

Light Water Reactor Sustainability Program

Dielectric Spectroscopy Cable NDE for Unequal Aging Over Different Lengths



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Dielectric Spectroscopy Cable NDE for Unequal Aging Over Different Lengths

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SUMMARY

The Pacific Northwest National Laboratory assessed the effect of unequal aging over different lengths of cable using dielectric spectroscopy (DS) bulk impedance measurements from the cable end. DS measurements can indicate the aged condition of insulated cables; however, most benchmark tests are based on accelerated aging of the entire cable. If only a portion of the cable is exposed to a harsh environment (as is frequently the case), the DS measurement will indicate a significantly less-aged cable than if the entire cable were exposed to a uniform environmental stress. The DS measurement is primarily related to the intrinsic insulation material relative permittivity—with values typically between 1.5 and 3.0. Insulation aging increases permittivity and, correspondingly, the overall capacitance of the cable measured from the cable end. To judge the health of the overall cable system, operators are primarily interested in the condition of the most severely aged section since that is where a failure is most likely to occur. This can be expressed as the dimensionless relative permittivity of the severely aged section divided by the corresponding permittivity of a pristine cable. This relative permittivity is an intrinsic material parameter independent of cable length and can serve as a quantitative indication of the insulation condition. If the relative percentages of cable length exposed to a harsh and benign environment are known, the DS measurement of the entire cable length, including both pristine and aged sections, can be compensated to predict the relative permittivity (relative to pristine permittivity) of the most severely aged segment.

A test was performed on three 50 ft (15 m) cables with 10%, 50%, and 90% of each cable inside a thermal aging oven. Predictably, the aging effect on the DS response was greatest in the 90% sample, followed by the 50% sample, and then the 10% sample. The more interesting result is the ratio of the aged insulation permittivity to the pristine insulation permittivity. Based on prior work, an end-of-life cable has a relative permittivity value of approximately 1.35. If the relative percentages of pristine and severely aged cable lengths are known, and the total cable-length capacitance of the initial pristine cable and the combined pristine plus aged cable are known, the relative aged permittivity (ratio of aged section permittivity / pristine section permittivity) can be estimated. The relative cable lengths exposed to a harsh environment may be known or estimated based on plant layout drawings or cable reflectometry tests that can locate the oven entry and exit points. The compensation was verified using a lumped-parameter model to predict the aged-segment permittivity ϵ_2/ϵ_1 , where ϵ_2 is the aged-segment permittivity and ϵ_1 is the pristine-segment permittivity. For all three percentages of aged cable lengths, the ratio was quite similar, as would be expected since all cable segments were exposed to the same aging environment. This ratio of aged permittivity to pristine permittivity can be compared to other damage indicating tests, including elongation at break, to enable cable aging management decisions.

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ACRONYMS AND ABBREVIATIONS

AMP	aging management program
C	capacitance
CPE	chlorinated polyethylene
δ	penetration depth
DBE	design basis event
DS	dielectric spectroscopy
ε'	complex permittivity
ε''	imaginary permittivity
ε	magnitude of permittivity
EAB	elongation at break
EPDM	ethylene propylene diene monomer
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
f	frequency
F	SI unit of capacitance (Farad)
FDR	frequency domain reflectometry
FTIR	Fourier-transform infrared spectroscopy
Gy	Gray (unit measure of ionizing radiation)
I&C	instrumentation and control
LCR	inductance-capacitance-resistance
LFDS	low frequency dielectric spectroscopy
LOCA	loss-of-coolant accident
LV	low voltage
LWRS	Light Water Reactor Sustainability Program
NIR	near infrared
NDE	nondestructive evaluation
NPP	nuclear power plant
OIT	oxidation induction time
PDC	polarization/depolarization current
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
sf	stranding factor
TDR	time domain reflectometry
XLPE	cross-linked polyethylene

1. OBJECTIVE

The primary objective of this milestone report from Pacific Northwest National Laboratory (PNNL) is to rigorously evaluate how dielectric spectroscopy (DS) measurements are influenced when only portions of the total length of a low-voltage cable have undergone accelerated global aging. Because DS is a bulk electrical property measurement, its response reflects the combined condition of all dielectric materials within the energized test domain. When a cable contains sections with differing degradation profiles, the measured spectrum becomes a convolution of pristine and aged segments, making interpretation non-trivial. The work described in this report aims to understand, quantify, and compensate for these effects so that DS can be used reliably for condition monitoring of field-deployed cables where aging is rarely uniform.

2. BACKGROUND AND LITERATURE REVIEW

As nuclear power plants (NPPs) apply for second or subsequent license renewals to extend their operating period from 60 to 80 years and beyond, it is important to understand how materials installed in plant systems and components will age during that time and to develop aging management programs (AMPs) to ensure continued safe operation under normal operation and design-basis events (DBEs). Degradation of cable insulation is known to occur as a function of age, temperature, radiation, and other environmental factors. Although system tests verify cable function under normal loads, concerns remain for cable performance under exceptional loads associated with DBEs. The ability of cables to perform safely over the initial 40-year planned and licensed life has generally been demonstrated, and there have been very few age-related cable failures [1]. With greater than 1000 km of power, control, instrumentation, and other cables typically found in an NPP, replacing all the cables would be a severe cost and logistical burden. License renewal to 60 years and subsequent license renewal to 80 years, therefore, requires a cable AMP in accordance with regulatory guidance [2] to justify cable performance under normal operation as well as accident conditions.

Acceptance criteria that define the threshold for degradation below which cables may continue to be used are a challenge, because it is impractical to subject each cable system to loss-of-coolant accident (LOCA) or seismic simulation events following 40+ years of service. The Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets report [3] develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers. The report describes 50% elongation at break (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. EAB inherently compromises the in-service cable use as it is a destructive ex situ test, so the challenge is to develop nondestructive evaluation (NDE) methods that can reasonably be correlated with EAB. Reliable in situ NDE approaches are needed to objectively determine the suitability of installed cables for continued service. One NDE test that has generally been shown to relate to EAB is a direct or indirect measurement of permittivity. A variety of tests are available to assess various aspects of electrical and mechanical cable performance, but none of the available tests are suitable for all cable configurations nor does any single test assess all features of interest. Direct current (DC) withstand tests at or above the rated cable voltage and low frequency dielectric dissipation factor ($\tan \delta$) tests are widely applied, particularly during commissioning to confirm quality installations, but these tests stress the polymers, which may reduce the life of the cable system and should not be used excessively.

Low voltage DS has been used for decades to characterize the electrical behavior of polymers and other dielectric materials without introducing any significant damage to the dielectric material [4]. Several researchers have applied this general method to cable tests as indicated below.

2.1 Technical Reports on Dielectric Spectroscopy of Cables

2.1.1 EPRI Technical Report 1022969 Plant Engineering: Electrical Cable Test Applicability Matrix for Nuclear Power Plants

Toman [5] describes the state of the art for in situ NPP cable tests and characterizes advantages and weaknesses of each test, with particular focus on aged unshielded power cables for instrumentation and control (I&C) (600V–5kV) from Canadian nuclear and thermal generation plants. That report describes a DS test as a current passing through the insulation in response to a step change in voltage that is analyzed by transforming the acquired current data into a function of frequency to arrive at dielectric impedance as a function of frequency. The variation in dielectric impedance is primarily due to bulk cable capacitance and conductance. The real and imaginary parts of the permittivity, the change in the real permittivity, and the $\tan \delta$ are evaluated with respect to voltage and frequency change. At each applied voltage, a frequency sweep is performed, and the permittivity and $\tan \delta$ parameters are evaluated.

