

Title: Advanced Models for Nondestructive Evaluation of Aging Nuclear Power Plant Cables

Technical Workscope Identifier No.: RC-4

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Proposal Summary

Approximately 1,000 km of power, control, instrumentation and other cables are deployed in a single nuclear power plant (NPP). Degradation of the cable jacket and electrical insulation layer has been identified as a factor that potentially limits the ability of cables to operate beyond their initial design life. We propose to develop advanced models that relate environmentally-induced microstructural and chemical changes in cable jacket and insulation polymers to their macroscopic electrical parameters that can be measured nondestructively. These parameters will be measured and modeled over a wide range of the electromagnetic spectrum, covering several potential nondestructive evaluation (NDE) techniques; capacitive, reflectometry, microwave, terahertz (THz) and infrared, enabling identification of the most sensitive techniques for future development.

Description of the proposed work

The reduction to 50% of the original elongation-at-break of NPP cable polymers is used as a guide for determining end-of-useful life of the cable. This method has two disadvantages. First, it is destructive, requiring a sample to be taken from the cable. Second, it is a mechanical test applied to a material whose function is electrical. In this proposed project, multiple mechanisms contributing to degradation of the electrical insulation properties of cable polymers will be studied. Relevant polymers will be aged under conditions of extended exposure to heat, neutron/gamma radiation, humidity, voltage and mechanical stress. Models will be developed that relate the resulting physical and chemical changes in the cable polymers to measurable macroscopic parameters, such as insulation permittivity, over a wide range of frequencies in the electromagnetic spectrum (10^{-2} to 10^{14} Hz). In this way, the frequencies at which the spectral parameters show highest sensitivity to environmentally-induced cable degradation can be identified. Based on these findings, relationships between the response of various NDE methods, such as capacitive, reflectometry, microwave, THz and infrared spectroscopy, to cable aging as a function of environmental exposure will be developed.

Background

A basic cable comprises a central conductor, formed from copper strands that are often tin-coated, covered by a polymeric electrical insulation layer, protected by a plastic jacket. Commonly, shielding layers are also applied between these three components. Examples of cables with this construction are low- and medium-voltage power cables. Multi-conductor cables comprise multiple insulated cables housed within a single jacket. Control, instrumentation and data cables are examples of these. Over extended periods of service, the cable insulation and plastic jacket suffer from degradation due to various environmental exposures such as heat, ionizing radiation, humidity, voltage, and mechanical stress, and may eventually fail, no longer properly insulating the cable and potentially leading to current-arcing and associated loss of power or control function [1]. Against this background, there is a need to:

- i) develop advanced, validated models for polymers commonly used in NPP cables that relate environmentally-induced polymer microstructural and chemical changes to observable changes in dielectric, microwave, THz and infrared spectra,
- ii) identify the frequencies at which spectral parameters are most sensitive to microstructural and chemical changes due to aging in polymers, and
- iii) calculate the response of proven cable NDE methods, such as capacitive, THz and reflectometry inspection, to cable aging as a function of environmental exposure.

In this work, three tasks will be pursued in accordance with the three needs stated above.

Approach

Task 1: Develop validated models relating environmentally-induced polymer microstructural and chemical changes to observable spectral changes. Two major NPP cable polymers – ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) will be aged under various conditions e.g. elevated temperature, neutron/gamma radiation, humidity, voltage and static mechanical load. The results of the experiments will inform the development of relationships between variables representing the environmental condition, the material microstructure (e.g. crystallinity) or chemistry (e.g. disappearance/appearance of chemical bonds/species or crosslink structures), frequency-dependent permittivity, dielectric breakdown strength, and time.

To predict spectral changes, understanding of the underlying atomic degradation mechanisms must be achieved through thermo-mechanical analysis experiments, e.g. [2], and quantum chemical models. Density functional theory methods, are known to accurately reproduce the structural, electronic, and dynamical behavior of covalent bonds in organic molecules and if needed van der Waals density functionals can be employed model the intermolecular interactions. Using these structures density functional perturbation theory can be used to identify the molecular vibrational spectra. It has been shown that for crystalline polymers the predicted vibrational spectrum in the THz range matches well to experiment and can be directly used to identify the atomic mechanisms of polymer degradation [3]. The theoretical models will be validated by comparison with spectra measured on aged samples.

Task 2: Identify spectral range(s) showing most sensitivity to polymer degradation. Recognizing that NDE techniques are not yet available for in situ cable inspection over the full spectral range proposed for study here (10^{-2} to 10^{14} Hz), this task will identify frequencies in the dielectric, microwave, THz and infrared spectra at which particular indications emerge in response to each type of aging. This will provide impetus towards future development of NDE methods targeted to the frequencies that show greatest sensitivity to degradation-induced changes in cable polymers.

