PNNL-23624

Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants – Interim Status for FY2014

Milestone Report M3LW-140R04022

September 2014

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

This interim report presents an update on the research being conducted to identify key indicators of in-containment cable aging at nuclear power plants (NPPs), and devise in-situ measurement techniques that are sensitive to these key indicators. The motivation for this study stems from the need to address open questions related to nondestructive evaluation (NDE) of aging cables for degradation detection and estimation of condition-based remaining service life. These questions arise within the context of a second round of license extension for NPPs that would extend the operating license to 80 years.

The most important criterion for cable performance in NPPs is its ability to withstand a design-basis accident. Degradation of the cable jacket, electrical insulation, and other cable components is a key issue that is likely to affect the ability of the currently installed cables to operate safely and reliably for another 20 to 40 years beyond the initial operating life. With nearly 1000 km of power, control, instrumentation, and other cables typically found in a NPP, it would be a significant undertaking to inspect all of the cables. The development of one or more NDE techniques and supporting models that could assist in determining remaining life expectancy of cables based on their current degradation state would be of significant interest. The ability to nondestructively determine material and electrical properties of cable jackets and insulation without disturbing the cables or connections has been deemed essential for this purpose.

Currently, the gold standard for determining cable insulation degradation (through a measurement of cable elasticity) is the elongation-at-break (EAB) measurement. This is an ex-situ measurement and requires taking a sample of cable insulation for laboratory investigation. The indentation method is accepted by industry as a nondestructive measurement of cable elasticity and has been correlated with EAB. In combination with visual and tactile assessments, the indentation method is widely used to assess cable aging and degradation. However, these techniques are applicable only to easily accessible cable sections. All other NDE techniques are used to find flaws in the conductor and do not readily provide information to determine the current health or life expectancy of cable insulation. Indeed, there is no single NDE technique that can satisfy all of the requirements needed for making a life-expectancy determination, but a wide range of methods have been evaluated for use in NPPs as part of a continuous evaluation program.

There are, however, several physical and chemical property changes in cable insulation as a result of thermal and radiation damage. In principle, these properties may be targets for advanced NDE methods to provide early warning of aging and degradation. Examples of such key indicators include changes in chemical structure, mechanical modulus, and dielectric permittivity. While some of these indicators are the basis of currently used technologies, there is a need to increase the volume of cable that may be inspected with a single measurement, and if possible, to develop techniques for in-situ inspection (i.e., while the cable is in operation). The evaluation of such key indicators and the ability to measure changes in these key indicators is the focus of the present report.

Several approaches to nondestructively measuring key indicators of cable aging and degradation may be available, and could include chemical, mechanical, and electrical measurements. Electrical and acoustic measurements are potential alternative NDE approaches (to currently used techniques) that may be capable of providing in-situ assessments of cable condition and remaining useful life.

Measurement studies were conducted with samples of aged (at 140°C) medium-voltage ethylene propylene rubber (EPR) cable using acoustic and electromagnetic methods to determine sound velocity and dielectric permittivity. A test-bed was fabricated to enable in-situ measurement of current and voltage on an aging cable system (conductor and insulation), along with aging of small specimens of the medium-voltage cable. These specimens were used for measurements of key indicators.

The complex permittivity results using the dielectric probe display promise for measuring a change in the real part of the dielectric constant and relating the change to cable age. Data appear to also show a correlation with EAB, although this correlation needs to be quantified using additional studies. Using acoustic methods that can provide a direct relation to the elastic modulus of the cable material seems feasible. Preliminary baseline velocity measurements in EPR polymers are in line with published data, and measurements on aged EPR rubber appear to show changes in sound velocity. However, variations in insulation thickness need to be accounted for in the calculations of sound velocity, and may hinder the field-applicability of such a measurement technique. Further, the acoustic measurement methods need further study with specimens with controlled thicknesses to determine if the sound speed (and potentially attenuation) may be an indicator of age that directly correlates with indenter modulus and EAB. Further work can be done to optimize the ultrasonic transducers and analysis methods selected as well as provide a more reliable method for positioning and coupling them. In-situ measurements using dynamic mechanical analysis (DMA) indicate that the storage modulus changes with specimen age; again, further studies are needed to establish a correlation with EAB for computing remaining life estimates. Additional studies may also be needed to determine the viability of approaches that directly measure changes in polymer chemistry as a result of aging; these are planned for future phases of research.

Acronyms and Abbreviations

ATR	attenuated total reflection
DMA	dynamic mechanical analysis
DSC	differential scanning calorimeter
DOE	U.S. Department of Energy
EAB	elongation at break
EPDM	ethylene propylene diene monomer rubber
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
FTIR	Fourier Transform Infrared (spectroscopy)
IAEA	International Atomic Energy Agency
ISI	in-service inspection
LWRS	Light Water Reactor Sustainability Program
NDE	nondestructive evaluation
NPP	nuclear power plant
PNNL	Pacific Northwest National Laboratory
TGA	thermogravimetric analysis
VNA	vector network analyzer
XLPE	cross-linked polyethylene

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1.0 Introduction

The aging of cables is considered to be one of the factors that may limit the ability of light water reactors to continue operations beyond their licensed period (up to 60 years, depending on the specific plant). The most important requirement for cables (electrical or instrumentation) in nuclear power plants (NPPs) is the ability to withstand a design-basis accident. Aging and subsequent degradation of insulation will impair the ability of cables to perform their function under all conditions, and there is therefore a need to assess the condition of cable insulation and estimate the corresponding remaining useful qualified life of the cable.

1.1 Background

In July 2012, a workshop (Simmons et al. 2012) was held to lay the groundwork for a research and development roadmap to address aging cable management in 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 nondestructive evaluation (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 the mechanical load (both static and dynamic) that 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.

Currently, the gold standard for determining cable insulation degradation (through a measurement of cable elasticity) is the elongation-at-break (EAB) measurement. This is an ex-situ measurement and requires taking a sample of cable insulation for laboratory investigation. The indentation method (Mantey and Toman 2013) is accepted by the nuclear industry as a nondestructive measurement of cable elasticity and has been correlated with EAB.

There have been many programs and years of research to address the problems of aging nuclear cables (for instance, Yamamoto and Minakawa 2009; Villaran and Lofaro 2010; IAEA 2012)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). In combination with visual and tactile assessments, the indentation method is widely used to assess cable aging and degradation. However, these techniques are applicable only to easily accessible cable sections. All other NDE techniques (such as time and frequency domain analysis, inductance and capacitance measurements, Tan δ, etc.) are used to find flaws in the conductor and do not readily provide information to determine the current health or life expectancy of cable insulation.

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.

Figure 1.1 succinctly illustrates the importance of using NDE to predict remaining useful life of aging cables and the individual properties that must be considered.

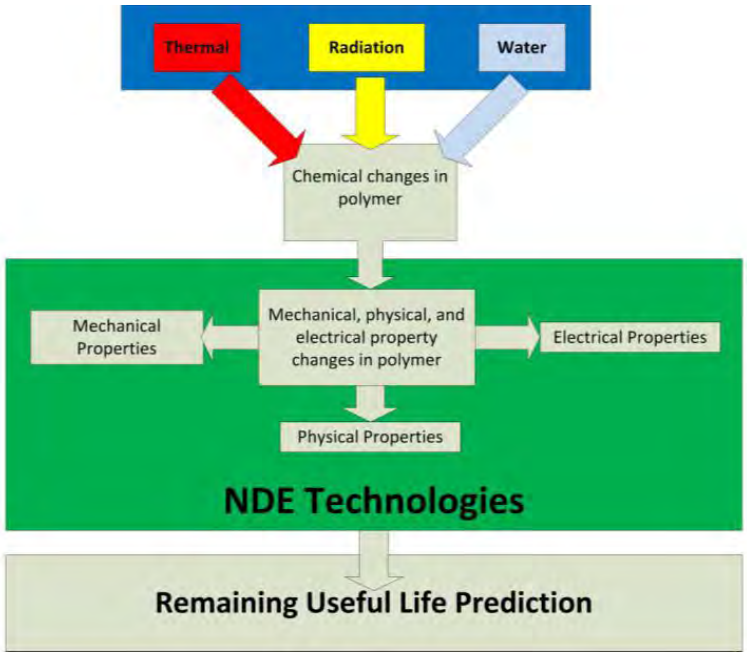


Figure 1.1. Overview of Research Tasks for Cable Aging Detection and Remaining Life Assessment

Subsequently (in late 2013 through early 2014), the research tasks listed in Figure 1.1 were integrated into a coordinated research plan jointly developed by DOE Office of Nuclear Energy (through the Light Water Reactor Sustainability Program [LWRS] program), the NRC, and industry (represented by EPRI). Several coordination meetings have taken place and the research activities under this integrated coordinated research plan have been shared and vetted among the lead research organizations.

Within the context of this project, developments from other research activities within this coordinated plan are leveraged for specimens, identification of key indicators, and access to measurement techniques. At the same time, results from this project are shared with the other activities for subsequent use in determining measurement techniques, analysis methods, and input into cable qualification techniques.

1.2 Project Objectives

The overall objectives of this project are to develop the technical basis for assessing the level and impact of cable aging and degradation in nuclear power plants. The project addresses the overall gaps that were identified at the workshop in FY2012 using a phased approach. This phased approach will address the three areas identified from the workshop:

1. Determination of the key indicators of cable aging.
2. Advance current, and develop new, NDE methods by using insights from the determination of key indicators.
3. Develop models that use the advances in key indicators and NDE methods to assist in predicting remaining life of cables.

The focus of the project thus far has been on measurements of physical properties that act as key indicators of aging of ethylene propylene rubber (EPR)-insulated cable, which is one of the primary cable types used in NPPs. The overall objective of this effort is to complete an assessment of measurements of physical properties on cables subjected to a range of accelerated aging conditions, and assess results for key early indicators of cable aging. The 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, 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 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 useful 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.

1.3 Objectives of this Report

This Pacific Northwest National Laboratory (PNNL) interim report 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. A key departure from previous measurements is the use of a cable system (cable with conductor and insulator intact) for aging and NDE measurements. In addition to these measurements of key indicators (conducted ex-situ for convenience in a laboratory setting), in-situ measurements of other variables were also recorded using an energized cable that was simultaneously aged in a test-bed. The report includes a description of the various measurement techniques and the test-bed, and presents results obtained to date.

This report is submitted in fulfillment of deliverable M3LW-140R04022 “Report on the assessment of experimental work for determining key indicators in aged cable correlation to NDE techniques” (Level 3 Milestone).

1.4 Report Organization

This document is organized as follows. Section 2.0 summarizes the measurement needs from a materials science perspective. Specifically, the impact of degradation mechanisms of concern on materials microstructure, and the key measurements that are needed for assessment of impact on structural integrity are summarized. Section 3.0 summarizes the leading candidates for nondestructive measurements that may be applicable to the problem at hand and describes the experimental approach. Section 4.0 summarizes the experimental data collected to date and describes the initial results of analysis of this data. Sections 5.0 and 6.0 summarize the findings to date and discuss the path forward. And Section 7.0 provides the references used in this report.

2.0 Key Indicators of Cable Degradation

The stressors in fielded polymers—such as heat, radiation, and moisture—modify polymer chemistry and result in changes in mechanical, physical, and electrical performance of the materials. The nuclear industry uses a variety of polymers and elastomers for insulators and jacketing materials with several of these materials often used in combination. The industry has accepted indentation modulus as a key indicator and elongation at break (EAB) as a measure of cable remaining useful life. EPRI Technical Report 1008211, "Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets" (EPRI 2005) develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers. The report describes 50 percent EAB as a conservative practical end-of-life threshold for cables that may be stressed during maintenance or subjected to loss-of-coolant accident exposure. The report also discusses the basis for cautious continued use of cables beyond the 50-percent EAB threshold.

EPRI document TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report; Revision 1" (EPRI 1994) 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 considered age-related degradation mechanisms, but does not appear to have correlated these with NDE detection methods. The industry also has a Class 1E qualification test that cables must be subjected to and that is in accordance with IEEE standards 323-2003 and 383-2003.

While these methods are broadly accepted in industry, the indentation modulus is a localized measure of cable insulation degradation that has been correlated to EAB. Measurements of modulus from one location cannot be readily extrapolated to assessing the condition of the cable over longer sections, especially in sections that are inaccessible and may experience different environmental conditions. EAB, on the other hand, is an ex-situ measure of cable remaining useful life.

Developing approaches for NDE that overcome the potential limitations of these methods will require a fundamental assessment of NDE methods for their applicability to cable remaining useful life estimation. The key to success in using 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.

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 involved, and their role in aiding or inhibiting aging-related polymer changes. The presence of multiple materials in a cable system (conductors, semiconductors, and insulators arranged in layers to form barriers to the external environment while minimizing electrical stresses during operation) may, on occasion, also impact aging rates and corresponding changes in the polymer chemistry. As a result, aging studies that include these other materials may provide additional insights into key indicators and likely NDE methods.

A previous interim report (Simmons et al. 2013) described the various chemical and physical properties that may be key indicators for cable insulation aging. Chemical indicators include changes in the levels of various additives, the level of crystallinity, the glass transition temperature, and the presence

of reactive species, among other quantities. The result of chemical changes (such as chain scission or cross-linking) can affect physical properties such as strength, gas or liquid uptake, color, refractive index, elasticity, and electrical polarizability. Details of these changes, their causes, and the effect on the polymer, are available in Simmons et al. (2013).

NDE measurements that target these types of changes in the polymer are of interest, as they provide a measurable quantity that may be tracked over time to quantify aging and degradation in the cable. Further, by correlating these changes with EAB (the currently accepted gold standard for cable remaining life), the NDE measurement becomes a proxy through which remaining life of the aged cable may be estimated.

3.0 Experimental Assessment of Key Indicators

A review of literature indicated several properties (physical, chemical, and electrical) of cable insulators that have the potential to serve as key indicators of aging-related degradation (Simmons et al. 2013). Based on this survey, we selected a number of properties for initial assessment. The selection was based on sensitivity of measurement techniques to the property, ease of obtaining measurements, potential for in-situ measurement, potential for developing measurement techniques that can interrogate the cable condition over longer distances, and availability of measurement equipment. This section describes the measurement techniques that are being evaluated experimentally for their sensitivity and reliability during this phase of the assessment. Additional properties (and related measurement techniques) will be evaluated in subsequent phases.

3.1 Materials

The outer sheath material of the cable used in this study is an ethylene propylene-based rubber material, typically referred to as EPR. This material has the registered trade name of Okoguard and is produced by the Okonite Company. It is important to note that EPR insulation is widely utilized in the nuclear power industry and available from a number of sources, and the material selected was primarily for ease of procurement in addition to being one of the major sources of cables in the nuclear industry. The differences with other EPR rubbers are typically because of minor changes in the level or type of various additives, and the measurement techniques described and evaluated in this study are expected to be equally applicable to other EPR rubbers used in the nuclear industry.

Specimens used in this study were largely comprised of sections of cable (Figure 3.1) approximately 20 cm (8 in.) in length. Each cable section had a conductor roughly 16 mm in diameter, surrounded by a semiconductor tape and EPR insulation of ~5.5-mm thickness. These samples were heated in a forced air oven at 140°C. Samples were removed at different time points up to ~1200 hours, and used in a number of the measurements described next. In addition, a longer section of cable (about 10 ft in length, with a 2-ft section inside the furnace) was aged continuously at the same temperature using the cable aging test-bed (Section 3.2).