The following four electrical response behaviors have been defined:

- Low-loss, linear permittivity: The permittivity response for new or non-water-tree-deteriorated cables are nearly frequency independent, the loss is low and has a very weak frequency dependence, and the real and imaginary parts of the permittivity are independent of applied voltage.
- Voltage-dependent permittivity: An indication of water treeing that is significant but has not yet penetrated the whole of the insulation, in which the real and imaginary parts of the permittivity are voltage dependent.
- Transition to leakage current: An indication that the water trees penetrate through the wall of the insulation and that the breakdown strength of the insulation is significantly reduced. The transition is indicated by an increased loss at the time of applied voltage. In other words, the second measurement at a specific voltage level has a higher loss than the initial measurement.
- Leakage current: An indication that water trees penetrate the whole of the insulation and the cable has very low breakdown strength. Leakage current is observed at low voltages; loss increases with decreasing frequency, and the real part of the permittivity shows a voltage-dependent response.

The study concluded that none of the conventional diagnostic measurements (DC insulation resistance, polarization index, high voltage partial discharge, capacitance, dissipation factor) utilized were sensitive to unshielded cable degradation. Moreover, the value of testing at frequencies other than power frequencies was highlighted.

2.1.2 U.S. NRC Report NUREG/CR-6904: Evaluation of the Broadband Impedance Spectroscopy Prognostic/Diagnostic Technique for Electric Cables Used in Nuclear Power Plants

Rogovin and Lofaro [6] focused on the application of broadband impedance spectroscopy as a condition monitoring tool for low-voltage (LV) I&C cables found in NPPs. Samples of a two-conductor I&C cable were subjected to thermal aging over their entire length or at discrete locations to simulate the effect of hot spots. The resulting sample population included cables with different levels of aging, ranging in length from 10 to 100 m. The presence of mechanical defects, such as abrasion and racks, was also investigated. Samples were tested with a broadband impedance analyzer over a frequency range of 100 Hz to 100 MHz. Impedance magnitude and phase were extracted from the complex impedance spectra to determine the sensitivity of the method to thermal aging. Analytical models were developed to simulate the test response and interpret the experimental data. The technique was found to be sensitive to global thermal aging in the frequency range below 1 MHz, with the measured impedance phase spectra showing an increase in the impedance phase angle for higher levels of aging. In the frequency range above 1 MHz, the impedance magnitude and phase spectra were downshifted to lower frequencies with increasing level of aging. These findings indicated that the method could be used as an indicator of thermal degradation on the cable.

2.1.3 European ADVANCE - Ageing Diagnostics and Prognostics of Low-Voltage I&C Cables - Project 269983

The ADVANCE project [7] was a European-led collaborative project involving partners from a number of industries, research and engineering institutes, and universities. The main objectives of the project were to evaluate and optimize promising nondestructive condition monitoring methods to assess the condition of safety-related LV cables over their entire length, and to develop acceptance criteria for these methods.

The first stage of the project established the potential application of state-of-the-art condition monitoring methods for LV cables in NPPs. The research looked at the advantages and disadvantages of laboratory and field techniques based on the physical/mechanical characterization of cable insulation and jacket materials. The use of electrical techniques was also investigated, and it was concluded that information about the effect of aging on electrical properties of LV cable insulation is still lacking. Based on this information a research program was developed to investigate and improve the most promising techniques. The program included long and short cable samples subjected to combined thermal and

radiation aging characterized at regular intervals with selected condition monitoring methods. The long cable samples also went through DBE testing to correlate condition indicators measured near the cable end of life with cable survivability.

No single-condition monitoring method was shown to be sufficient to track degradation at all stages; therefore, it was recommended to use a combination of techniques until aging mechanisms are sufficiently identified. From tests on longer samples (about 20 m), no general behavior was observed and it was hypothesized that each cable type (or group) may require the most appropriate condition monitoring method/marker to be defined or at least tuned. Among electrical techniques investigated in the work, low frequency dielectric spectroscopy (LFDS) (obtained using frequency domain techniques) showed the most promising results. In particular, between 10^{-2} Hz and $\sim 10^6$ Hz, test results on short samples showed that both real (ϵ') and imaginary (ϵ'') parts of permittivity of cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR)-based, and ethylene propylene diene monomer rubber (EPDM)-based insulations increased over the whole frequency range. The variation of ϵ' was more evident at low frequency, while ϵ'' increased markedly also in the high frequency range. The change in electrical properties appeared to correlate well with traditional material-based characterization techniques.

Other techniques, such as frequency domain reflectometry (FDR), were noted as being able to locate hot-spots or locations for the greatest potential for damage. Defect location is not provided by DS measurements. The importance of measurement techniques and environmental controls, particularly of temperature, were also noted.

2.1.4 IAEA Coordinated Research Project Condition Monitoring and Management of Ageing of Low Voltage Cables in Nuclear Power Plants

The intent of this large collaborative project [8] between 17 participating countries was to provide comprehensive information and guidelines on how to monitor the condition of LV cables in NPPs. To achieve this goal, a benchmarking program assessed both well-established and new condition monitoring techniques on cables exposed to accelerated thermal and radiation aging. Fourteen different methods, material-based and electrical, were used to test 12 different types of cables. The various participants used the selected methods and results were compared to determine their respective efficacy and accuracy to measure the level of aging for each cable. Among the material-based techniques, EAB and indenter modulus were found to be the most sensitive to degradation by aging for most materials. Oxidation induction time (OIT) and oxidation induction temperature also yielded trendable results for several cable formulations. Fourier-transform infrared spectroscopy (FTIR), ultrasonic velocity, and density were found to be promising in the early stage of aging and have trendable potential for some materials.

LFDS and FDR were found to be the only electrical tests with the potential to trend the degradation of the insulation materials. While FDR was determined to be most useful to detect local areas of degradation, LFDS was found to be able to track changes in the bulk properties of the insulation, more so for irradiated samples than for thermally aged samples. The LFDS tests were conducted between 10^{-2} and 10^6 Hz on short cable samples (up to 1 m) by the University of Bologna. The measurements were made between individual wires or between shield and individual wires for shielded cables. Only a few cables were tested as part of this work but the influence of stray capacitances on the repeatability of results for unshielded cables was noted. It was also reported that testing at higher temperatures enhances the sensitivity of the method to detect material degradation induced by aging.

2.1.5 EPRI Technical Report 3002010403: Long-Term Operations: Initial Findings on Use of Dielectric Spectroscopy for Condition Monitoring of Low Voltage Nuclear Power Plant Cables

The Electric Power Research Institute (EPRI) [9] sought to address the question: Is there a diagnostic test that can be applied to a wide range of LV cable insulation types and configurations that provide a global indication of thermal degradation of a cable circuit, whether it is shielded or unshielded? The research applied LFDS and polarization/depolarization current (PDC) methods that focused on both time-domain (for very low frequencies [0.01–10 Hz]) and frequency-domain (for >10 Hz) methods to assess thermal aging effects on several cables, including:

- a 3-conductor control cable
- a 3-conductor power cable
- a conductor instrument and control cable.

DS tests were performed in various configurations (e.g., electrode grounding, external mandrel grounding, applied voltage level, ambient temperature) and were compared to common physical and chemical cable aging tests of indenter modulus, EAB, near infrared (NIR), infrared (FTIR), etc. Key findings included the following:

- LFDS and PDC measurements can be sensitive enough to detect bulk thermal aging effects (e.g., structural changes in polymer, depletion of antioxidants) in a variety of shielded and unshielded LV cable insulation types and geometric configurations.
- A variety of diagnostic “metrics” derived from the variable frequency and time dependent dielectric response data showed quantifiable trends versus increasing levels of thermal aging. The trends varied depending on the analyzed parameter, and temperature.
- Experimental parameters and test configurations specific to the cable under test must be carefully considered to obtain optimal dielectric response measurement data.
- The results from the study highlighted the unique (cable specific) frequency and time dependent dielectric response characteristics of LV multi-conductor cables with different insulation types to bulk thermal aging.

2.1.6 PNNL-27982 Dielectric Spectroscopy for Bulk Condition Assessment of Low Voltage Cable – Interim Report

Glass et al. [10] investigated nondestructive test methods focusing on bulk cable insulation testing using a DS approach. That report addressed relevant literature coupled with a discussion of the theory of DS measurements and use of modeling to appreciate the influence of damage/defect profile on the bulk total cable measurement.

