electrical conductivity may provide useful measures of the state of change of the material composition of an aging polymer. This state of change may be correlated with other measureable properties of the polymer such as elongation at break, and tied to the remaining functional lifetime of the cable insulation or jacket material.

Current Cable Inspection Methods

Current electrical cable inspection methods include both destructive and nondestructive methods. The focus from the workshop and the direction of this project is to identify and further develop nondestructive methods to evaluate aging cables. As mentioned earlier in this memorandum, there have been many NDE methods and techniques evaluated as potential candidates for providing information that can assess the condition of an electrical cable in a NPP. Many of these inspection methods have been tabulated during the workshop (Simmons, et.al.) and include a brief summary of advantages and disadvantages of the various methods. The table is not all-inclusive. Research is ongoing and new methods and techniques are being developed and coming to market. The table identifies the main methods that have a considerable amount of literature indicative of substantial research in those inspection methods.

Aging Conditions and Measurement Methods for Key Indicators

After performing an assessment of key aging indicators, parameters that will be investigated initially are the dielectric constant, the tangent of dielectric loss angle, the dielectric strength, and the electrical conductivity. Other parameters such as elastic modulus will also be considered for this phase of the evaluation. Each of these will need to be investigated under stressors such as temperature and radiation. Considerable work has already been performed on these indicators with data and relevant conclusions formed in various studies. However, gaps exist in the published literature that will need to be bridged, if high-impact NDE methods are to be developed. In particular, not all polymers of interest to the nuclear power industry have been studied in this context, and methods of estimating the remaining life of cables with aging insulation from these parameters are in their infancy. In most cases, the remaining life is estimated from correlative data (between the parameter and the elongation-before-break information) that may not account for the variability between cable types (and even within a single cable type due to variability in processing and fabrication). To address these gaps and gain an understanding of 1) the fundamental relationships between these parameters, 2) stressor variables and 3) their effect on polymer chemistry and the age of the cable, PNNL will perform limited assessments to underpin the basic physics of the measurement processes with the understanding that the information will drive further studies to improve these inspection methods or find new methods. This investigation will evaluate the propensity to provide data relevant to making decisions on the ability of the NDE method(s) to ascertain the life expectancy of an aging in-use electrical cable in a nuclear power plant.

PNNL will use NDE methods to evaluate the key indicator parameters identified above. The investigation will review existing equipment that can perform these measurements and provide some empirical data to support this. Additionally, new techniques will be investigated that may provide in-situ measurements that correlate data obtained from the above analyses as well as tie in other related stressor data such as temperature and radiation. The resulting information will be correlated with cable age, as well as with currently accepted "gold standard" measurements of cable degradation such as elongation-at-break.

PNNL plans to narrow the focus to cables that are of highest risk to safe operation. These cables can be either power cables, control cables, or instrumentation cables, and PNNL will choose an assortment of these cables for evaluating with the most common polymer types such as XLPE and EPR which constitute approximately 72% of the polymer material used in nuclear power plant cables. These studies will be performed in a phased manner, with the initial focus on measurements from aged tensile specimens to gain insights into the changes in electrical and mechanical properties, and their correlation with chemical changes as the polymer ages. This will be followed by studies on cables where controlled aging of segments is performed. These studies will provide the basis for the further development of selected NDE methods for in-situ cable degradation detection and remaining life assessment.

These studies are planned over the next several months, and the results of these studies will be documented in follow-on reports.

Please let me know if you have any questions regarding this report.

Regards,

Kevin Simmons
Senior Research Scientist

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