Figure 3.1. Schematic of Cable with EPR Insulation for Use in Measurements of Key Indicators

In addition to the sections of cable, thin sheets (~1.6 mm in thickness) of EPR rubber (from the same source described earlier) were also used. Small sections (~1 cm × 1 cm squares) were cut from the sheets and aged at 140°C. In addition, some of these small sections were used in a dynamic mechanical analysis (DMA) tester under isothermal conditions to assess changes in elastic properties with aging.

3.2 Cable Aging Test-bed

PNNL has developed a test setup that can age the cable while cable property measurements are performed. The concept is to supply an operating voltage and current to an electrical cable that is representative of a cable used in a nuclear power plant. In the test setup, a medium-voltage EPR cable is run through a forced-air oven. The cable remains in the furnace for the duration of testing and measurements can be made on the cable exterior to the oven. Figure 3.2 provides a graphic representation of the test apparatus and Figure 3.3 provides a photograph of the test setup assembled.

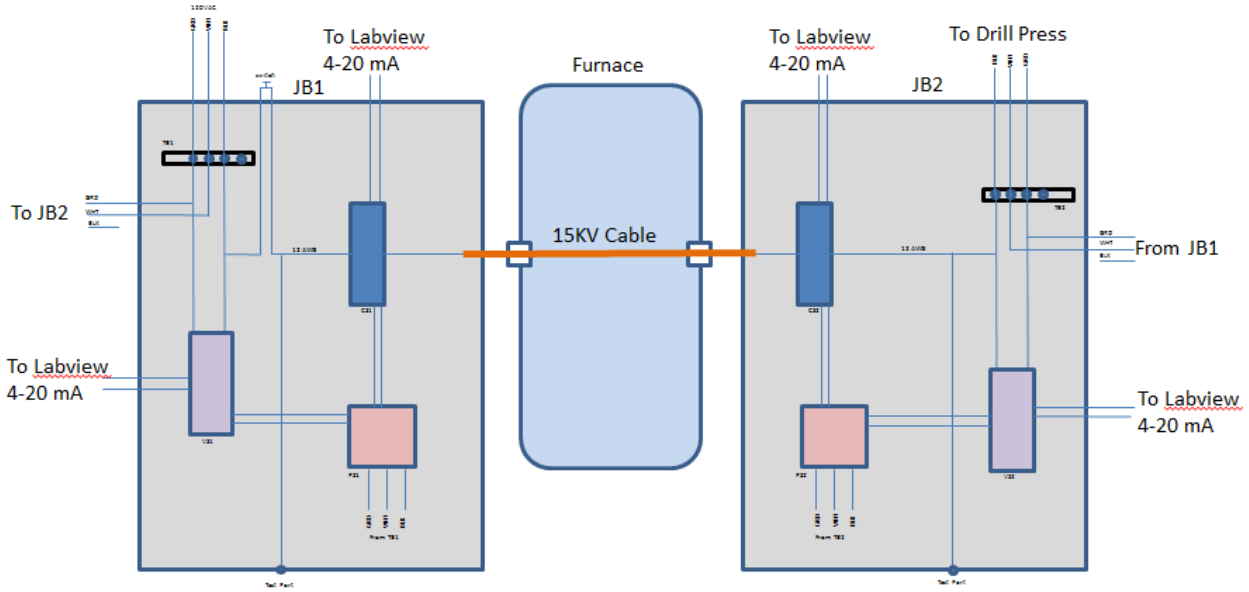


Figure 3.2. Graphic Representation of Measurement Circuit (where JB – Junction Box, TB – Terminal Block, CS – Current Sensor, VS – Voltage Sensor, PS – Power Supply)

(a)

(b)

Figure 3.3. Photograph Showing the Cable Aging Test-bed. The load (motor) is on the right of the oven and the integrated control system is on the left.

The cable is connected at one end to the wall outlet through a junction box. A load (in our case, a motor operating at 120 VAC, and drawing a maximum current of 7.5 A) can be connected to the other end of the cable through a second junction box, and turned on or off based on the test protocol. The circuit is monitored from a LabVIEW integrated control system (Figure 3.4), which allows measurements to be taken continuously at specified intervals. Temperature is monitored by 8 thermocouples located both inside and outside the furnace, to ensure steady temperature and to track temperature shifts from the door being opened or possible power outages. An example of the data collected by the online-monitoring of the EPR is shown in Figure 3.5.

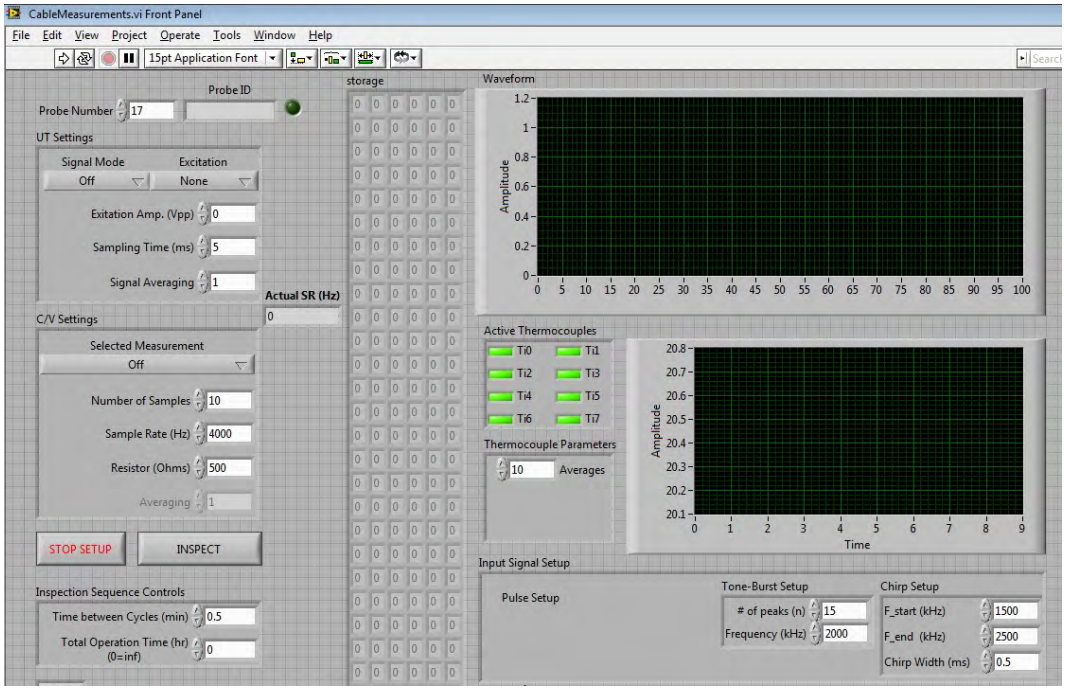


Figure 3.4. LabVIEW Integrated Control Interface

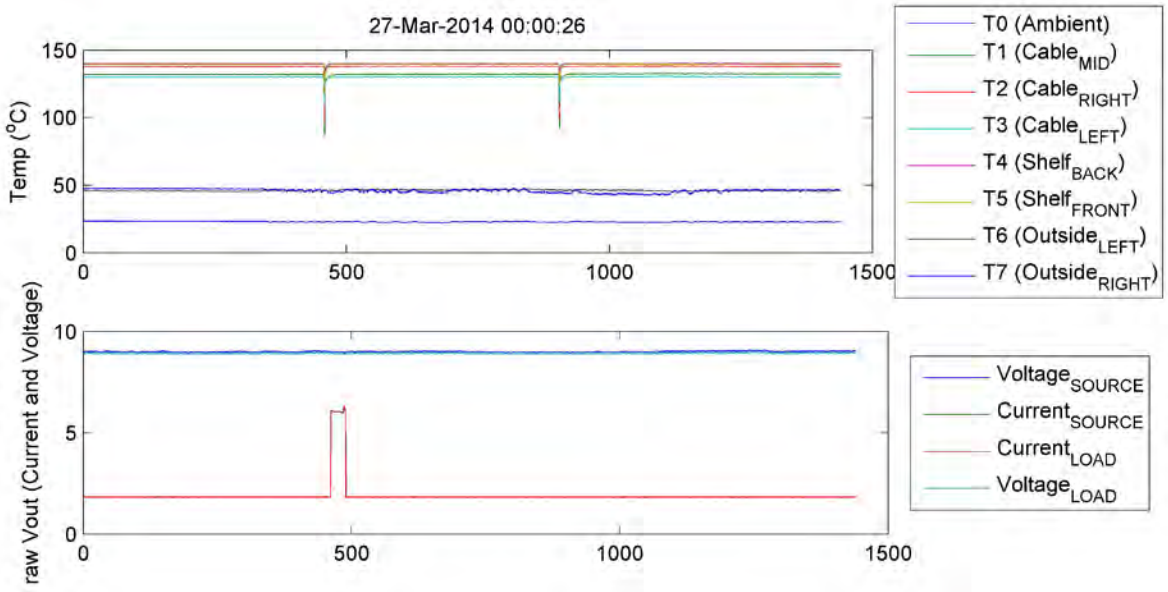


Figure 3.5. Data Recorded by the Control System Measuring Dynamic Shifts in Sensors

Additional test points are located in each junction box (input and output) to allow for additional (more precise) instrumentation to be added. For the series of experiments conducted to date, voltage and current sensors were used to monitor the input and output voltages and currents as the load was cycled during the aging process. A rack that can hold up to 12 cable specimens allows for simultaneous aging of smaller samples for ex-situ nondestructive or destructive testing.

3.3 Measurement Techniques for Chemical Properties

Chemical changes that polymers undergo with aging include oxidation, cross-linking, and chain scission. Polymer mechanical and electrical properties change with the chemical properties of polymer systems. As a result, analytical techniques are needed to determine the changes in chemistry to better form correlations with mechanical and electrical properties. Commonly used analytical techniques for cable material chemical property changes include Fourier transform infrared spectroscopy (FTIR) (Seguchi et al. 2011), differential scanning calorimetry (Özdemir 2008), and thermogravimetric analysis (Seo et al. 2011)

3.3.1 Fourier Transform Infrared Spectroscopy

Oxidation and crosslinking of cable insulation polymers such as EPR and cross-linked polyethylene (XLPE) inherently introduce new chemical bonds within the material, including C=O carbonyl and C=C carbon bonds, that have unique vibrational frequencies. A convenient method, therefore, for characterization of related polymer degradation is FTIR spectroscopy. An example FTIR spectrum of EPR is provided in Figure 3.6.

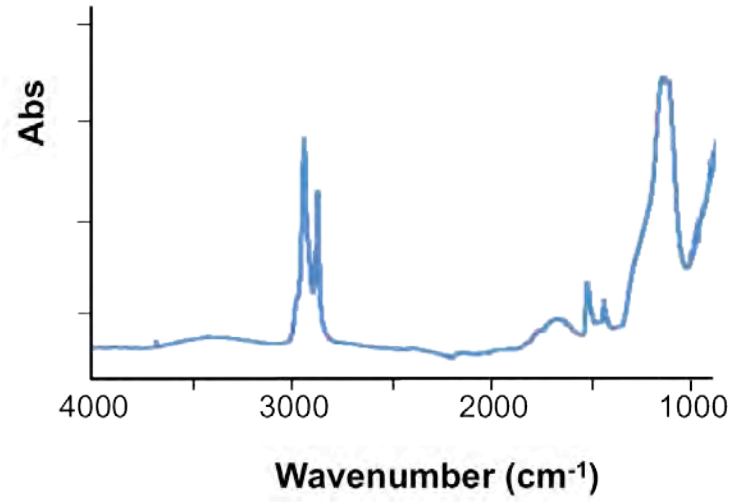


Figure 3.6. FTIR Spectrum of EPR

3.3.2 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) is a technique that is especially useful for characterization of semi-crystalline polymer systems. DSC measures the flow of heat in and out of test samples over time as a function of sample temperature. Features in a DSC curve include phase change transitions. As illustrated in the DSC curve of ethylene propylene diene monomer rubber (EPDM) in Figure 3.7, heat flows into a sample with rising temperature to effect endothermic transitions including transition from solid to a glassy state, the glass transition, and from a glassy solid to a melted liquid. Heat is also consumed in the evaporation of volatile compounds such as added processing aids. In a semi-crystalline polymer, it is the material in the crystalline regions that undergoes a distinct melting transition. The

integral of the melting peak in the DSC curve is thus a direct measure of the crystalline content of the system. The shape of the DSC curve, including the location of glass transition, is also related to chain scission and cross-linking that the polymer may have experienced.

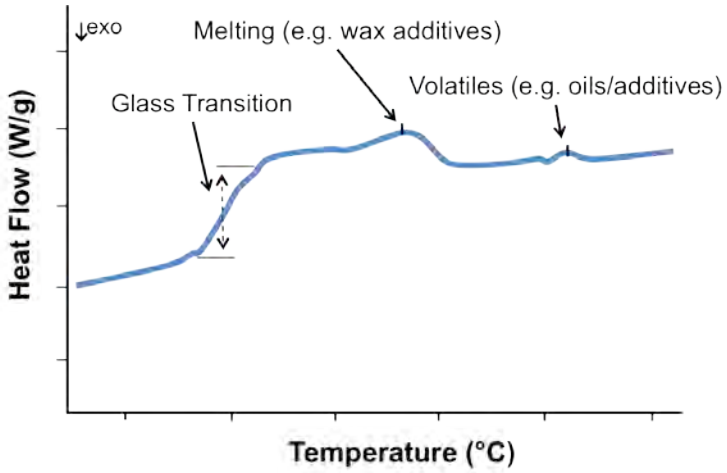


Figure 3.7. Illustrative DSC Curve of EPDM Showing Glass Transition, Melting Point, and Evaporation of Processing Additives

3.3.3 Thermogravimetric Analysis

In thermogravimetric analysis (TGA), the mass of a sample is monitored as a function of temperature and time. The experiment may be performed under inert, reactive, or oxidizing atmosphere and the TGA may be combined with a mass spectrometer to detect mass fragments of species volatilized during sample heating. Mass loss with heating can reveal copolymer ratio, moisture content, volatile additive content, and inorganic filler content. The decomposition behavior of polymer samples at higher temperatures can also reveal information regarding the extent of chain scission and cross-linking in the polymer. Thermal decomposition in the TGA experiment may be a useful measure of relative degradation and history of polymer samples. The thermogram curve in Figure 3.8 illustrates transitions with 1) onsets of mass loss of distinct constituents, 2) inflections of mass loss curve, and 3) conclusion of mass loss.

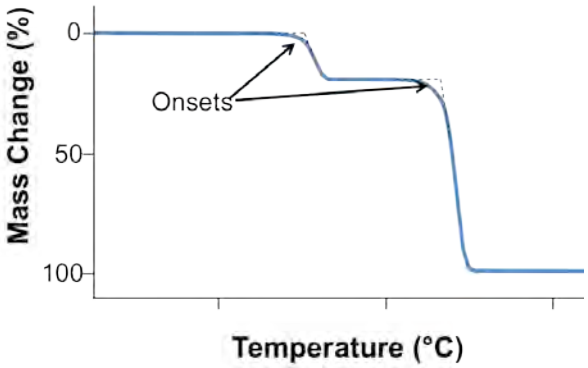


Figure 3.8. Illustrative TGA Showing Mass Loss due to Decomposition of Distinct Components

3.4 Measurement Techniques for Mechanical Properties

The most common measurement for sensitivity to aged conditions is destructive tensile testing known as EAB. Tensile strength may increase during aging and then dramatically decrease with some insulators. However useful in research, it is not practical to destructively test in-use cables for determining their aged condition (Gillen et al. 1999).