2.1.7 PNNL-35504 Radiation Aging of Cable Insulation Systems to Support Extension of Cable Electrical Assessment Techniques

Murphy [11] and Elen et al [12], investigated the condition monitoring of electrical cables used in NPPs using electrical diagnostic techniques such as LFDS, PDC techniques, along with other reflectometry techniques such as FDR and time domain reflectometry (TDR), on XLPE and EPR insulated cables, subjected to gamma irradiation and thermal aging. LFDS showed trends of increasing $\tan \delta$ at frequencies above 0.1 Hz across the “single conductor” samples and 30-conductor “mandrels.” A larger increase of $\tan \delta$ is noted for samples subjected to progressive thermal plus gamma radiation aging than for radiation aging alone. It was reported that additional analysis metrics and condition indicators, especially for the more complex responses observed with the cable mandrels, will require more in-depth analysis of the data.

2.2 Journal and Conference Proceedings

Various research groups have published journal and conference articles on the research work performed using DS on NPP cable materials.

A high-voltage DS system was developed under Werelius et al. [13] for diagnostics of water tree deteriorated extruded medium voltage cable-based on measurements of non-linear dielectric response in the frequency domain to measure relatively low loss and small variation of permittivity as a function of frequency and voltage. Experience from more than 200 field measurements was combined with laboratory investigations of accelerated aged samples. The dielectric response of water tree deteriorated XLPE cables was shown to correlate with aging and breakdown strength. Two different field studies of

implementation of this diagnostic method were also presented. The field studies showed the fault rate decreased significantly when replacement strategy was based on the diagnostic criteria formulated.

Linde et al. [14] evaluated DS as a condition monitoring technique for aged XLPE electrical insulation in NPPs. Bare core XLPE samples were aged at 55°C and 85°C and under exposure to ^{60}Co γ -radiation at different dose rates (0.42–1.06 kGy h⁻¹). Samples were assessed using a variety of methods including DS, tensile testing, crystallinity, density, and FTIR. Results suggest that DS can be used for in situ measurements of the degree of oxidation of XLPE cables to assess cable condition and remaining useful life.

Imperatore [15] examined low voltage DS responses of polyvinyl chloride/ethylene propylene rubber (PVC/EPR) multi-conductor cables aged at PNNL compared to EAB and other cable condition metrics. Specific capacitance and dissipation factor measurements showed a monotonic trend that correlated well with aging at 10 Hz, 1 kHz, and 100 kHz. For these samples, the 1 kHz response was the best DS diagnostic marker. The DS change preceded any significant change in EAB, thereby indicating that this measurement could be an earlier indicator of the onset of damage than mechanical measurements.

Fabiani et al. [16] examined combined radiation and thermal aging effects on permittivity. They found an imaginary part of the permittivity at 100 kHz to correlate well with mechanical properties, such as EAB. It was further demonstrated that a post-irradiation effect occurs even years after aging is stopped, increasing the imaginary permittivity and worsening mechanical properties due to the slow conversion of radicals into oxidized species. One consequence is that when cable insulation is subjected to a nuclear accident, the health of cable insulation must also be followed for a long time after the accident occurred, since aging due to oxidation progresses even when the radiation source is switched off.

Cable insulation performance was studied by Mustafa et al. [17] through nondestructive DS and hardness techniques, along with destructive techniques such as OIT and EAB. The use of three parameters, antioxidant depletion factor (*ADF*), degradation index (*DI*), and degradation rate (*DR*), provided a thorough representation of the state of degradation of cable insulation. It was observed that the presence of antioxidants deeply influenced XLPE degradation, slowing down the degradation process in the initial phases of aging. The cable gradually reached its end-of-life criterion, the 50% value of EAB, which was also observed by the *DI* and *DR* trends. The $\tan \delta$ and *DI* correlated highly with the chemical and mechanical parameters under study, establishing them as reliable aging indicators of NPP cables, and demonstrating the effectiveness of dielectric spectroscopy as a viable non-destructive condition monitoring technique.

Suraci et al. [18] explored both DS and TDR. Ten-meter-long coaxial cables were thermally aged and characterized using non-destructive methods (i.e., DS and TDR). Both techniques allowed changes of electrical properties to be revealed with aging; however, the coupling of these two techniques permitted an effective cable aging assessment including recognition of local defects. Indeed, it has been demonstrated that DS is more sensitive when the cable is globally aged, while TDR, in addition to a global investigation, can also single out aging occurring in a limited portion of cable (local aging).

3. DIELECTRIC SPECTROSCOPY THEORY

3.1 Parallel Plate Capacitor to Measure Dielectric Coefficient

The simplest form of a DS measurement is the characterization of the electrical impedance of a parallel plate capacitor. Capacitive sensors are utilized in the area of materials characterization known as *dielectrometry* [19, 20]. The output capacitance of a capacitive sensor placed in the vicinity of a test material is sensitive to the dielectric properties of that material. Capacitance can be measured using a typical inductance-capacitance-resistance (LCR) meter, connected to a capacitive probe.

Generally familiar is the parallel plate capacitor configuration with a dielectric wafer sandwiched between charged (+/-Q) conductive plates (Figure 3-1) whose complex capacitance $C^*(f)$ is given by

$$C^*(f) = \varepsilon^*(f) A/d \quad [\text{Equation 3-1}]$$

where $\varepsilon^* = \varepsilon' - j\varepsilon''$ [F/m] is the complex permittivity of the material that fills the space between the capacitor plates, ε' and ε'' are the real and imaginary parts, respectively, of complex permittivity, ε^* , $|\varepsilon|$ is the magnitude of permittivity (also $= \sqrt{\varepsilon'^2 + \varepsilon''^2}$), A [m²] is the area of one of the two identical capacitor electrodes, d [m] is the uniform separation between them, and f [Hz] is frequency. Parallel-plate electrodes are suitable for dielectrometry on flat specimens of uniform thickness that are sufficiently thinner than the diameter of the electrodes and can be accessed on both sides. For other sample shapes, and in the case of samples that can be accessed from only one side, custom capacitive electrodes including inter-digital-capacitance electrodes can be designed according to various considerations [21-23]. These design considerations usually involve a trade-off between signal amplitude and sensitivity.

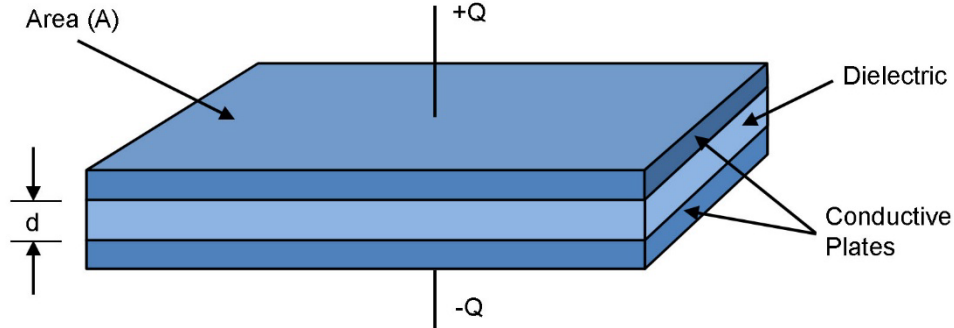


Figure 3-1. Parallel capacitor model with dielectric sandwiched between two conductive plates.

A typical LCR meter measures C as the real part and D as the loss factor of the complex capacitance, where

$$C^*(f) = C(f)[1 - jD(f)] \quad [\text{Equation 3-2}]$$

and this means, for the parallel-plate geometry, $C = \varepsilon' A/d$ and $D = \varepsilon''/\varepsilon'$. A typical LCR meter for cable test applications may cover a frequency range ~ 1 Hz to ~ 1 MHz.