Task 3: Develop validated models relating NDE signals to cable polymers state. Three electrical NDE methods with proven capability in the assessment of cable polymers degradation are capacitive [4] and THz NDE [3], and reflectometry [5]. In this task, models of the expected response of these three NDE methods will be developed as a function of changes in the permittivity spectra of the polymers as a function of degradation type and time. The models will be validated by comparison with data measured on cables aged under the same conditions as for the aged polymer samples from which the dielectric spectra were developed in Task 1.

Logical path to work accomplishment	Year 1	Year 2	Year 3
Task 1: Develop models relating polymer changes to spectral changes (Full Team)			
1.1: Conduct detailed literature survey of aging response of EPR & XLPE to heat, neutron/gamma radiation, humidity, voltage, and mechanical stress	♦		
1.2: Design and conduct accelerated aging of EPR & XLPE <i>samples</i> (to complement published data identified in Task 1.1)		♦	
1.3: Apply thermal and mechanical characterization techniques to elucidate aging mechanisms of EPR & XLPE due to heat, neutron/gamma radiation, humidity, voltage and mechanical stress		♦	♦
1.4: Measure dielectric, THz and infrared spectra of aged polymers ($\sim 10^{-2}$ to 10^{14} Hz)		♦	♦
1.5: Measure dielectric breakdown strength of aged polymers		♦	♦
1.6: Develop and validate models relating microstructural and chemical changes in aged polymers to observed spectral changes		♦	♦
Task 2: Identify spectral range(s) showing most sensitivity to polymer degradation (Bowler)			

2.1: Identify from literature spectral ranges sensitive to degradation		♦	♦			
2.2: Identify from experimentation (Task 1.4) spectral ranges sensitive to degradation				♦	♦	
Task 3: Develop models relating NDE signals to cable polymers state (Bowler, Chiou, Simmons)						
3.1: Conduct accelerated aging of EPR & XLPE-based <i>cables</i> (simultaneously with Task 1.2)		♦	♦			
3.2: Measure broadband capacitance on cables aged in Task 3.1 with interdigital patch or clamp capacitors applied to cable jacket				♦		
3.3: Measure THz and reflectometry signals on cables aged in 3.1				♦		
3.4: Calculate broadband capacitance, for the same sensors used in Task 3.2, using measured and calculated dielectric spectra from Tasks 1.4 and 1.6 as inputs					♦	
3.5: Calculate THz and reflectometry signals using spectral inputs from Tasks 1.4 and 1.6.					♦	
3.6: Validate models developed in Tasks 3.4 and 3.5 by comparison with data measured on aged cables in Tasks 3.2 and 3.3						♦

Relevance of the proposed work

In a report emerging from the Light Water Reactor Sustainability Program NDE roadmapping workshop held in Knoxville, TN in July 2012 [6], it is stated that two major areas of importance are

- i) ‘determining key indicators of cable aging that correlate with measureable changes in material properties at macroscopic scale’, and to
- ii) ‘advance state-of-the-art in current cable NDE methods and develop new and transformational NDE methods’.

Task 2 (supported by Task 1) proposed in this work directly addresses area i). Task 2 also informs area ii) in identifying frequencies in the electromagnetic spectrum at which key indicators of polymer degradation appear, suggesting development of future NDE techniques targeting those frequencies. The proposed work is also directly relevant to an ongoing IAEA Coordinated Research Project [7] in which the PI is participating. Aged cable samples from the IAEA project are available to this project.

References

1. G. von White II, R. Bernstein & K. T. Gillen, *Trans. Am. Nuclear Soc.*, **107**, 438-440, 2012.
2. **N. Bowler**, *et al.*, Electromagnetic Nondestructive Evaluation of Wire Insulation and Models of Insulation Material Properties, Report Number: NASA/CR-2012-217330, NF1676L-14135, at: <http://www.sti.nasa.gov/>
3. M. Hosobuchi, *et al.*, 2013 Annual Report *Conf. Electr. Insul. Dielectr. Phenomena*, pp. 1046-1049.
4. T. Chen and **N. Bowler**, *NDT&E International*, 52, 9-15, 2012.
5. C. Furse, *et al.*, *Smart Struct. Syst.*, **2**, 25-46, 2006.
6. K. L. Simmons, *et al.*, LWRS Program-NDE R&D Roadmap, PNNL-21731, September 2012.
7. IAEA Coordinated Research Projects (CRP), “Qualification, Condition Monitoring, and Management of Aging of Low Voltage Cables in Nuclear Power Plants,” Online at: <http://www.iaea.org/NuclearPower/Engineering/CRP/ALVC/index.html>

Deliverables and Outcomes

1. Validated models relating degradation of EPR and XLPE to associated changes in their dielectric, microwave, THz and/or infrared spectra.
2. Library of spectral indicators of particular aging mechanisms in EPR and XLPE.
3. Validated models relating polymer cable state to nondestructive measurements by capacitive, THz and reflectometry methods.

Timeframe: 3-year period, October 1, 2014 through September 30, 2017.

Estimated Cost of Project: \$800,000.