One of the key indicators that has previously been discussed (Yamamoto and Minakawa 2009) is the change in modulus of elasticity of the outer sheath material of a nuclear-grade cable. Aging of polymers used as cable insulation and jacket materials typically causes them to harden, thereby changing their elastic modulus.

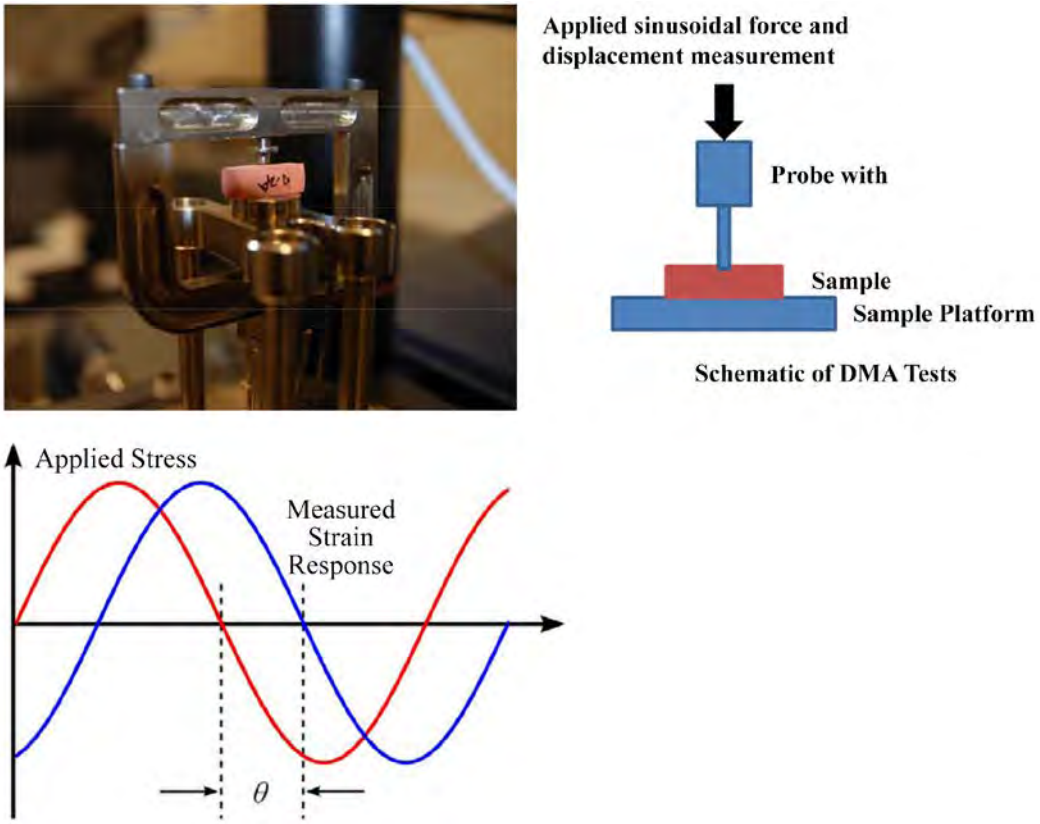
Several approaches to measuring elastic modulus (or quantities that are related to the modulus) are possible. The industry standard for measuring modulus is the indenter method (IAEA 2012), which is related to the elastic modulus. Studies indicate that the elastic modulus generally increases with thermal aging (Lofaro et al. 2001). Approaches besides the indenter method may provide greater sensitivity to changes in elastic modulus. These are described in greater detail below.

3.4.1 Dynamic Mechanical Analysis

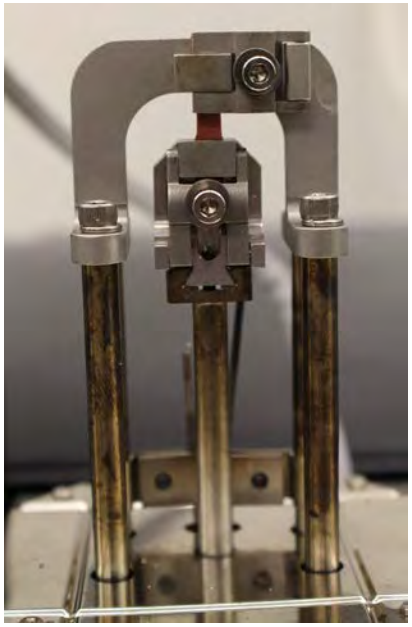
PNNL used an advanced measurement system from TA Instruments and a technique known as dynamic mechanical analysis. DMA measurements are sensitive to polymer transitions, levels of crystallinity, chain scission, and crosslinking (Sepe 1998). The DMA measures the material response to the stimulated stressors applied. The stressors can be temperature, frequency, applied stress, or applied strain, and the DMA can be used to characterize the material's properties as a function of temperature, time, frequency, stress, and atmosphere. The DMA can also be used in thermomechanical analysis mode that can simulate not only the indenter test, but also look at mechanical stressors such as tensile, creep, and stress relaxation.

The DMA measurements typically apply a sinusoidal force at a 1-Hz frequency while sweeping temperature from −150°C to 150°C or higher at 2°C/min. The test geometry can vary with tensile grips for specimens of thin geometries up to 3–4 mm in width. The shear stress mode using various probe tips can have different geometries depending on the stress level of interest. PNNL has used a 0.91-mm probe diameter with right cylinder geometry. Cross-section samples of ~5.5-mm thick and ~0.635-mm wide were cut from aged tensile specimens and subjected to DMA measurement conditions. The DMA tensile mode used geometries of 3-mm wide and 1.5-mm thick. Okonite provides EPR cable material compound for testing in 15 cm × 15 cm sheets, 1.5-mm thick.

Figure 3.9 illustrates how the system is configured to measure the material properties. The oscillating probe with its applied stress and measured strain compares the lag between the applied and measured conditions to calculate storage and loss moduli. The storage and loss moduli are the stored (elastic in-phase) and dampened (viscous out-of-phase) energy components, respectively. The ratio of the loss to stored moduli, a measurement of energy dissipation in the material, is the Tan δ. The Tan δ is analogous to that of the electrical property measurements of which the ratio is a measurement of the lag between the applied and measured loads.



(a)



(b)

Figure 3.9. (a) Image of the DMA Instrument with Compression Tip for Shear Modulus and an Illustration of a Simple Schematic and Input/Output Waveforms for Analysis;
(b) Photograph of Tensile DMA Instrument Setup with Cable Insulation Specimen

Figure 3.10 illustrates how information from DMA measurements can be used to compare changes in materials based on process conditions or changes in the polymer structure and morphology. Given the types of information that are available from these measurements, it is apparent that DMA is an extremely valuable tool for polymer characterization.

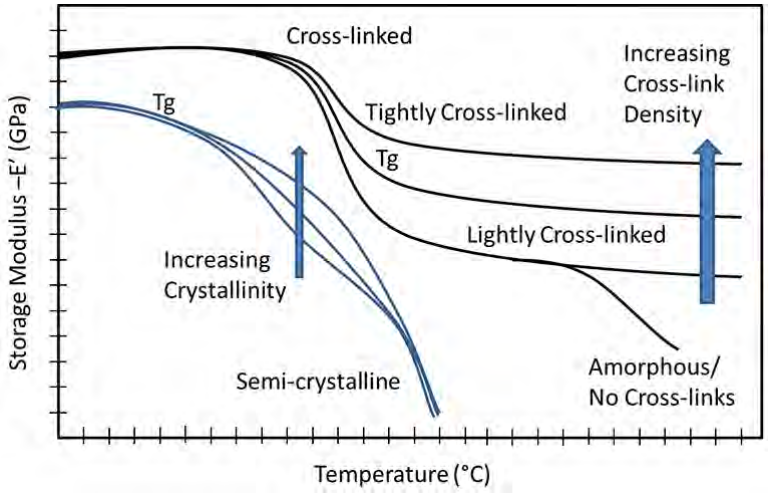


Figure 3.10. DMA Data Schematic Illustrating the Available Information Determined by DMA

DMA storage modulus data is related to tensile modulus for the material. This type of data is valuable for assessing techniques for acoustic measurements and the change in properties as it thermally degrades. In Figure 3.11, the DMA storage and loss modulus data from the Okoguard jumper cable is shown in the baseline, unaged condition. The data reveals a glass transition temperature of −48°C and very compliant soft material at room temperature relative to its high stiffness below the glass transition. The rise in storage modulus of the Okoguard cable with oven aging is illustrated in Figure 3.12.

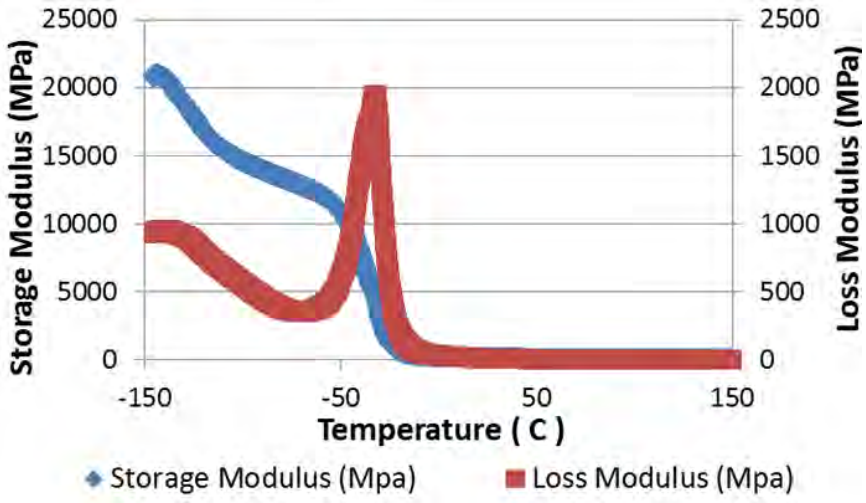


Figure 3.11. DMA Data for Unaged Okoguard Jumper Cable

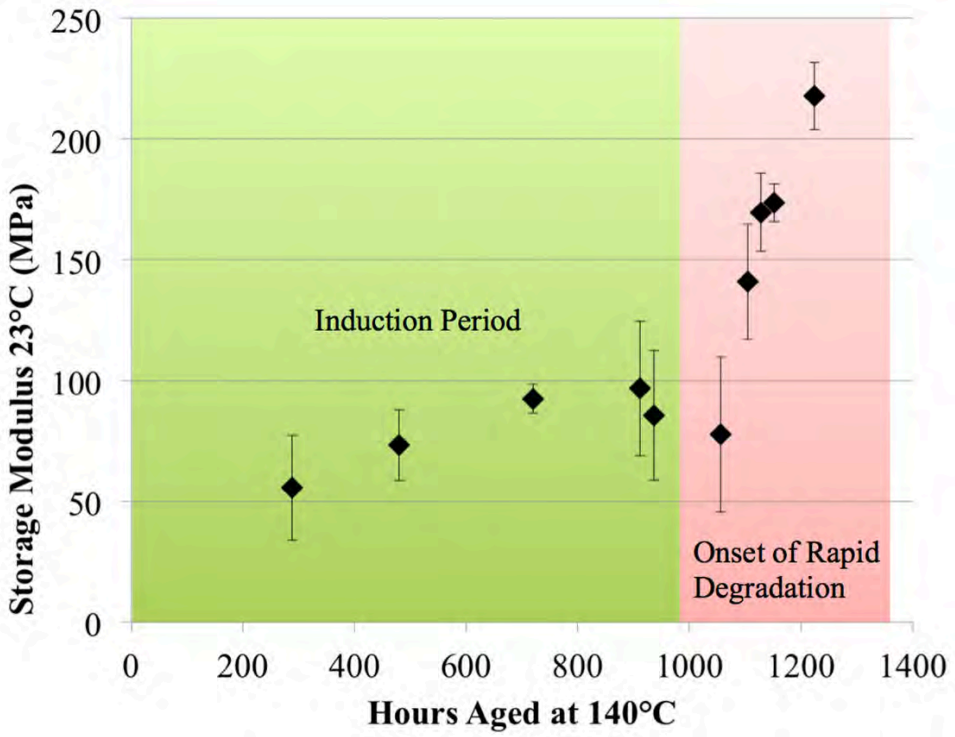


Figure 3.12. Storage Modulus of 140°C Thermally Aged EPR Okoguard Jumper Cable

A new test was evaluated using DMA tensile modulus in situ under isothermal conditions. The test was run for 45 days in a nitrogen atmosphere at 140°C. A second test was run at 160°C to help reduce test time and to see the impact of the DMA capability. The results of the data will be correlated to NDE methods for their sensitivity to changes in the material modulus and chemistry.

3.4.2 Ultrasonic Measurements of Sound Speed and Attenuation

Acoustic wave interactions with solids depend on mechanical properties of the material (Pao 1983) such as density and elastic moduli (Krautkrämer and Krautkrämer 1990). In solids, these waves are also referred to as elastic or stress waves. The behavior of acoustic waves in solids is also a function of the wave mode. The three bulk wave modes usually considered are longitudinal or compressional (called L or P), horizontally polarized shear (SH), and vertically polarized shear (SV). In addition to these modes, surface and plate wave modes (and other modes) can also be generated, depending on the particular parameters and component geometry.

The wave speed c_l in solids for compressional waves is given by (Krautkrämer and Krautkrämer 1990):

$$c_l = \sqrt{\frac{E}{\xi}\frac{1-\mu}{(1-\mu)(1-2\mu)}} \tag{3.1}$$

where E is the modulus of elasticity (units: N/m^2), ξ is the material density (kg/m^3), and μ is Poisson's ratio for the material (a dimensionless quantity). For plane waves or spherical waves, the sound pressure p (related to the applied force) and (compressional) displacement ζ are related by (Krautkrämer and Krautkrämer 1990):

$$p = \xi c_l \omega \zeta = Z \omega \zeta \tag{3.2}$$

where Z is the acoustic impedance.

These two relations indicate that sound speed measurements may be a proxy to measuring the elastic modulus. When the velocity measurements are coupled with measurements of density of the medium, the resulting acoustic impedance of the medium may, in turn, be capable of providing a quantity that is, in form, similar to the indenter modulus. However, the ability to do so using acoustic methods may enable faster measurements of elastic modulus than can be made with the indenter method. Further, acoustic measurement of modulus may enable measurements over larger regions of the cable, something that requires manual positioning using the indenter method.

As a consequence, in this study, we investigate how acoustic velocity varies with thermal aging of EPR rubbers. Literature indicates that acoustic methods have been evaluated to some extent and that good correlations exist between velocity and breaking elongation (Ikehara et al. 1998). A challenge with velocity measurements in polymers is the generally higher level of damping introduced by these materials. Thus, initial trials have been focused on developing and refining the measurement protocol for acoustic velocity measurement in EPR rubber.

While multiple protocols are possible for velocity measurement, we examine longitudinal wave velocity measurement methods. In the longitudinal wave approach, sound is propagated through the thickness of the specimen. The applied acoustic energy is reflected from the surfaces of the specimen (shown in Figure 3.13) and received by the transmitting transducer (or a second receiving transducer if one is used). The transit time through the thickness of the specimen (corresponding to an acoustic path length of twice the thickness) is generally used to compute the sound velocity. A delay line (such as an acrylic block) may be used to increase the stand-off of the transducer from the specimen, and provide better separation of the responses from the near and far surfaces.