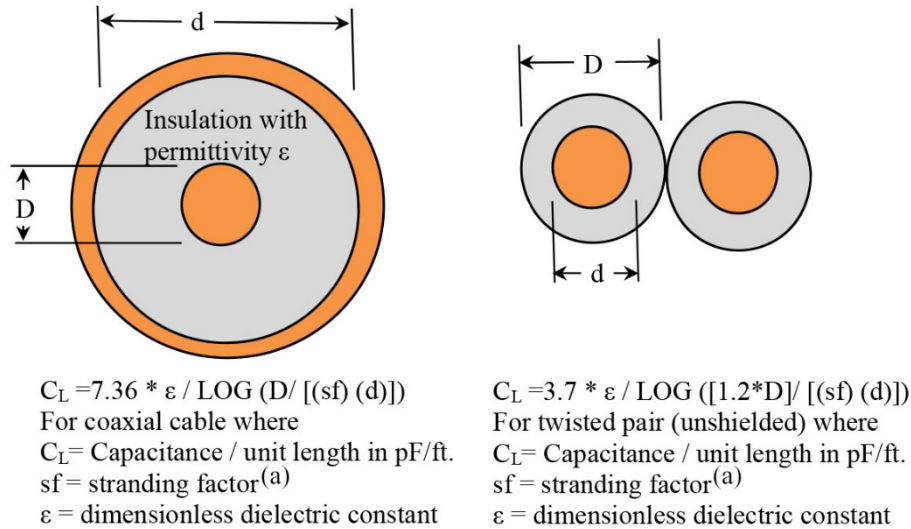
Permittivity, ε^* , is an intrinsic physical property of a material that describes its ability to store electrical energy in the presence of an electric field. It is measured in Farads per meter (F/m). The dielectric constant, ε_r , is a dimensionless ratio of the permittivity of a material to the permittivity of free space ε_0 . In SI units, $\varepsilon_0 = 8.85419 \text{ E}^{-12}$ [F/m].

$$\varepsilon_r = \varepsilon^* / \varepsilon_0 \quad [\text{Equation 3-3}]$$

While permittivity quantifies the absolute ability of a material to store charge, the dielectric constant provides a relative measure compared to free space. This distinction is critical in designing and optimizing electrical devices.

3.2 Cable System Capacitance and Relative Permittivity

The concept of measuring the capacitance and impedance of a cable system including conductors and dielectric material can be extended to either co-axial cables or multi-conductor cables by considering the conductors as analogous to parallel plates. The measured cable capacitance relation to the insulation permittivity is more complex than for the parallel plate case, but the idea is the same. The nominal capacitances and open-circuit impedances can be calculated from standard formulas [24]. Configurations and formulas for calculating nominal cable capacitance for a co-axial case and a single conductor pair are shown in Figure 3-2 . Formulas for distributed line capacitance for the two cases illustrated in Figure 3-2 are shown below the images.



(a) Stranding factor is typically provided in the cable specifications and relates to the conductor void space. For a single-strand conductor, the stranding factor is 1.0.

Figure 3-2. Configuration and formulas for calculating nominal cable capacitance [22].

If C_L [F/m] and cable geometry are known or measured, and cable aging is uniform over the full cable length, the absolute and relative permittivity can be calculated as indicated in Figure 3-2. Frequently however, cable aging is far from uniform. As the cable approaches the reactor with higher temperatures and radiation levels, or as it passes near a hot steam pipe, or as it goes through successive rooms with substantially different temperatures or radiation levels, cable aging/damage occurs at different rates. The overall cable health is governed by the cable segment that is the most aged. A simple lumped parameter cable model as shown in Figure 3-3 can be used to estimate the ratio of the aged section permittivity to a pristine cable section based on the total measured cable capacitance (C_t) after aging, the pristine capacitance ($C_{pristine}$), and the relative cable length that is pristine/unaged, and the length that is aged.

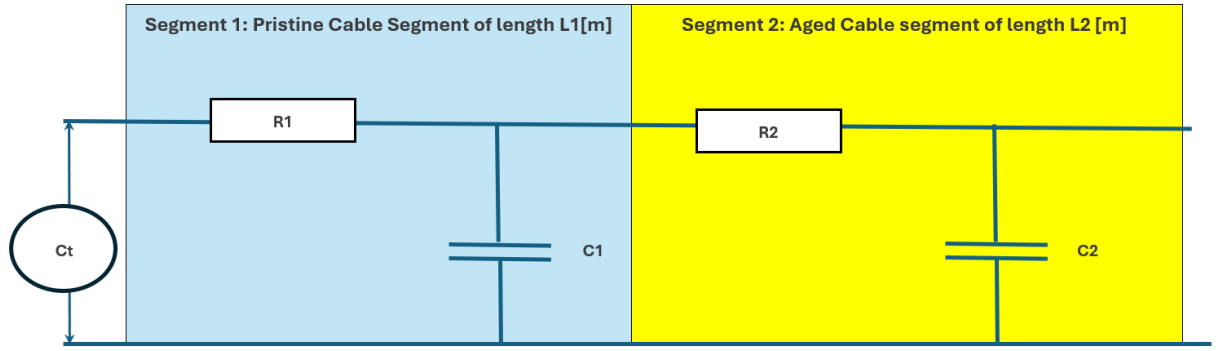


Figure 3-3 Two-segment (pristine and aged) cable lumped parameter model can be used to estimate the relative permittivity of the most aged segment.

To calculate ϵ_2/ϵ_1 for a length of cable with an aged and a pristine segment, the following relations are known or given:

$$C_t = C_1 + C_2$$

where C_t is the measured two-segment total capacitance, C_1 is the lumped parameter of the pristine segment, and C_2 is the lumped parameter of the aged segment

$$L_t = L_1 + L_2$$

where L_1 is the pristine segment length and L_2 is the aged segment length

$$C_1 = C_p \times L_1$$

where C_p is the pristine capacitance (in Farads per meter, F/m)

$$C_2 = C_a \times L_2$$

where C_a is the aged segment capacitance (F/m)

$$C_{tpristine} = C_p \times (L_1 + L_2)$$

where $C_{tpristine}$ is the capacitance of the entire cable before any aging.

$$C_a/C_p = \epsilon_2/\epsilon_1$$

Rewriting the above terms of known or measured $C_{tpristine}$, C_t , L_1 , and L_2 , the above can be rewritten as:

$$\frac{\epsilon_2}{\epsilon_1} = \frac{C_a}{C_p}$$

Solve for C_p from the pristine-total measurement:

$$C_p = \frac{C_{tpristine}}{L_1 + L_2}$$

Solve for C_a from the mixed cable measurement:

$$C_a = \frac{C_t - C_p L_1}{L_2}$$

Therefore:

$$\frac{C_a}{C_p} = \frac{C_t - C_p L_1}{L_2 C_p} = \frac{C_t}{L_2 C_p} - \frac{L_1}{L_2}$$

$$\text{Substitute } C_p = \frac{C_{tpristine}}{L_1 + L_2}$$

$$\frac{\epsilon_2}{\epsilon_1} = \frac{C_a}{C_p} = \frac{C_t(L_1 + L_2)}{L_2 C_{tpristine}} - \frac{L_1}{L_2}$$

Equivalent single-fraction form:

$$\frac{\epsilon_2}{\epsilon_1} = \frac{(L_1 + L_2)C_t - L_1 C_{tpristine}}{L_2 C_{tpristine}} \quad [\text{Equation 3-4}]$$

4. TEST SETUP AND DS MEASUREMENTS

4.1 Direct Measurement of DS Response Compared to EAB

A 62-day thermal aging study was conducted on unshielded general cable (14AWG-3/C) with EPR insulation to evaluate measures of EPR degradation. EPR-insulated cable was selected for the study because EPR, along with XLPE, is one of the two most common cable insulation types found in U.S. reactors and because accelerated thermal degradation of EPR (months) was more compatible with the research study timeline than that of XLPE (years). A 30-ft section of the 100-ft cable was subjected to 140°C aging inside a mechanical convection oven. During the aging period, witness samples consisting of insulation straws extracted from the cables and short cable segments were aged in the oven in parallel with a 30-ft section and collected at regular intervals (see Figure 4-1). Straw specimens were evaluated for their EAB, and DS was performed on aged segments using the Spectano 100 instrument. These samples were silver-painted on the insulation—with the inner conductor used as an inner electrode, and silver paint serving as the outer electrode—and the measurement was performed similar to the coaxial cable geometry (cylindrical electrodes). Complex permittivity, capacitance, and $\tan \delta$ values were measured and analyzed.

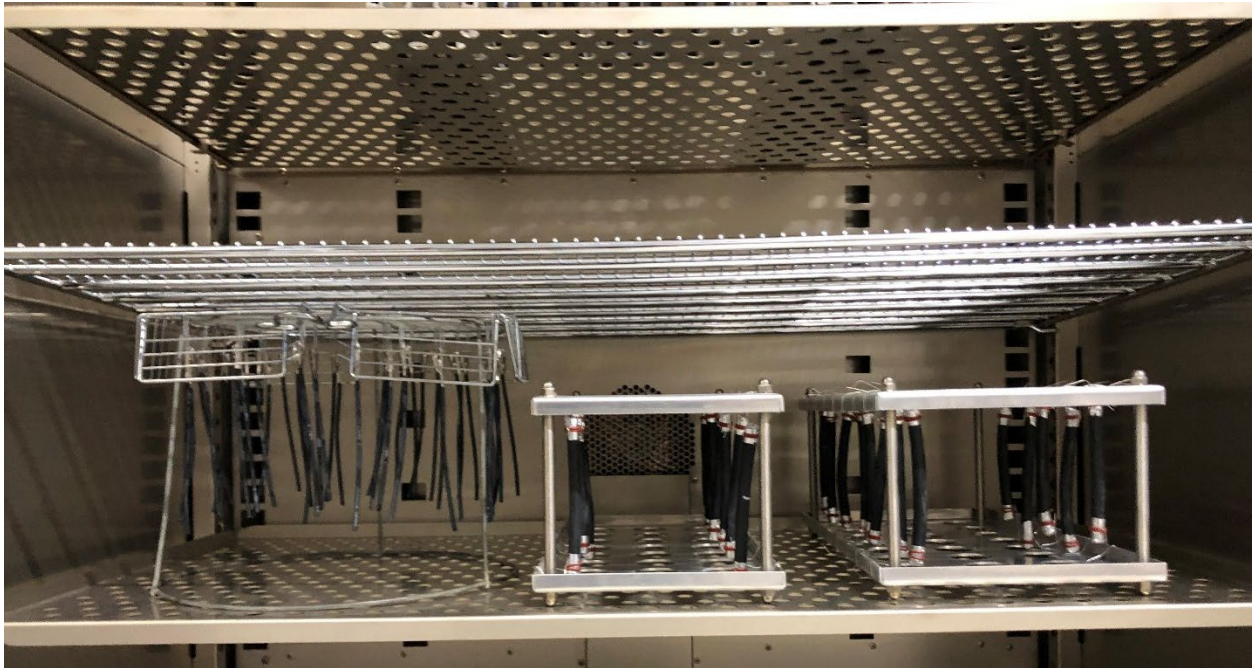


Figure 4-1. Thermal aging of witness samples at 140°C in the thermal oven

As shown in Figure 4-2, the permittivity values measured through DS were compared with the EAB values, and it can be observed that the permittivity values trend fairly linearly while EAB values remain fairly constant (up to 37 days of aging) before dropping rapidly (37 to 55 days of aging). The permittivity-to-EAB correlation coefficient is -0.82. Both the instrinsic standard EAB method and permittivity track with aging of the insulation, but permittivity is seen to track monotonically over the entire aging range investigated, whereas EAB has an induction period of little change with age before onset of rapid property loss. While identification of an endpoint for cable aging from EAB is more straightforward as the point of significant loss, permittivity is demonstrated to be a more useful overall monitor of cable aging since it is nondestructive and increasing steadily over the entire aging period (see Figure 4-2). Furthermore, permittivity may more directly correspond to the critical functional property of interest to maintain for aging cables.

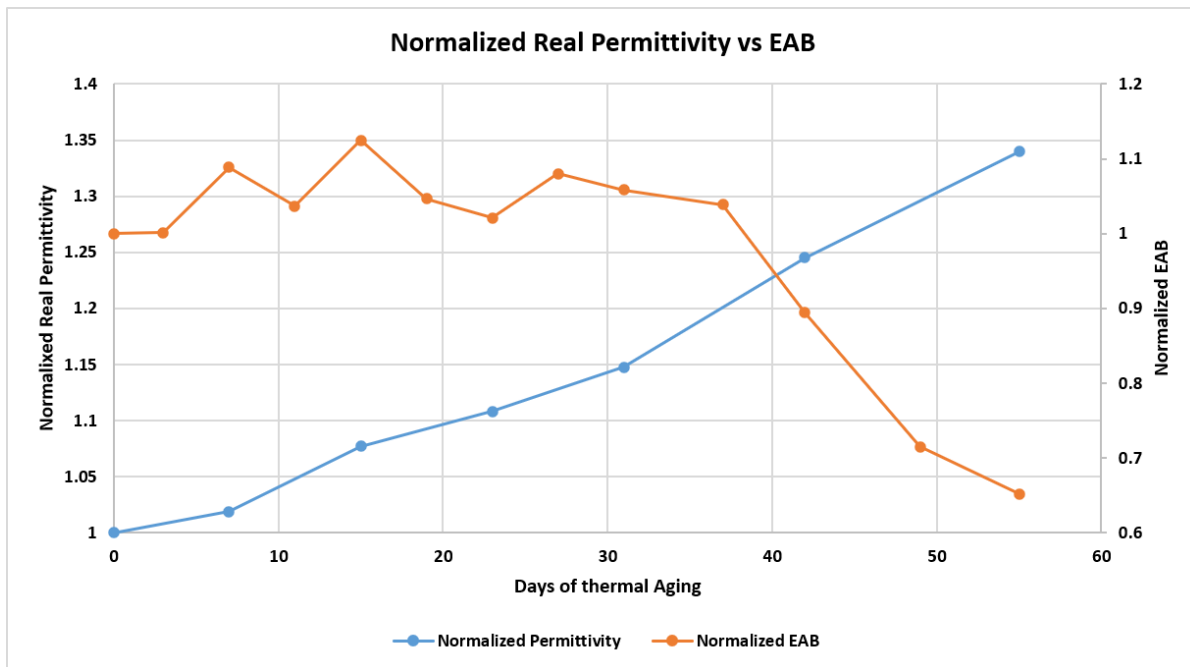


Figure 4-2. Normalized Permittivity vs. Normalized EAB; correlation coefficient between normalized permittivity and EAB is -0.82.

4.2 DS Response for Different Percentages of Cable Length Exposed to Thermal Accelerated Aging

Three identical shielded EPR cables with chlorinated polyethylene (CPE) jacket (jacket description: GENERAL CABLE® (WC) FREP 1TS 16AWG EPR/CPE SHIELDED (UL) TYPE TC-ER 90C WET OR DRY 600V DIR BUR SUN RES) of 50 ft (15.24 m) length were prepared as shown in Figure 4-3. The three cable had 10%, 50%, and 90% (5 ft, 25 ft, and 50 ft) of their length, respectively, in the oven set to 150°C for accelerated aging. Figure 4-4 shows the experimental setup of the cables inside the oven. Unlike the previous experiment, DS measurements were taken on the entire cables, using one conductor connected to the positive lead of DS, and other conductors with shield connected to the negative lead of DS. The measurements were taken weekly for six weeks. The DS response (including capacitance) was logged weekly. As expected, the capacitance response increased from the pristine case as shown in Figure 4-5.