Surface waves differ from bulk longitudinal and shear wave modes in that the waves follow the contour of the surface and penetrate the medium to only about one wavelength deep from the surface (Roberts 1990; Ensminger and Bond 2011). While two types of surface waves are possible, Rayleigh surface waves are the more common form used in ultrasonic measurements. The velocities of Rayleigh surface waves c_R, bulk longitudinal waves c_l, and shear waves c_s are related by Ensminger and Bond (2011):

$$\frac{c_R^6}{c_s^6} - 8\frac{c_R^4}{c_s^4} + c_R^2\left(\frac{24}{c_s^2} - \frac{16}{c_l^2}\right) - 16\left(1 - \frac{c_s^2}{c_l^2}\right) = 0 \tag{3.3}$$

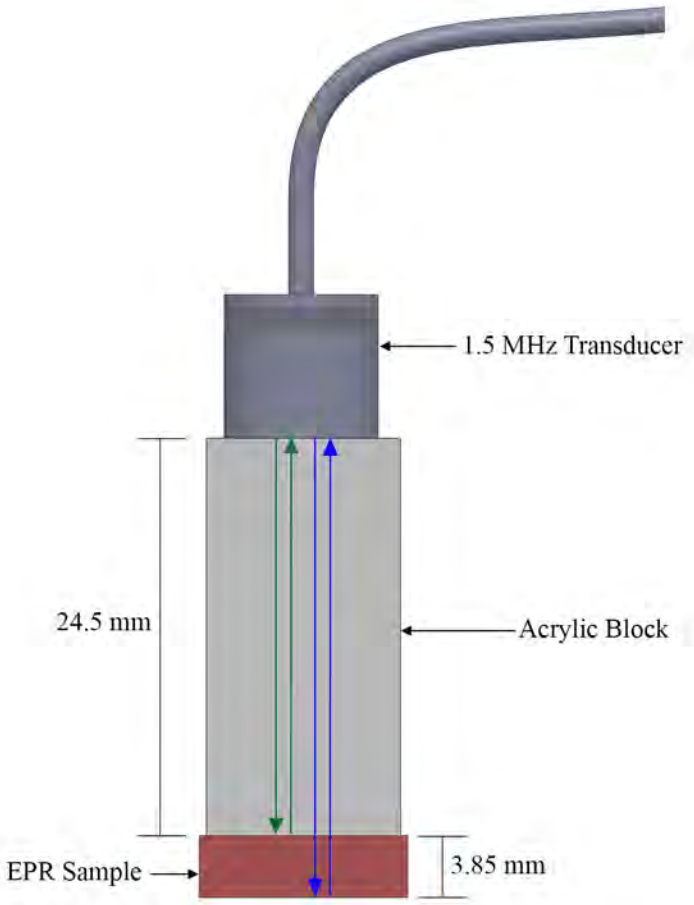


Figure 3.13. Ultrasonic Transducer Configuration for Standoff Measurement of EPR Sample

Surface wave generation in solids uses the fact that, as sound propagates from one medium to another, it is refracted, with the propagation angle θ_2 in the second medium a function of the incident angle θ_1, and the ratio of the sound velocities in the two media:

$$\frac{\sin(\theta_1)}{c_1} = \frac{\sin(\theta_2)}{c_2}. \tag{3.4}$$

Clearly, at a certain angle (called the second critical angle), the refracted energy propagates along the interface between the two media ($\theta_2 = 90°$). Measurements using a second spatially separated probe, also at the critical angle, can provide the necessary transit time used to compute the wave velocity.

For the materials used in this study, several challenges exist with respect to measurement of sound velocity. First, accurate measurement of sound velocity requires precise knowledge of the thickness of the insulation. However, the as-fabricated cable sections have variable thickness of insulation (although still within tolerances necessary for nuclear power plant application). Specifically, the thickness varied across cable sections, with standard deviation of insulation thickness across all specimens being 0.235 mm. This variation (and the difficulty in precise measurement of thickness at arbitrary locations on

the cable section), necessitated the use of thin sheets in the assessment of acoustic velocity measurement methods.

A second challenge related to the measurement of surface wave velocity. As discussed above, the generation of surface waves requires the incident sound waves to be past a certain critical angle that depends on the ratio of sound velocities in the two media. However, the slower speeds in the EPR rubber (when compared to speeds in typical solids such as acrylic or Rexolite that are used to apply sound at an angle) results in critical angles that are close to 90 degrees—effectively requiring incident sound along the surface itself. Overcoming this requires special fixtures that may be used with curved surfaces (such as an intact cable section) that take advantage of transducer beam spreading to generate bulk compressional waves with some energy transferred to surface wave modes.

A final potential issue with surface waves is the relatively slow propagation speeds anticipated. Calculations indicate that shear wave mode speeds in EPR rubber may be as slow as a few meters per second (in contrast to compressional wave speeds that are on the order of 1400 m/s–1500 m/s). Surface wave speeds are, based on calculations, also likely to be on the same order of magnitude as shear wave speed, and measurement equipment will need to be configured accordingly.

The samples that are being aged and characterized by DMA are also being acoustically examined using a low-frequency ultrasonic technique that provides a measurement of acoustic compressional wave speed. These samples are being examined using a 5-MHz transducer mounted in a fixture to hold it at a constant height, shown in Figure 3.14, with the sample immersed in a shallow water-tank. The probe is driven with a high-power pulser and data is collected on an oscilloscope. Instrument calibration uses the known fixture standoff from the back surface of the tank and the acoustic properties of water.

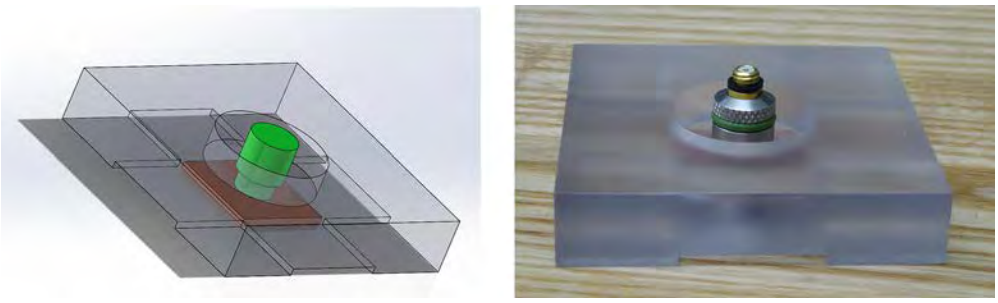


Figure 3.14. Acoustic Measurement Fixture and Probe

3.5 Measurement Techniques for Electrical Properties

Prior to investigating different electrical nondestructive methods as possible measurement techniques for cable degradation, a consensus understanding of what research has already been accomplished was necessary. The International Atomic Energy Agency (IAEA) Nuclear Energy Series *Assessing and Managing Cable Ageing in Nuclear Power Plants* (IAEA 2012) and a recent workshop *Light Water Reactor Sustainability (LWRS) Program – Non-Destructive Evaluation (NDE) R&D Roadmap for Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants* (Simmons et al. 2012) proved to be valuable resources in identifying the latest research applicable to electrical measurements on

cables. From these reports, Table 3.1 identifies electrical measurements and their advantages and disadvantages. The main advantage to electrical measurements is the possibility of evaluating the entire cable length in-situ. The main disadvantage is that they are not very sensitive to insulation degradation.

Table 3.1. Commercially Available Techniques for Cable Inspection

Inspection Method	Advantages	Disadvantages
Time-Frequency Domain Reflectometry (TDR and FDR)	Commonly used for determining the condition of instrumentation, control, and power cables where they are inaccessible.	Currently intrusive, requires disconnecting the cables to install instrumentation.
Insulation Resistance	Commonly performed in industry to determine the condition of the cable insulation.	Currently intrusive, requires disconnecting the cables to install instrumentation.
Inductance/Capacitance/ Resistance (LCR)	Good for detecting changes in electrical circuit (cable and termination) by trending changes in inductance, capacitance, and resistance.	Currently intrusive, requires disconnecting cable at one end. Does not indicate location or cause of change in measurement.
Tan Delta (Tan δ)	Determines changes in insulation (dielectric) properties by measuring change in dielectric loss angle. Can measure aging effects over entire cable length.	Intrusive, requires decoupling both ends. Single number from long cable makes isolating location of aging section difficult. Loss angle may be trended; however, single measurement insufficient to estimate remaining life.
Partial Discharge	Good for determining voids or defects in insulators of medium voltage cables.	Test can damage the insulator with localized heating that causes degradation.

FDR = frequency domain reflectometry
LCR = inductance/capacitance/resistance
TDR = time domain reflectometry

Prior to pursuing an NDE technique for each of these inspection methods, a basic understanding of the underlying physics is needed. Therefore, it was necessary to establish criteria for further investigation. The criterion uses the requirement that the method to be evaluated must have the ability to perform a nondestructive test to determine electrical properties of the cable jackets and insulation without significant disturbance of the cables and connectors as they lay in-situ. Each of the electrical methods described in the table was considered intrusive in that one or both ends of the cable would have to be disconnected. Therefore, the circuit that is operated by that cable would go off-line.

The initial premise is then to address electrical measurement techniques that may potentially be amenable to in-situ (online) assessment of cable insulation degradation. With the exception of reflectometry (ideal for identifying faults in the conductors in cables) and partial discharge (which may, under certain conditions, result in added degradation to the cable insulation), the remaining methods each can potentially be used in-situ. Initial evaluations resulted in investigating the Tan δ method as a first step towards understanding the physics underpinning these types of measurements. Other methods (insulation resistance and LCR) will be examined in future phases.

3.5.1 Tan δ Measurement Technique

The tan delta technique or Tan δ can be derived from one of Maxwell's four equations, which relates the magnetic field intensity to the electric field intensity. Expressed in phasor form, the equation contains the relationship between the conduction current density ($\sigma\mathcal{E}$) and the displacement current density ($j\omega\varepsilon'$) for dielectric materials.

$$\nabla \times \mathcal{H} = \sigma\mathcal{E} + j\omega\varepsilon'\mathcal{E}\left(\mathrm{Am}^{-2}\right) \tag{3.5}$$

where: $\mathcal{H}$ = magnetic field intensity (A/m)
$\mathcal{E}$ = electric field intensity (V/m)
σ = conductivity (℧/m)
ω = angular frequency (rad/sec)
ε' = real portion of the complex permittivity where $\varepsilon = \varepsilon' - j\varepsilon''$ (F/m)

The relative permittivity ε_r describes how a specific material will interact with an applied electric field. Known as the dielectric constant of the material, it is derived from the permittivity of free space $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m where $\varepsilon = \varepsilon_r \varepsilon_0$.

This complex permittivity can therefore be written as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ and shown on a simple vector diagram (Figure 3.15).

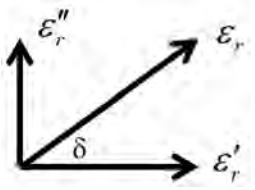


Figure 3.15. Phasor Relationship between the Real and Imaginary Components of Permittivity

The tangent of the angle δ between them is the ratio of these two vector quantities and is a measure of the ratio of energy from the applied electric field that is stored in a specific material to the amount dissipated or lost. This quantity is known as the loss tangent and defined as:

$$\mathrm{Tan}\ \delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{3.6}$$

for that material.

3.5.2 Coaxial Dielectric Probe Technique

To understand the fundamental relationship between aged samples of electrical cables, PNNL employed a vector network analyzer (VNA) to acquire complex permittivity measurements. The VNA

used was an Agilent Technologies model E8361A with integrated software and an associated high-temperature coaxial dielectric probe with a frequency bandwidth of 200 MHz to 20 GHz as shown in Figure 3.16.

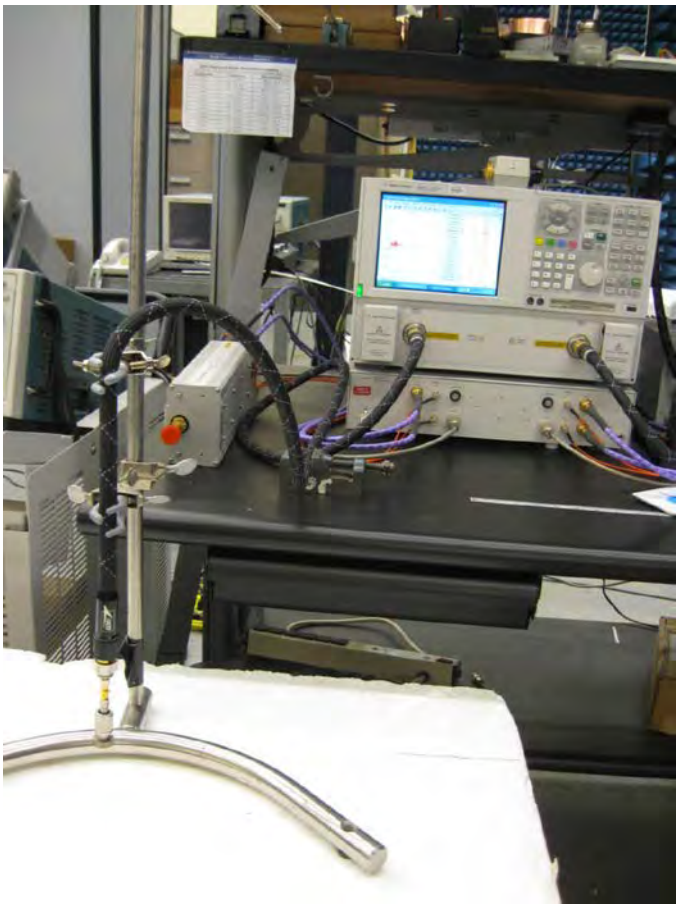


Figure 3.16. Agilent Technologies Vector Network Analyzer

Calibration of the VNA is essential to assure accurate, repeatable measurements of the complex permittivity. Calibration of the VNA is performed by subjecting the measuring probe to air, then shorting the probe using a short-circuit standard provided by Agilent, and then placing the probe in deionized water at a reference temperature. The reference temperature was 23°C for these measurements. Figure 3.17 shows each of these steps in the calibration process.

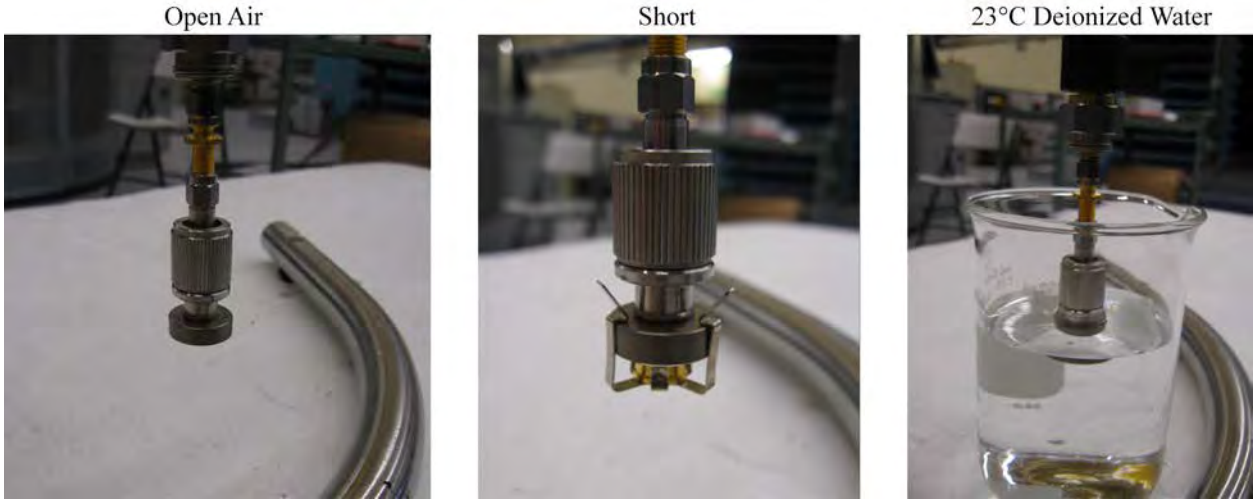


Figure 3.17. Steps of Calibration Process

Once calibration was completed, measurements of the complex permittivity of known materials were used to verify the accuracy of the calibration. Plots shown in Figure 3.18 show the values attained for air and Rexolite.