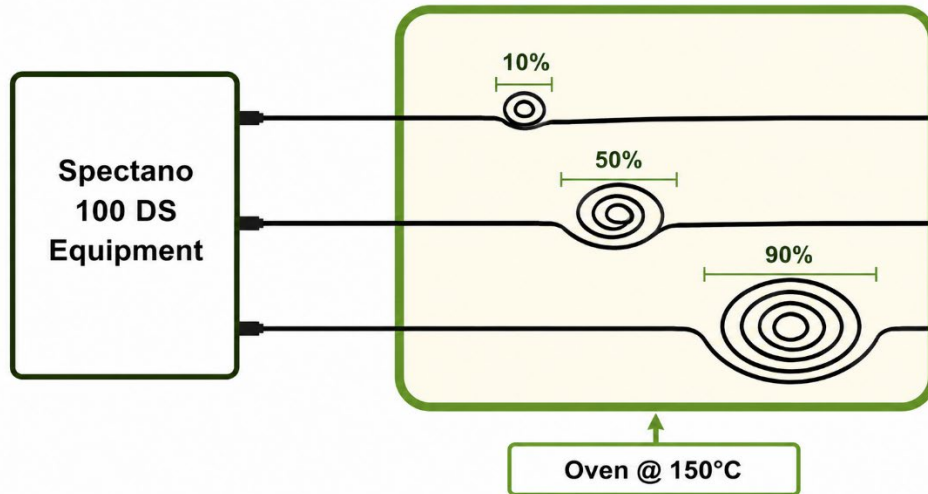


Figure 4-3 Test setup with 10%, 50%, and 90% of the full 15.24 m cable wrapped around a glass carboy in the oven for accelerated aging at 150°C.

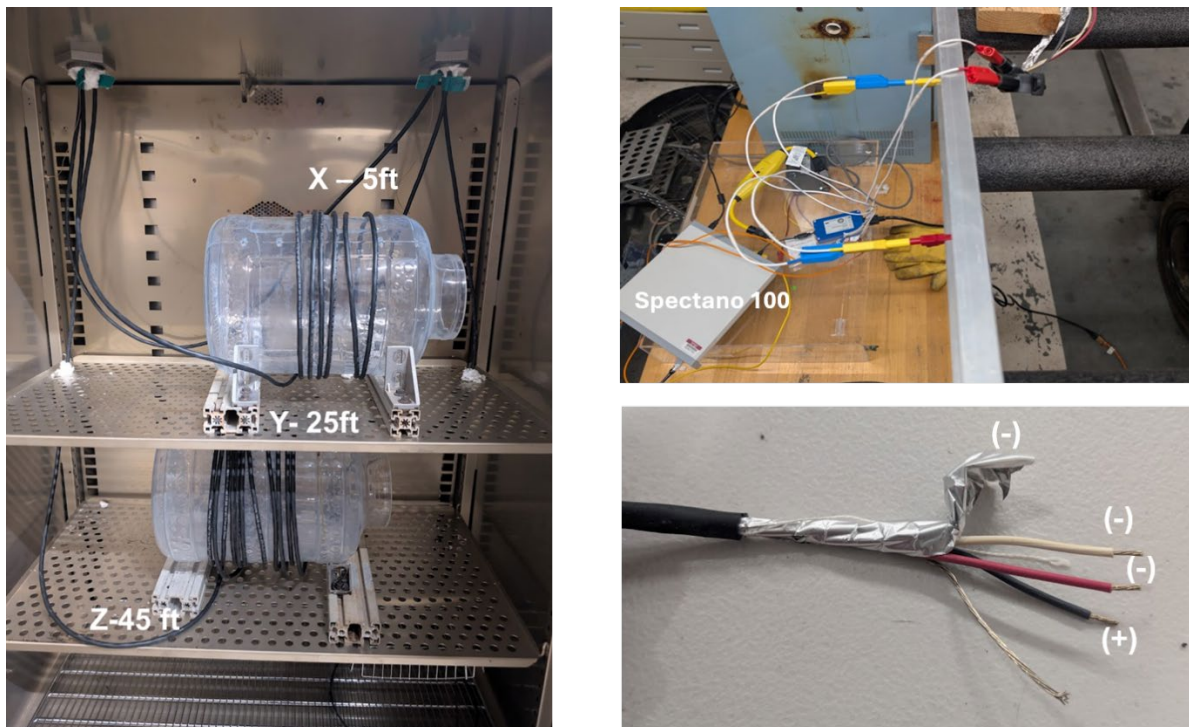


Figure 4-4. (left) Three cables with different sections in the oven; (top right) Spectano 100 DS equipment connected to the cable in ARENA rack for DS measurement; (bottom right) DS positive connected to the black lead, and DS negative connected to the other conductors and shield.

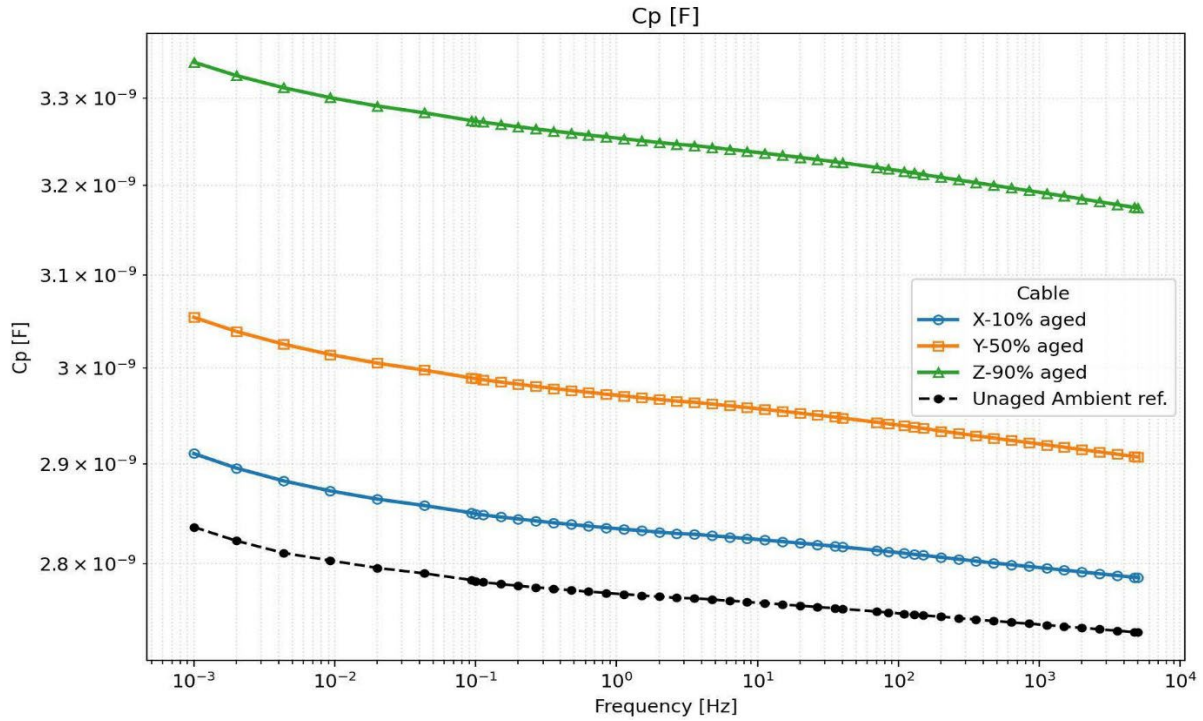


Figure 4-5. DS response (C_p) of pristine case plus the response for 10%, 50%, and 90% of the 50 ft (15.24 m) cable exposed to 42 days of accelerated aging at 150°C.

The measured DS values plus the known lengths of aged and pristine cable enable calculation of the ratio of ϵ_2/ϵ_1 , which is indicative of the aged state of the cable. For the three cables with different % lengths in the oven, the actual ϵ_2/ϵ_1 value was calculated in accordance with Equation 3-4. The ratio was essentially the same for all three cases as indicated in Figure 4-6 showing the 14 day and 42 day ϵ_2/ϵ_1 values. This was as expected since the aged cable sections of all three cables were in the same environment and so should be similarly aged. Note that the order of the ratio (top to bottom) was 10%, 90%, and 50%, for 14 day and 42 days thermally aged cable. This is likely due to differences between the target and actual cable lengths.