- Air $\left(\varepsilon' = 1.0, \quad \varepsilon'' = 0.00\right)$
- Rexolite $\left(\varepsilon' = 2.5, \quad \varepsilon'' = \sim 0.00\right)$

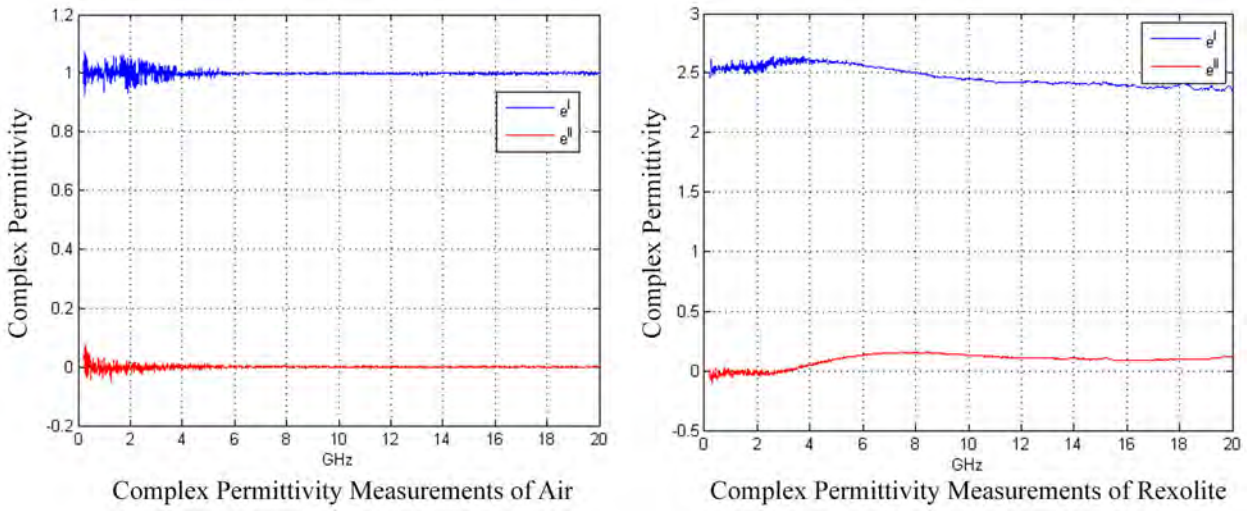


Figure 3.18. Complex Permittivity Measurements Obtained during Calibration Process

Complex permittivity measurements were performed on aged cable samples to determine if there is a measureable trend in the change in dielectric constant vs. cable aging. A total of 20 cable samples were created by curing the segments of cable at 140°C for different durations. These cable samples

were then placed in a test fixture to contact the cable housing surface to the high-temperature dielectric probe. The test fixture was developed to provide consistent contact pressure between the high-temperature probe and the cable housing (see Figure 3.19).

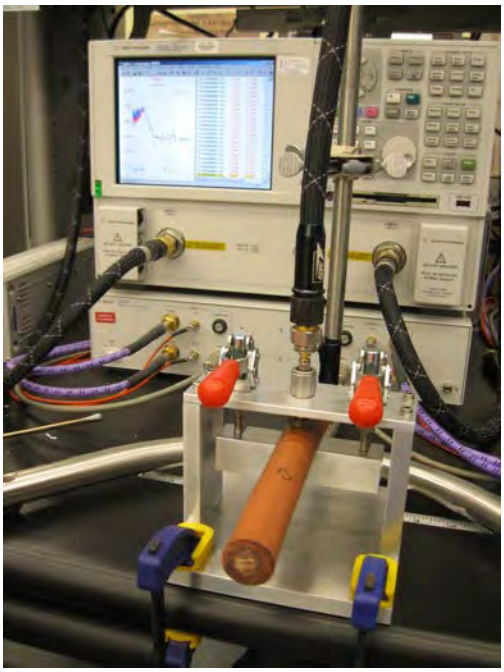


Figure 3.19. Cable Dielectric under Test in Dielectric Probe Fixture

3.5.3 Interdigital Capacitor Technique

In addition to the VNA-based reflection coefficient measurements using the coaxial dielectric probe, low-frequency capacitance measurements with a conformal sensor placed on the cable were performed to investigate changes in dielectric properties as a function of aging. These measurements were conducted using the custom-designed interdigital capacitor and Agilent 4294A precision impedance analyzer shown in Figure 3.20. Interdigital sensors are a mature technology and have been widely used in numerous applications for many years (Hobdell 1979; Mamishev et al. 2004; Abu-Abed and Lindquist 2008). Recent work has been published on the design of interdigital sensors for nondestructive evaluation of aircraft wire insulation dielectric properties to detect material degradation (Sheldon and Bowler 2013). Because the device capacitance is linearly proportional to the material dielectric constant and independent of the applied test voltage, this type of sensor was also selected for an initial characterization of the aged cable sections at low frequencies. Another compatible feature of the interdigital sensor is that only single-sided access to the material sample is required.

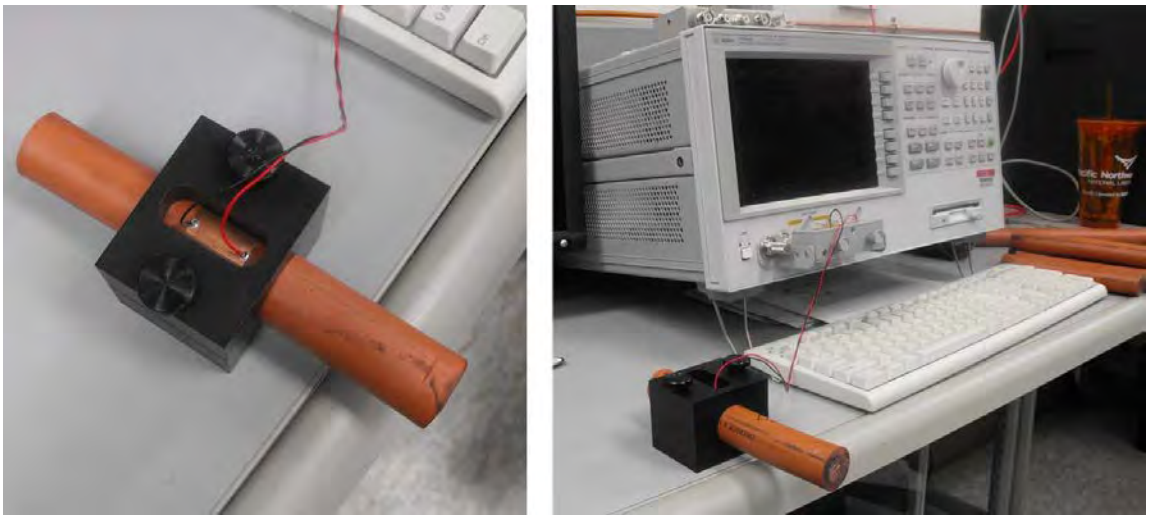


Figure 3.20. Experimental Configuration for Capacitance Measurements Showing Impedance Analyzer and Clamshell Fixture Used to Wrap the Sensor onto the Outer Surface of the Cable

The interdigital sensor shown in Figure 3.20 was designed using the Ansys Maxwell electrostatic finite element simulation software. The design geometry consists of a 15-electrode capacitor printed on a thin flexible polyimide substrate with an approximate width of 13 mm and length of 25 mm. The measured capacitance of the sensor installed on an unaged reference cable was 15 pF at 10 MHz, which agreed well with the predicted value of 13 pF. Figure 3.21 shows the simulation model of the sensor wrapped onto the cable insulation and the penetration of the electric field through the cable cross section. For this design, the calculated electric field penetrated into the uppermost 1–2 mm of the cable insulation and the capacitance measurements were performed over a frequency range of 10–100 MHz.

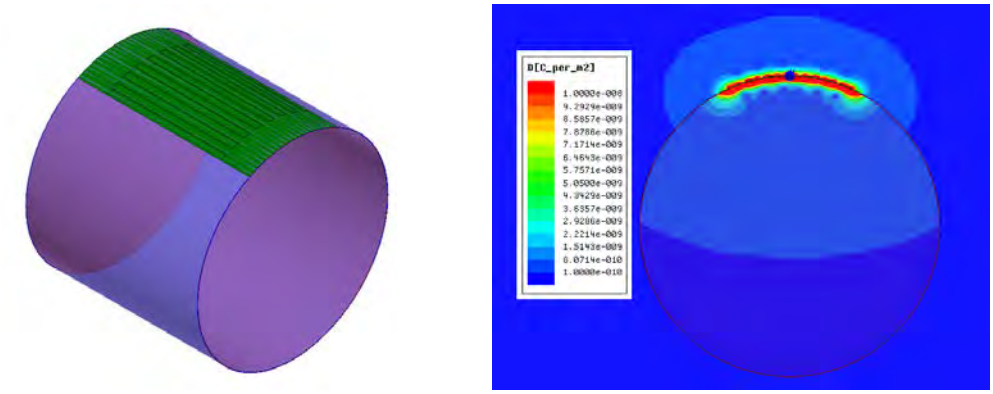


Figure 3.21. Electrostatic Field Simulation Model of Interdigital Capacitive Sensor and Electric Flux Distribution Inside Cable Insulation

4.0 Results

The measurement techniques described above were used to acquire data on samples of unaged and aged EPR rubber, described in Section 3.1. The electrical measurement protocol is relatively mature, and was used to perform measurements and analysis on a set of unaged and aged specimens. The protocols (for acoustic measurements) and the data (for both electrical and acoustic measurements) are summarized in this section.

4.1 DMA Measurements

DMA tensile mode was evaluated as a new technique to simulate tensile modulus changes using isothermal temperatures and by monitoring the storage modulus as a function of time. The method also evaluated using nitrogen gas to determine the impact of thermal stress in the absence of air. Figure 3.9 illustrates the tensile specimen behavior in the DMA.

The specimen geometry is 3-mm wide and 1.5 mm-thick with an overall length of 15 mm. The gap between the grips is ~10 mm. A series of frequency and strain sweeps were performed to determine the optimum range in frequency and amplitude for the test. The optimum values were determined to be 1 Hz frequency, 10 microns in amplitude, and stress of less than 1 MPa. The first temperature evaluated was 140°C in nitrogen gas and the test ran for 50 days (1200 hours). Figure 4.1 illustrates a minimal change in the storage modulus after 50 days. The storage modulus increased by less ~25%. Typical EAB results after exposures at the same test temperature and time in air would be below 50%. The results were quite revealing as to the impact without atmospheric air. There were no significant changes to the properties of the material.

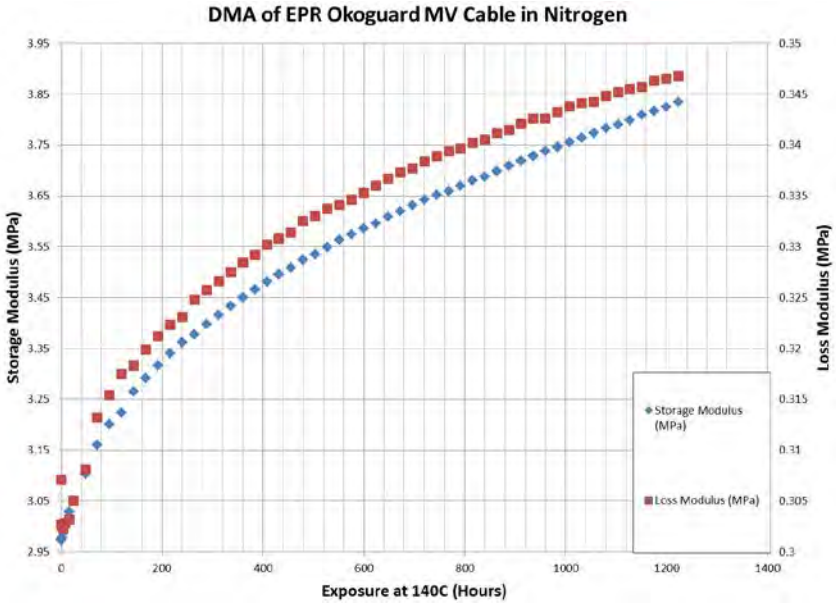


Figure 4.1. Change in Storage and Loss Modulus after 50 Days at 140°C in Nitrogen, as Measured using DMA

Due to the length of time to perform these in-situ measurements, a second test was performed at 160°C isothermally and aged in air. The geometry is the same as the described previous experiment. There is a risk of diffusion-limited oxidation (DLO) at this temperature; however, the material thickness is thin and DLO is hypothesized to have less of an impact on the cross section for this new technique. Future experiments will be conducted at lower temperatures to minimize the diffusion-limited oxygen effect. Figure 4.2 (green trace) shows the impact of the air on degradation of the EPR material through the significant, nearly 2 orders of magnitude increase in the storage modulus (from around 3 to greater than 300 MPa), which would be expected based on the sensitivity of DMA techniques to material changes.

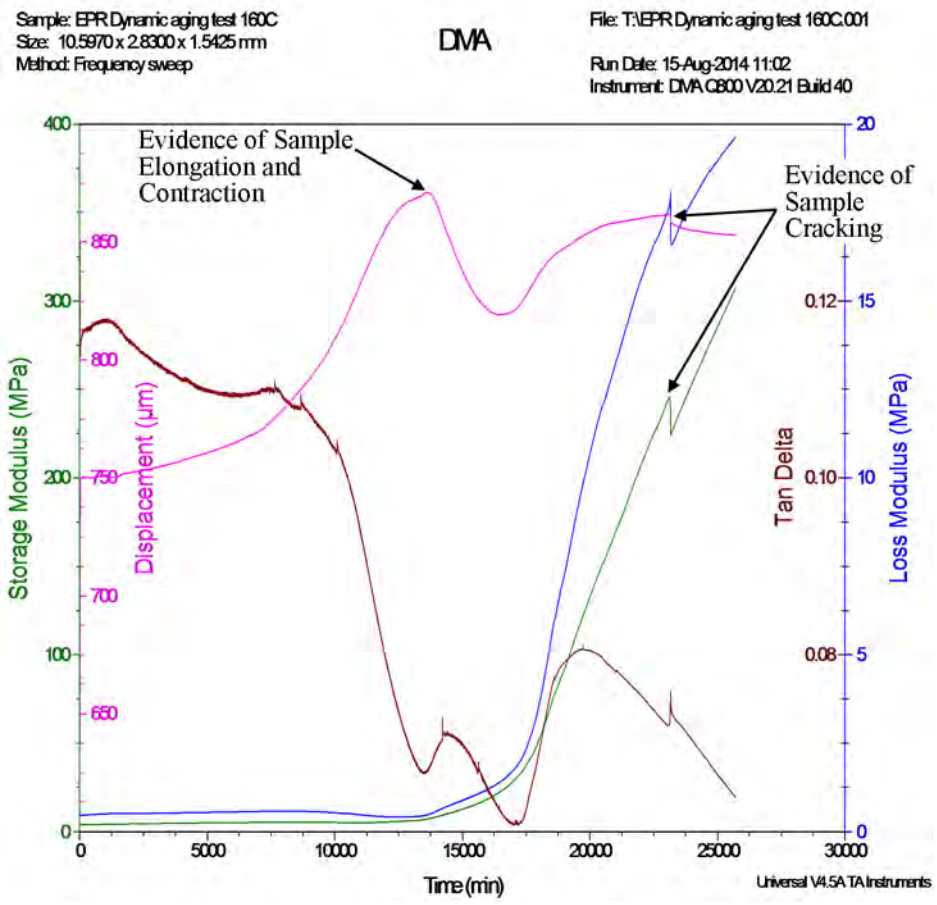


Figure 4.2. DMA Plot after 17.8 Days at 160°C in Air

4.2 Fourier-Transform Infrared Spectroscopy

The energies associated with infrared wavelengths of light correspond to the stretching and bending transitions in chemical bonds. FTIR can be a very sensitive method for identifying the presence of specific bonding in materials, such as carbon to oxygen double bonds (C=O, carbonyls), through characteristic infrared absorptions corresponding to those bonds. As chemical changes occur in cable

insulation material with exposure to stresses including heat and radiation, the elimination of certain bonding and the creation of new bonds with chemical damage can be tracked with FTIR.

Pink EPR material from aerial jumper cable was milled into a powdered, particulate form and aged in a circulating air oven at 140°C to investigate chemical property changes in form of the material easier to characterize than fully-thick insulation. FTIR absorption peaks associated with unsaturated carbon bonds in the as-produced EPR (2800–3000 cm^{-1}) were observed to decrease with aging of the material at 140°C in air, and new peaks associated with carbonyl (~1700 cm^{-1}) and hydroxyl groups (3000–3500 cm^{-1}) were observed to appear. The contrasting spectra are provided in Figure 4.3. These changes in infrared absorption with cable aging provide a method to assess the extent of cable degradation.

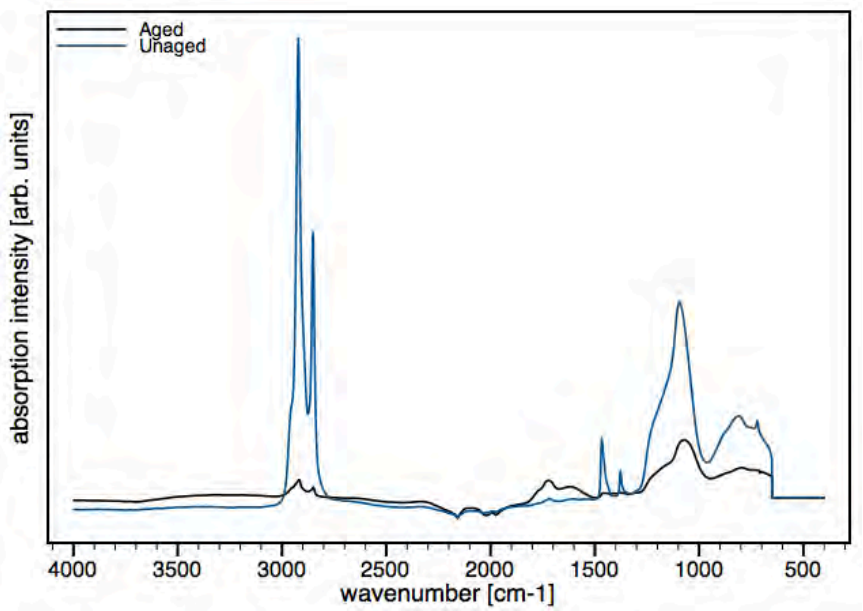


Figure 4.3. FTIR Spectra of Aged and Un-aged EPR

4.3 Differential Scanning Calorimetry

The rate of heat flow in (and out) of a material, measured in joules per second or Watts, is a sensitive measure of the state of the material and can reveal phase transitions in such as crystalline solid to liquid (melting, T_m) and glassy solid to liquid (glass transition, T_g) in polymeric materials. The temperatures at which phase transitions occur, as well as how well defined those transitions are, change with material state. Differential scanning calorimetry is a technique for measuring heat flow in a material with applied temperature that can be used to obtain information about material composition and degradation state.

The heat flow behavior was determined for aged and unaged EPR material heated in a nitrogen atmosphere up to 600°C and then in air up to 800°C. Heating in inert atmosphere reveals phase transition within the material, while heating in air reveals the nature of the combustion reaction and phase change from solid to vapor products. The results of the EPR experiments are plotted in Figure 4.4. The greater areas under the curve of endo-thermic heat flow peaks for the unaged material indicate a larger fraction

remaining of volatile components of the material. These might include processing aids, plasticizer, or anti-oxidant that is lost from the material with aging.

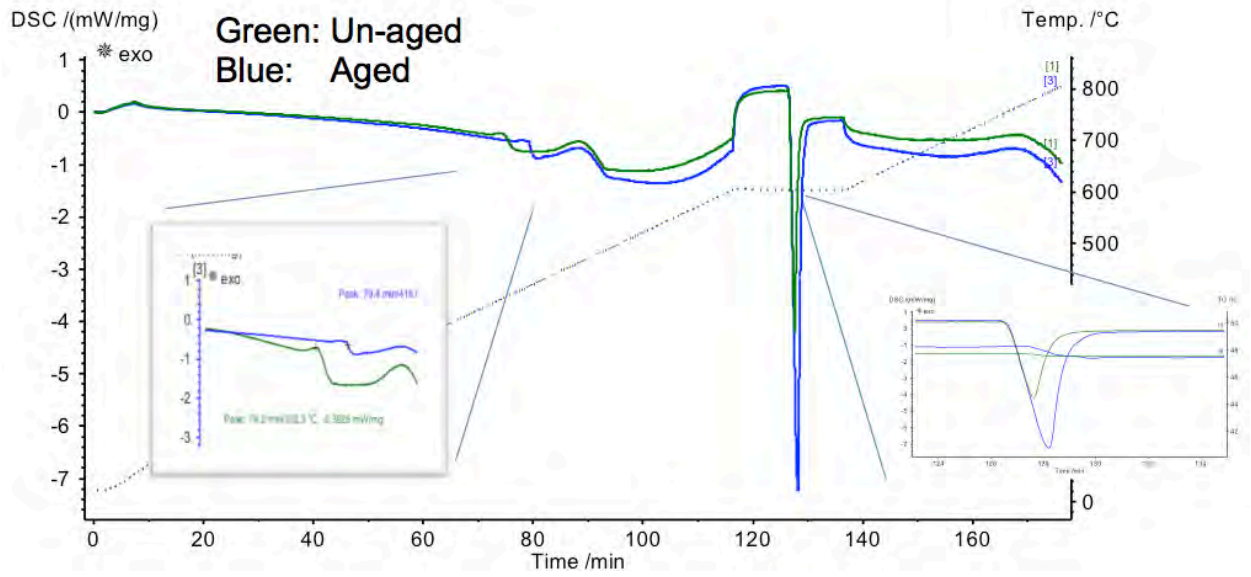


Figure 4.4. Heat Flow Curves Showing Subtle Differences in EPR Material with Aging

4.4 Thermogravimetric Analysis

The changes in mass of a material when heated in an inert atmosphere can quantitatively reveal the relative amounts of differing components within the material, as each may volatilize under characteristic inputs of thermal energy. Changes in mass of a material with heating in reactive atmosphere, such as in air at elevated temperatures, can quantitatively reveal amounts of different reactive materials and the temperatures at which they under reaction. Thermogravimetric analysis is a technique in which the mass of a sample is very sensitively monitored while the sample is exposed to inert or reactive atmosphere and thermal energy (heating).

Differences in total mass loss for unaged and aged EPR samples heated to 600°C in nitrogen followed by heating to 800°C in air are illustrated in Figure 4.5. The unaged sample is observed to exhibit a larger extent of mass loss during the inert gas heating and an even greater difference in mass loss with heating in air. The former is likely because of the presence of relatively volatile compounds in the unaged EPR including processing aids, plasticizer, and anti-oxidant that are still present to a lesser degree in the EPR material after it has undergone aging. The mass of the material following the heating in air, the residual mass, is a measure of the non-combustible, inorganic fraction of the material. This fraction contains the silica, talc, or clay filler in the EPR. The lesser extent of mass loss of the aged EPR sample may indicate that combustible carbon-carbon bonds in the material have been converted to carbon-oxygen bonds during aging.

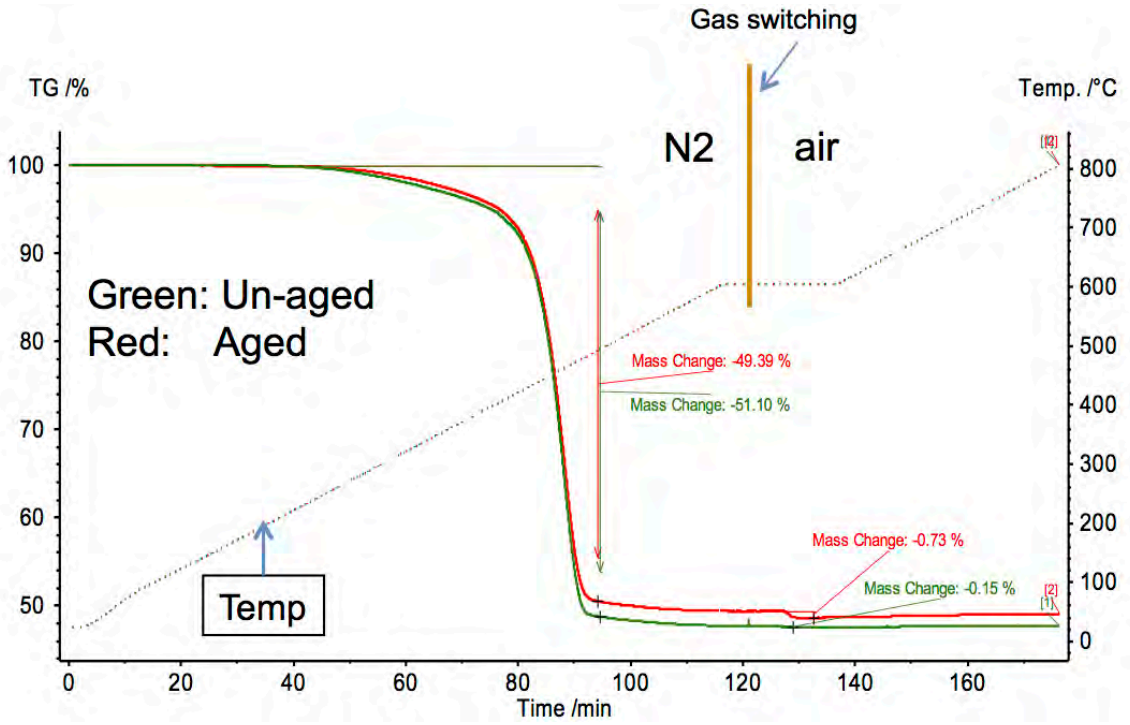


Figure 4.5. Mass Change with Heating of Aged and Unaged EPR

4.5 Acoustic Measurements

Preliminary measurements were performed using the acoustic microscopy system on a new unaged sample of cable (Okoguard) that was machined into a uniform thickness. Figure 4.6 shows the sample with a focused acoustic probe.

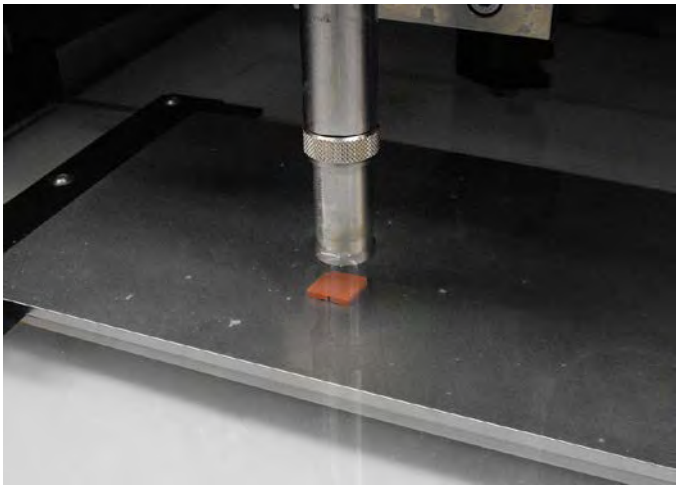


Figure 4.6. EPR Sample – Immersion Technique

To help mitigate the thickness variability across specimens while trying to measure velocity, the probe fixture described in Figure 3.14 (and shown in Figure 4.7 with the specimen inserted) was used with a 5-MHz transducer. Baseline measurements were performed on 55 such samples. Figure 4.8 shows an example of the waveform acquired from one such measurement. The measurement was repeated five times on each specimen to ensure repeatability of the transit time computations. A sample of the transit time calculations from these data, along with the standard deviation on each specimen, is shown in Figure 4.9. As seen in the figure, the measurements for each specimen have a low deviation, but each sample has variability with respect to other samples within the set. The reason for this variability has not yet been established, but it is likely because of variabilities in thickness even within these thin sheet specimens.