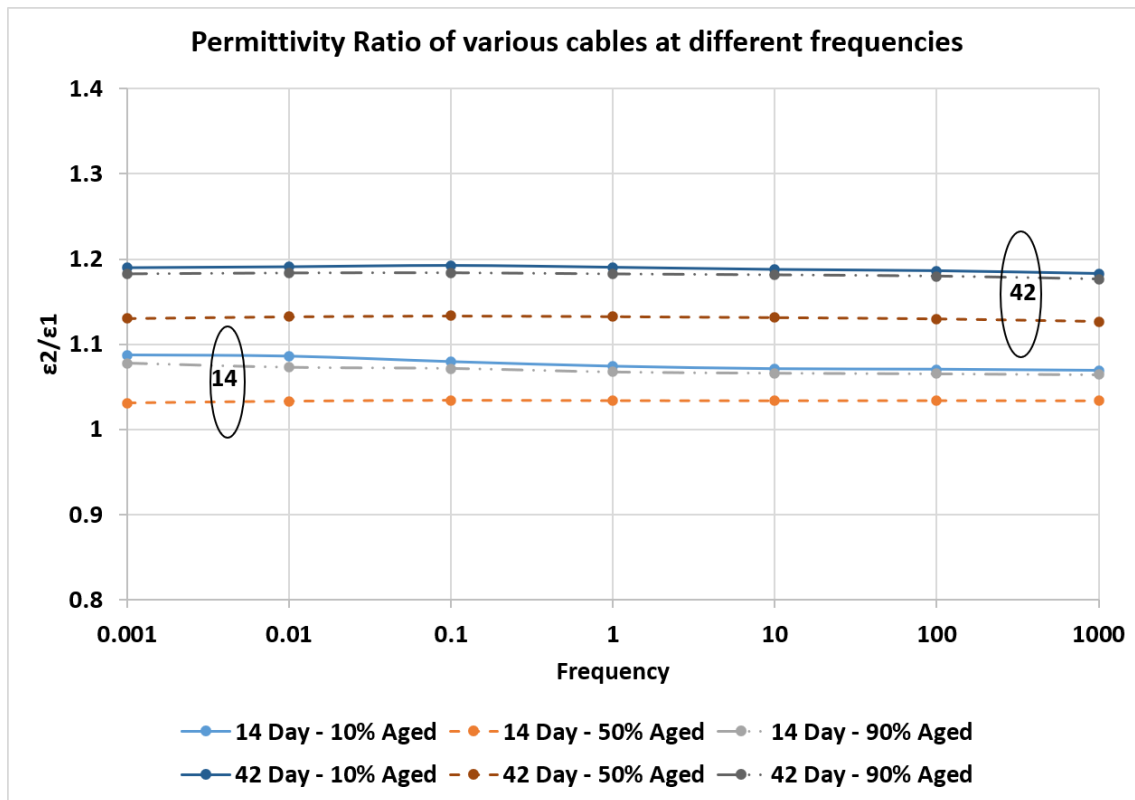


Figure 4-6. This plot shows the ratio of ϵ_2/ϵ_1 for the three different percentages of cable lengths subjected to thermal aging for 14 and 42 days.

Note that the ratio is relatively independent of frequency and so selecting either a single frequency (like 0.1 Hz which is where $\tan \delta$ is normally measured) or an average value over all frequencies will produce similar results. Plotting the 0.1 Hz ϵ_2/ϵ_1 value vs. days aging gives the expected gradual increase in the permittivity ratio (Figure 4-7).

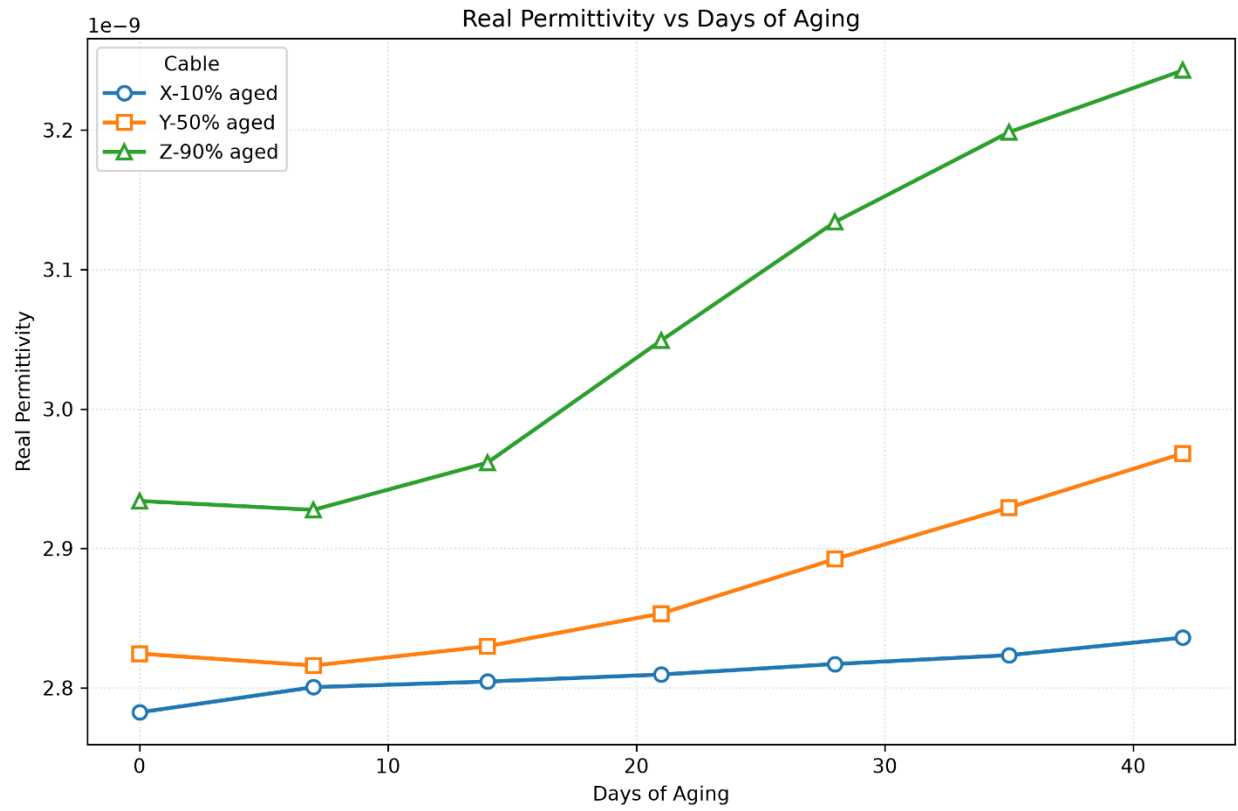


Figure 4-7. Permittivity at 0.1 Hz vs Aging days

5. CONCLUSIONS

PNNL performed an experimental study to evaluate the condition of cable health affected by thermal aging conditions using dielectric spectroscopy. An experiment was conducted by thermally aging different lengths of the cable and measuring the dielectric response. The primary focus was on cable with only a portion subjected to severe aging. Conclusions and observations of the investigation are as follows:

- A substantial body of work suggests feasibility to measure cable insulation damage using various forms of DS.
- There are differences in specific capacitance and inferred real and relative permittivity measured on pristine cables versus those with a thermally aged cable.
- Prior studies showed permittivity (both real and complex parts) to correlate with damage metrics such as obtained using EAB, indenter modulus, and FTIR analysis. This study affirmed prior work by showing an EPR insulated multi-conductor cable exhibited permittivity increases that generally correlate with EAB (correlation coefficient = -0.77) as a damage indicator but there are notable differences in the indicator trend shape. Permittivity is revealed as a preferred metric for installed cable aging compared to EAB as it is non-destructive and trends steadily with aging rather than changing abruptly following a long induction period of little change.
- The DS measurement represents an average of the dielectric condition over the entire cable. If only a small percentage of the cable is damaged, this should be considered when assessing the DS measurement. The metric of interest to predict if a cable will fail is the most damaged segment, not an average. An assumption that the damage is distributed along the entire cable length is a non-conservative assumption.
- If the cable is exposed to two separate environments and the relative cable length in the harsh and benign environments are known, the ratio of ϵ_2/ϵ_1 can be estimated (where ϵ_2 is the permittivity of the aged cable section and ϵ_1 is the permittivity of the pristine cable segment). The cable lengths may be known either based on design drawings, or by reflectometry measurements where transitions from benign to harsh environments produce detectable reflectometry peaks.