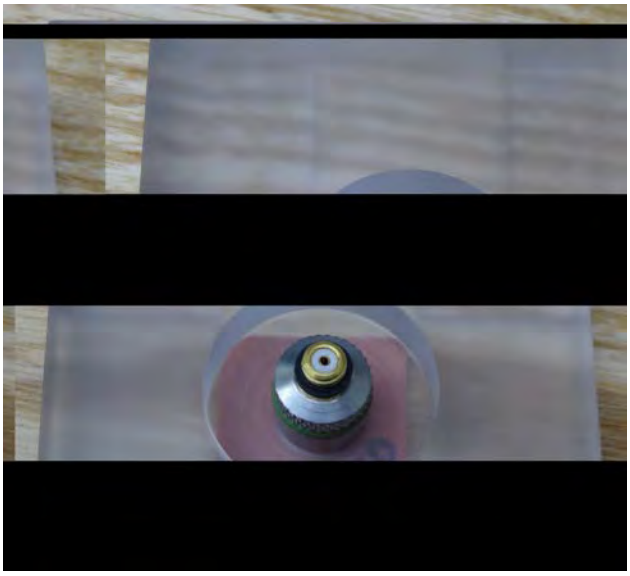


Figure 4.7. Probe Fixture Setup for Measurement

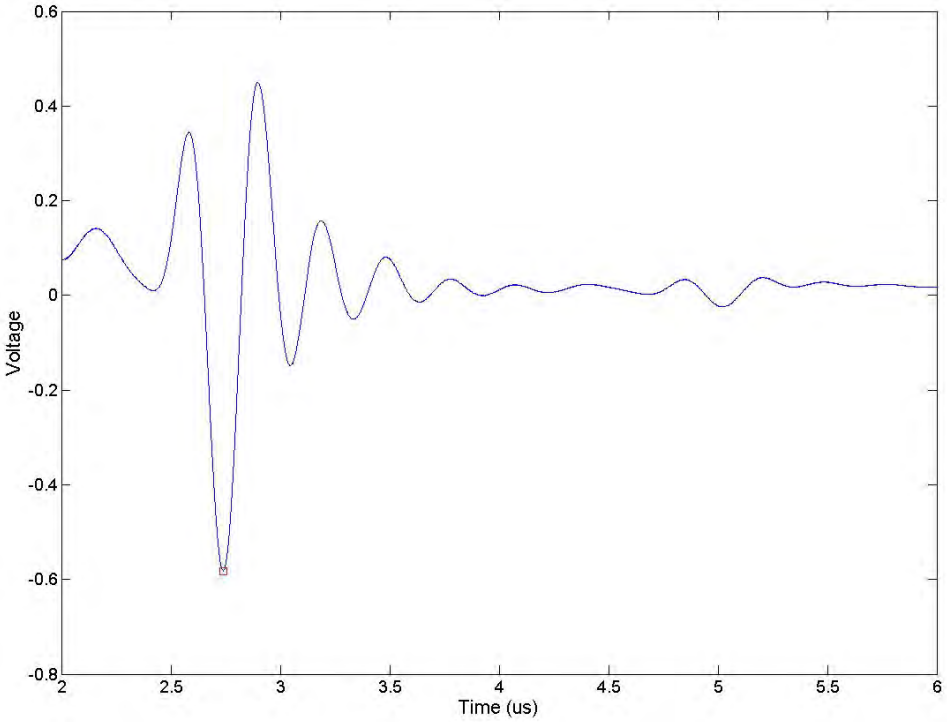


Figure 4.8. Example of Ultrasonic A-scan Collected with the Probe Fixture

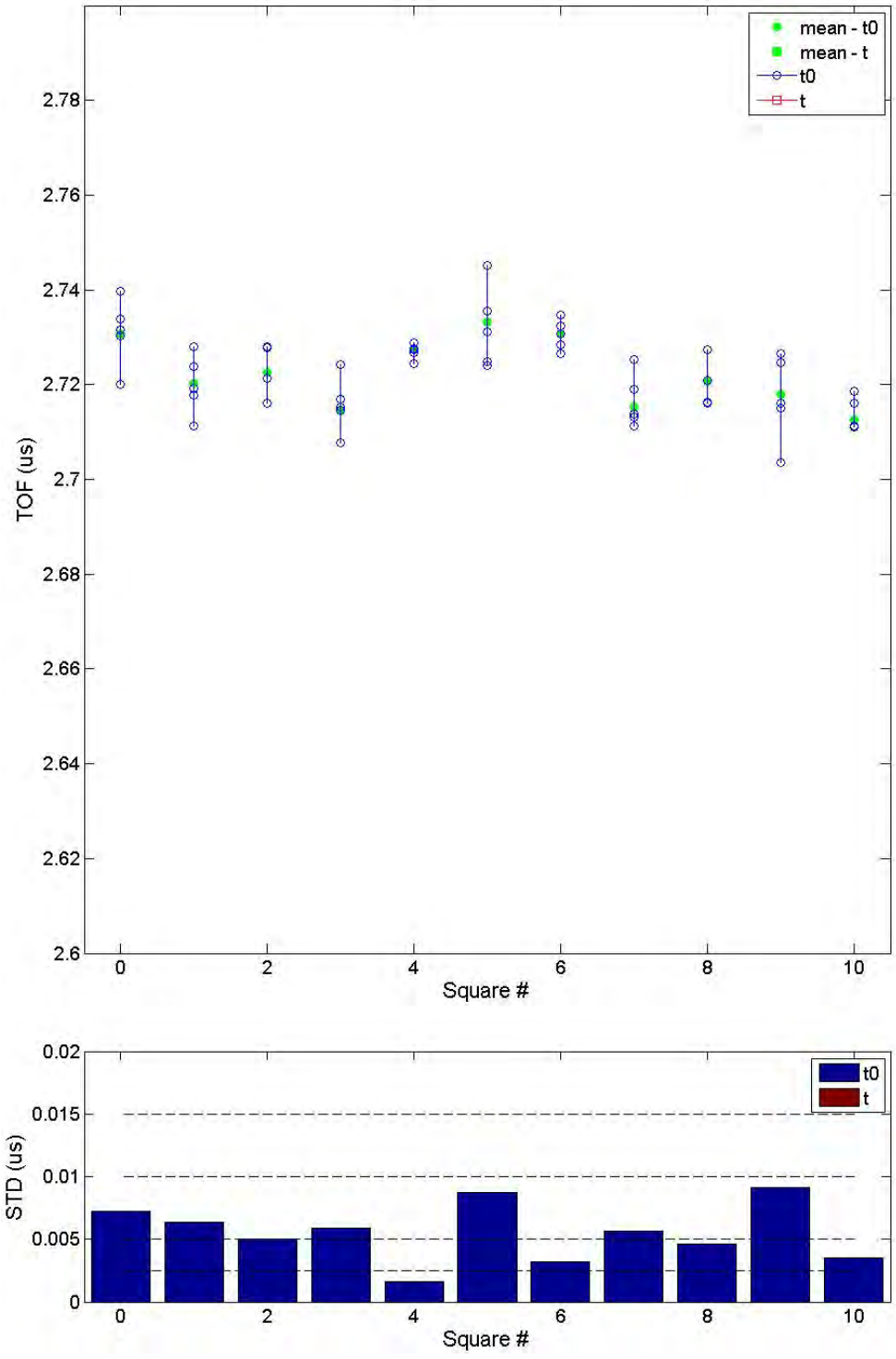


Figure 4.9. Preliminary Time-of-Flight Measurements for Specimens #0–10

These specimens were subjected to thermal aging at 140°C, and additional measurements on the aged specimens will be conducted as the aging progresses.

4.6 Electrical Measurements

4.6.1 Coaxial Dielectric Probe Measurements

Based upon promising results from earlier work (Simmons et al. 2013), the dielectric probe technique investigation was continued in FY2014 with an improved experimental configuration that included the use of a mechanical fixture to ensure repeatable coupling of the probe. In contrast to the DMA and acoustic velocity measurements, the dielectric measurements were performed on aged cable sections described in Section 3.1. A total of 20 cable sections were generated that represent 20 different cable degradation levels. A list of the cable samples is shown below in Table 4.1 and a subset of the cable samples is shown in Figure 4.10.

Table 4.1. Cable Sample Sets

Sample Name	Quantity	Description
C1	1	Cable exposed to 140°C for 0 hrs
C2	1	Cable exposed to 140°C for 101 hrs
C3	1	Cable exposed to 140°C for 201 hrs
C4	1	Cable exposed to 140°C for 392 hrs
C5	1	Cable exposed to 140°C for 603 hrs
C6	1	Cable exposed to 140°C for 849 hrs
C7	1	Cable exposed to 140°C for 895 hrs
C8	1	Cable exposed to 140°C for 965 hrs
C9	1	Cable exposed to 140°C for 1007 hrs
C10	1	Cable exposed to 140°C for 1056 hrs
C11	1	Cable exposed to 140°C for 1104 hrs
C12	1	Cable exposed to 140°C for 1150 hrs
C13	1	Cable exposed to 140°C for 1200 hrs
C14	1	Cable exposed to 140°C for 800 hrs
C15	1	Cable exposed to 140°C for 750 hrs
C16	1	Cable exposed to 140°C for 300 hrs
C17	1	Cable exposed to 140°C for 712 hrs
C18	1	Cable exposed to 140°C for 650 hrs
C19	1	Cable exposed to 140°C for 550 hrs
C20	1	Cable exposed to 140°C for 500 hrs

Figure 4.10. Cable Samples under Test

The complex permittivity of the cable samples was measured over a large bandwidth using the high-temperature dielectric probe shown in Section 3.5.1 to investigate if changes appeared in the real or imaginary component of the dielectric constant (permittivity) with respect to an increase in cable insulation age at 140°C.

The requirements for accurate complex permittivity measurements include strong surface contact between the probe and the material under test. The presence of air gaps between the probe and material surface will significantly affect the material measurements. Because the dielectric probe measurement method assumes that the material is isotropic and homogeneous, the sample must appear infinitely wide and thick to the probe's fringing fields. For the probe used in this study, the diameter of the material under test must be no smaller than 20 mm in order to perform the measurement over a range of 200 MHz to 20 GHz. The equation to satisfy the appearance of infinite electrical thickness is

$$S = \frac{20}{\sqrt{\varepsilon'}} \tag{4.1}$$

where S is the material thickness and ε' is the real part of the dielectric constant. For the material studied here, a nominal sample thickness of 12 mm is required. The thickness of the cable insulation samples was measured to be 5.8 mm; therefore, the two samples for each cable age were measured together in a stacked configuration to obtain a thickness appropriate for the probe. A large amount of pressure was required to ensure that no air gap was present at the interface between the two samples and to flatten the curved cable insulation front surface.

To ensure repeatability of the complex permittivity measurements, four data sets were collected per cable-degradation level. For each of the four data sets collected, the position of the samples was swapped, resulting in measurements 1 and 3 having the same sample configuration, and measurements 2 and 4 having the same sample configuration. This tested the repeatability of data for each specimen set and also per each sample in that set.

For these measurements, the real component of the complex permittivity proved to be more responsive than the imaginary component to cable aging. The loss tangent measurements show a diminished response to increased aging because of the relatively small changes in the imaginary term when compared to the changes in the real term. Therefore, the results shown below focus on the real component versus frequency as a function of cable aging.

A series of 10 measurements were collected for each of the 20 cables samples in Table 4.1 that represent cable exposed to 140°C from 0–1200 hours. The 10 measurements were collected over different locations on the cable housing to provide statistical data for each cable sample ensuring the results were not due to an outlier data point. For each cable sample, a plot was created that overlays all 10 measurements on a single plot. An example is shown in Figure 4.11. As previously discussed, the plots focus on ε' vs. frequency.

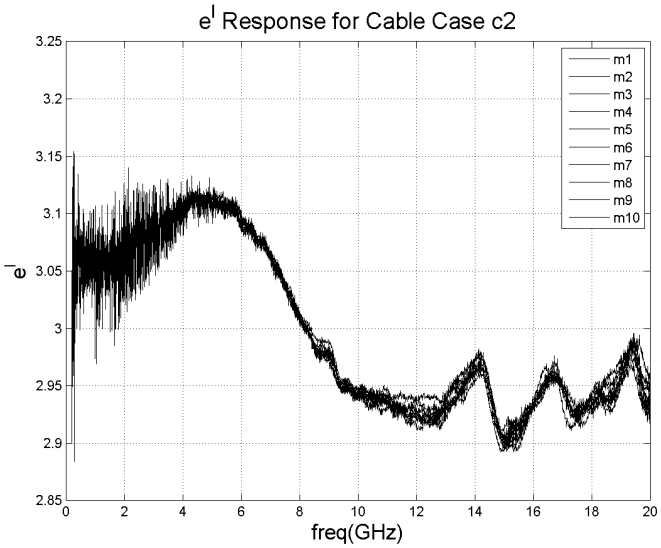


Figure 4.11. Real Part of the Dielectric Constant for Cable Sample 2 vs. Frequency for All 10 Measurement Locations

A holistic view of the data reveals a linear response region of the dielectric measurements. The lower frequencies are more sensitive to the thickness of the cable, where the higher frequencies are more sensitive to the surface contact between the probe and the cable under test. Because the cable housing is curved and it gets more rigid vs. exposure time, the housing becomes less conformable under pressure to the probe tip and causes variations in the complex permittivity response. Therefore, the selected frequency range of focus was 6–8 GHz.

Once the appropriate bandwidth was selected, for each cable sample the average ε' at every frequency sample was computed, to construct an average response from 6–8 GHz (Figure 4.12).

The results from the averaged response were then isolated into single frequency samples in order to view the data more clearly. Each cable sample was now correlated to an exposure time to 140°C in order to plot single frequency measurement results of average ε' vs. exposure time in hours. Using the 10 measurements for each cable sample, the standard deviation was calculated for each sample case and plotted for each discrete exposure time sample. Figure 4.13 displays the results for the averaged ε' at 7 GHz (7000 MHz) vs. exposure time, demonstrating an observable trend in ε' changing vs. exposure time. Note the large deviation on the 1200-hour sample—the deviation is due to one data point in the 10 measurements for the 1200-hour sample—the single data point was observed to be repeatable in the specific cable location.

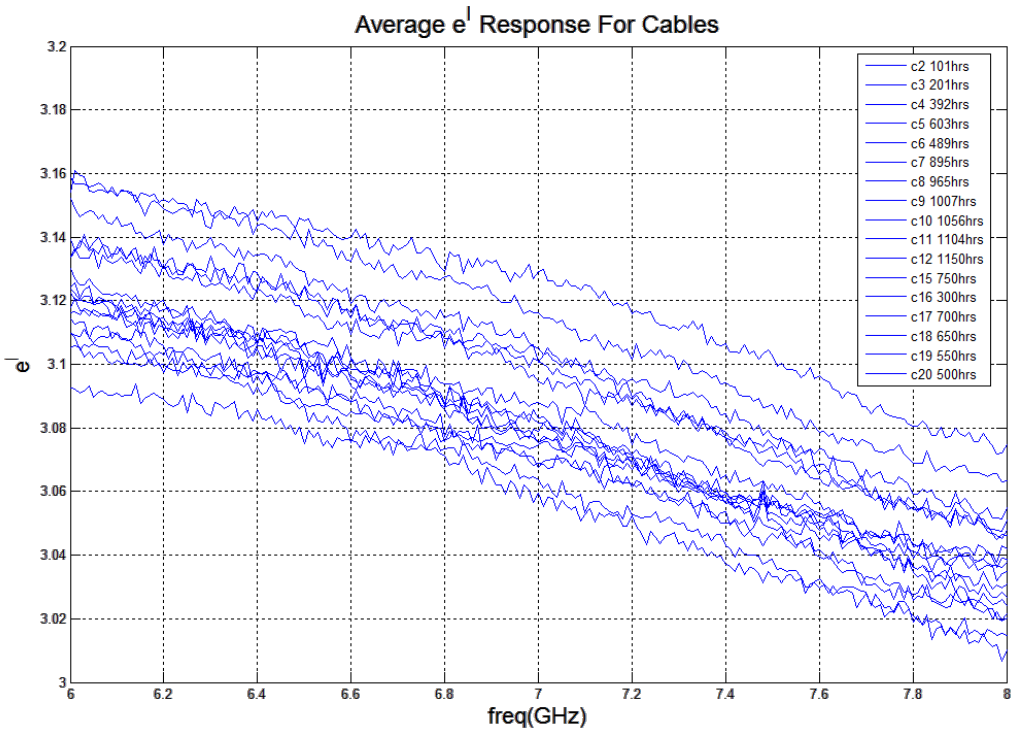


Figure 4.12. Averaged ε' vs. Frequency for Each Cable Case

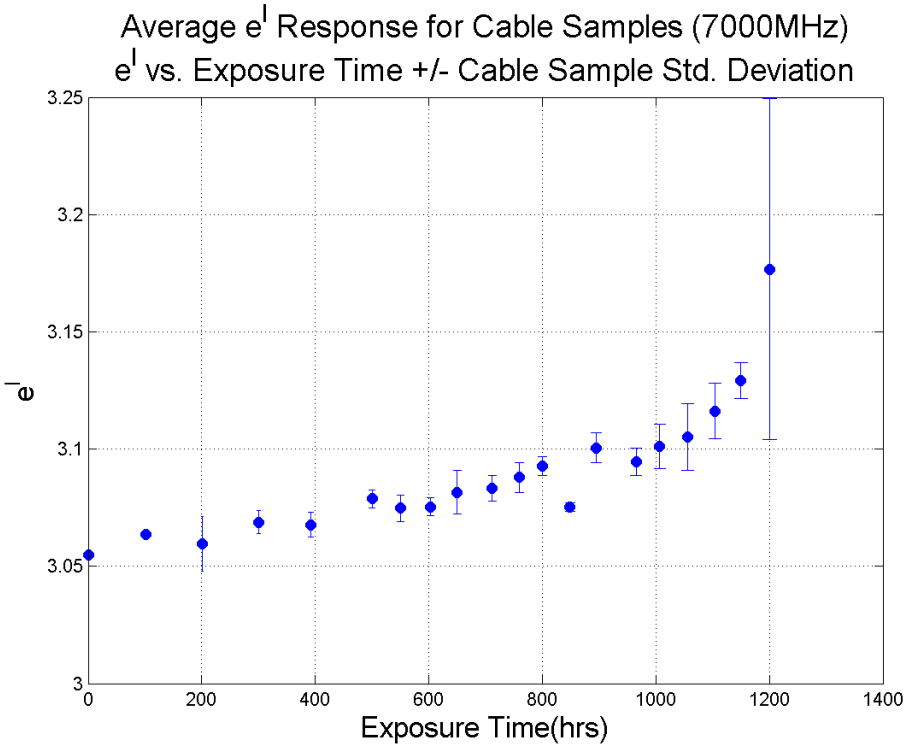


Figure 4.13. Averaged ε' vs. Exposure Time ± Standard Deviation

Single frequency results were plotted every 100 MHz over the 6–8 GHz band generating a total of 21 plots. Because the plotting techniques are automated, finer frequency sampling plots can be processed and generated very quickly. The additional single frequency plots also display the trend of ε' increasing vs. exposure time. The complete single frequency sample data sets are shown in Appendix A.