6. REFERENCES

- [1] EPRI, "Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis - Update," 3002005321, Electric Power Research Institute, Palo Alto, California, 2015. <https://www.epri.com/research/products/000000003002005321>
- [2] NRC, "Condition-Monitoring Techniques for Electric Cables Used in Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Washington, D.C., 2012. <http://pbadupws.nrc.gov/docs/ML1035/ML103510447.pdf>.
- [3] EPRI, "Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets," 1008211, Electric Power Research Institute, Palo Alto, California, 2005. <https://www.epri.com/research/products/1008211>
- [4] F. Kremer and A. Schonhals, *Broadband Dielectric Spectroscopy*. Berlin: Springer, 2003.
- [5] G. Toman, "Plant Engineering: Electrical Cable Test Applicability Matrix for Nuclear Power Plants," 1022969, Electric Power Research Institute, Palo Alto, California, 2011. <https://www.epri.com/research/products/1022969>
- [6] D. Rogovin and R. Lofaro, "Evaluation of the Broadband Impedance Spectroscopy Prognostic/Diagnostic Technique for Electric Cables Used in Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Washington, D.C., 2006. Available: <http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6904/cr6904.pdf>.
- [7] European Commission, "Final Report Summary - ADVANCE (Ageing Diagnostics and Prognostics of low-voltage I&C cables)," Electricite de France, S.D., France, 2014. Available: https://cordis.europa.eu/result/rcn/149266_en.html.
- [8] IAEA, "Benchmark Analysis for Condition Monitoring Test Techniques of Aged Low Voltage Cables in Nuclear Power Plants: Final Results of a Coordinated Research Project," International Atomic Energy Agency (IAEA), Vienna, Austria, 2017. Available: <https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1825web.pdf>
- [9] EPRI, "Long-Term Operations: Initial Findings on Use of Dielectric Spectroscopy for Condition Monitoring of Low Voltage Nuclear Power Plant Cables," 3002010403, Electric Power Research Institute, Palo Alto, California, 2017. <https://www.epri.com/research/products/000000003002010403>
- [10] S. W. Glass III et al., "PNNL-27982 Dielectric Spectroscopy for Bulk Condition Assessment of Low Voltage Cable – Interim Report," in "Light Water Reactor Sustainability Program," Pacific Northwest National Laboratory, Richland, WA. 2018. <https://www.doi.org/10.2172/1491578>.
- [11] M. K. Murphy et al., "PNNL-35504 Radiation Aging of Cable Insulation Systems to Support Extension of Cable Electrical Assessment Techniques," in "Light Water Reactor Sustainability Program," Pacific Northwest National Laboratory, Richland, WA, 2023. <https://www.doi.org/10.2172/2428981>.
- [12] M. Elen et al., "Evaluation of Thermally Aged and Gamma-Irradiated Nuclear Cables using Electrical Diagnostic Tests," 2024 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Auburn, AL. 2024. pp. 1-4, <https://www.doi.org/10.1109/CEIDP61745.2024.10907422>.
- [13] P. Werelius, P. Tharning, R. Eriksson, B. Holmgren, and U. Gafvert, "Dielectric Spectroscopy for Diagnosis of Water Tree Deterioration in XLPE Cables," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 8, no. 1, pp. 27–42, 2001, <https://www.doi.org/10.1109/94.910423>.
- [14] E. Linde, L. Verardi, D. Fabiani, and U. W. Gedde, "Dielectric Spectroscopy as a Condition Monitoring Technique for Cable Insulation Based on Crosslinked Polyethylene," Polymer Testing, vol. 44, pp. 135–142. 2015. <https://www.doi.org/10.1016/j.polymertesting.2015.04.004>.
- [15] M. V. Imperatore, "Dielectric Spectroscopy as a Condition Monitoring Diagnostic Technique for Thermally Aged PVC/EPR Nuclear Power Plant Cables," Masters, Electrical Engineering, University of Bologna, Italy, 2017. <https://doi.org/10.13140/RG.2.2.14193.30564>

- [16] D. Fabiani and S. V. Suraci, "Broadband Dielectric Spectroscopy: A Viable Technique for Aging Assessment of Low-Voltage Cable Insulation Used in Nuclear Power Plants," (in eng), *Polymers (Basel)*, vol. 13, no. 4. 2021. <https://www.doi.org/10.3390/polym13040494>.
- [17] E. Mustafa et al., "Thermal degradation and multi-performance aging assessment of low voltage nuclear cable," *Electric Power Systems Research*, vol. 250, p. 112128, 2026/01/01/ 2026, <https://doi.org/10.1016/j.epsr.2025.112128>.
- [18] S. V. Suraci, D. Fabiani, and J. Cohen, "In situ defect recognition analysis on long cables through nondestructive reflectometry and dielectric spectroscopy methods: a comparison," in 2020 IEEE Electrical Insulation Conference (EIC), 22 June–3 July 2020 2020, pp. 41–44, <https://www.doi.org/10.1109/EIC47619.2020.9158583>.
- [19] A. A. Nassr and W. W. El-Dakhkhni, "Non-destructive Evaluation of Laminated Composite Plates Using Dielectrometry Sensors," *Smart Materials and Structures*, vol. 18, no. 5, p. 055014, 2009, <https://www.doi.org/10.1088/0964-1726/18/5/055014>.
- [20] R. T. Sheldon and N. Bowler, "Dielectrometry Sensors for Nondestructive Testing of Glass-fiber Polymer-matrix Composites," *Mater. Eval.*, vol. 72, no. 11, pp. 1421–1427, 2014. <https://source.asnt.org/dielectrometry-sensors-for-nondestructive-testing-of-glass-fiber-polymer-matrix-composites/>
- [21] R. T. Sheldon and N. Bowler, "An Interdigital Capacitive Sensor for Nondestructive Evaluation of Wire Insulation," *IEEE Sensors Journal*, vol. 14, no. 4, pp. 961–970, 2014, <https://www.doi.org/10.1109/JSEN.2014.2301293>.
- [22] T. Chen and N. Bowler, "Design of Interdigital and Concentric Capacitive Sensors for Materials Evaluation," *Proceedings of the 39th Annual Review of Progress in Quantitative Nondestructive Evaluation*, Denver, Colorado, July 15–20, 2012, 2013. <https://doi.org/10.1063/1.4789232>
- [23] T. Chen and N. Bowler, "Analysis of Concentric Coplanar Capacitor for Quantitative Dielectrometry," in *Studies in Applied Electromagnetics and Mechanics, Volume 33: Electromagnetic Nondestructive Evaluation (XIII)*, J. S. Knopp, M. P. Blodgett, B. Wincheski, and N. Bowler Eds. The Netherlands: IOS Press, 2009, pp. 61–68. <https://ebooks.iospress.nl/volumearticle/22770>
- [24] Standard_Wire_&_Cable. "Formula for CAPACITANCE in 2 Conductor (Shielded & Non-Shielded) Wires & Coax." <https://standard-wire.com/resource/formula-for-capacitance-in-2-conductor-shielded-non-shielded-wires-coax/> (accessed 2026).