To compare trends in the mechanical performance of insulation samples to the ε' trend shown in Figure 4.13, an overlay plot was generated based on EAB measurements performed on EPR specimens from the same source in earlier studies (Figure 4.14). The data presented in Figure 4.14 indicate correlation between EAB data and dielectric measurements, although this evidence must be tempered with the fact that the two sets of measurements were on specimens aged in different experiments (although under nominally the same conditions).

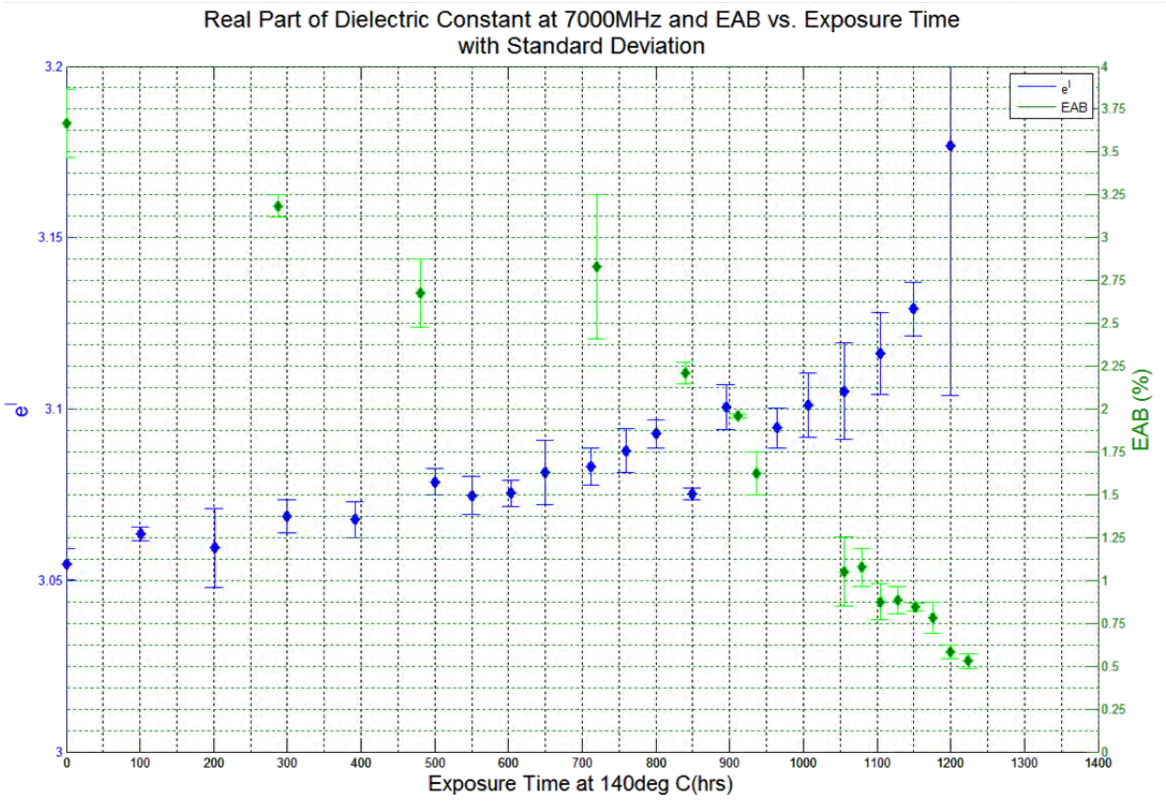


Figure 4.14. Averaged ε' vs. Exposure Time ± Standard Deviation and EAB Percentage ± Standard Deviation

4.6.2 Interdigital Capacitor Measurements

The complex impedance of the conformal interdigital capacitive sensor mounted on the aged cable sections was measured using the experimental configuration shown in Figure 3.20 over a range of 10–100 MHz in 1-MHz steps. The impedance analyzer was set to use 4-point averaging and the second-highest measurement bandwidth in order to capture high-fidelity real and imaginary impedance components at each frequency. The sensor impedance was measured for the collection of 20 cable

sections with a range of 0–1200 aged hours. For each measurement, the sensor was held in intimate contact with the outer surface of the cable with a Delrin clamshell fixture. Each cable section was manually inserted into the fixture, and then the top and bottom halves of the fixture were fastened around the cable using thumbscrews. The fixture design ensured that the flexible sensor substrate conformed to the cable insulation surface.

Figure 4.15 shows the measured reactance of the interdigital sensor mounted on the aged cable sections as a function of frequency. The slope of the line is inversely proportional to the excitation frequency as expected for a capacitive probe, and the extracted value of the capacitance at 10 MHz is near the expected value at 15 pF. A net inductive effect is apparent at higher frequencies because the overall reactance is positive rather than negative. Figure 4.16 shows the sensor reactance measurements presented as a function of aged hours. The plot shows no clear trend of low-frequency capacitance vs. aged hours for this sensor measurement. Figure 4.17 shows the percent change in sensor reactance vs. aged hours, with a consistent trend of higher percentage changes for higher frequencies but again no trend of reactance change vs. aged hours. Although not shown, as part of this study selected cable measurements were repeated multiple times with agreement between the measurements of approximately 2–3%.

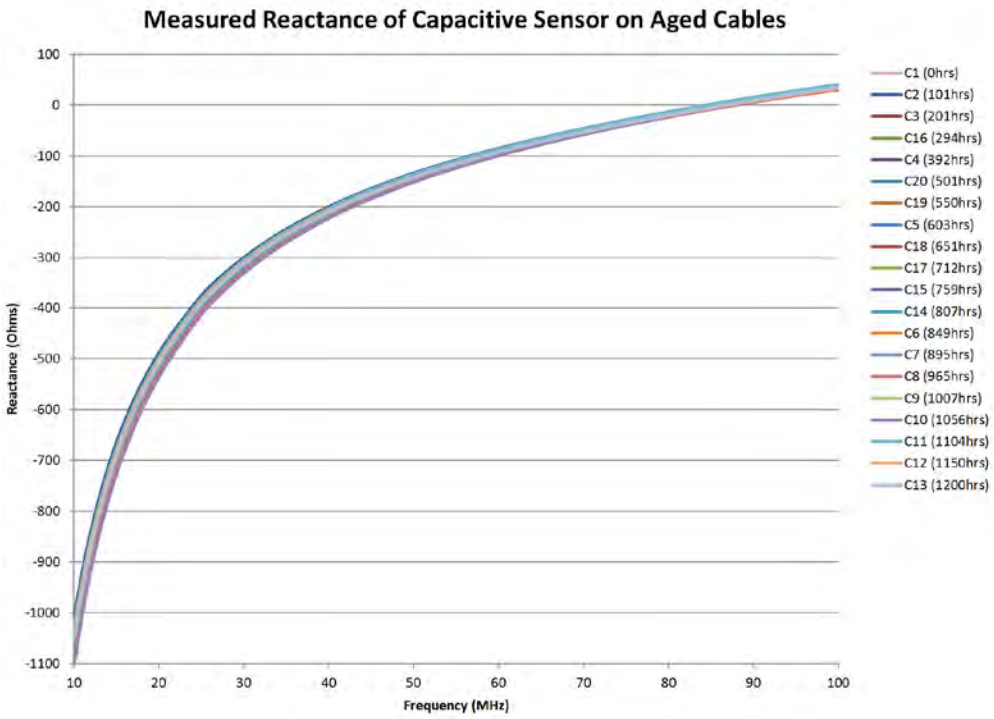


Figure 4.15. Measured Reactance vs. Frequency of Interdigital Sensor Mounted on Aged Cable Sections

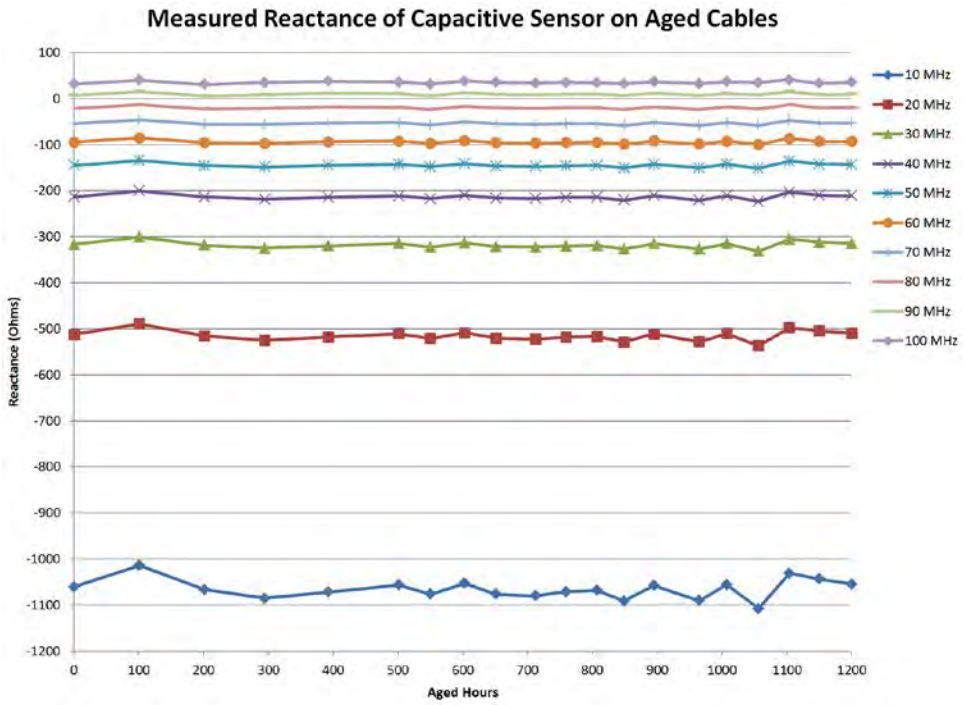


Figure 4.16. Measured Reactance vs. Aged Hours of Interdigital Sensor Mounted on Aged Cable Sections

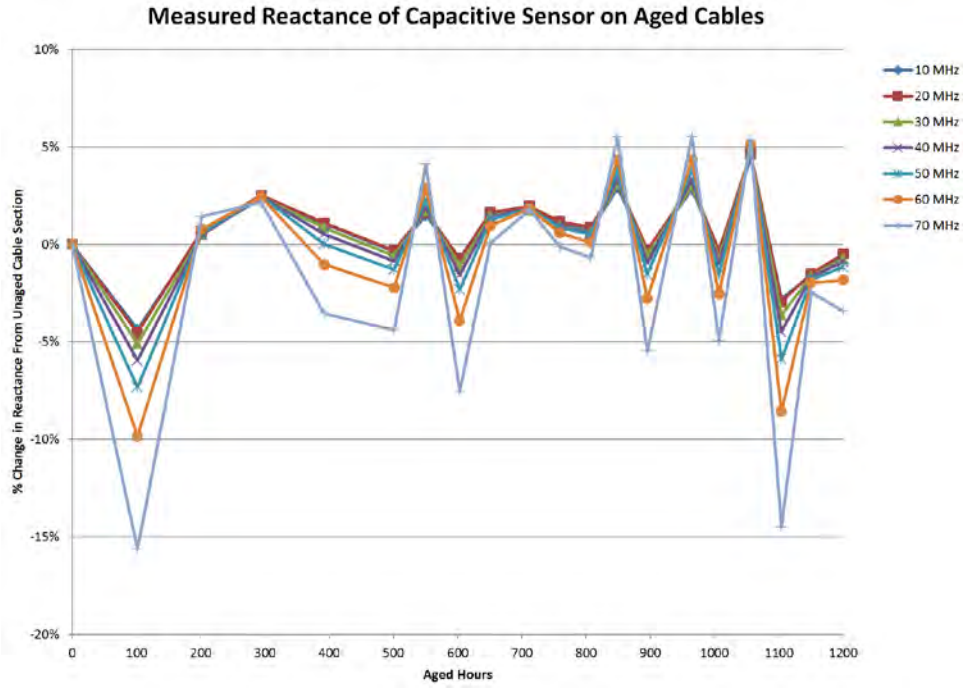


Figure 4.17. Measured Percent Change in Reactance vs. Aged Hours of Interdigital Sensor Mounted on Aged Cable Sections

4.7 Discussion

Several approaches to measuring key indicators of cable aging and degradation are available, and include chemical, mechanical, and electrical measurements. The initial measurements (electrical) reinforce the assessment that measurements of dielectric permittivity as measured using the coaxial dielectric probe (related to Tan δ) are capable of providing information on cable age (and potentially remaining useful life, based on the relatively smooth increase of the real part of the dielectric constant with age). However, the measurements also indicate a certain level of sensitivity to a number of other factors, including the fixture used for the probe as well as physical effects (surface damage) of the accelerated aging methodology.

In contrast to the high-frequency dielectric probe measurements, initial low-frequency capacitance measurements obtained using a conformal interdigital sensor did not exhibit a trend as a function of aged hours. Because the capacitance of this device is directly related to material dielectric constant, this indicates that the interdigital probe was not able to sense any changes that may be present in the dielectric constant at these frequencies. Further study is needed to investigate factors such as designs with increased field penetration depth, the effects of sensor placement and fixturing impacts on measurement repeatability, and designs with extended frequency ranges above 100 MHz. The measurements using the capacitive probe may be consistent with dielectric measurements at lower frequencies (below about 1 GHz) that showed no particular trend with aging. Given that the depth of penetration of energy using both techniques is a function of frequency (lower frequency implies higher penetration depth), it is unclear at this stage whether the lack of a trend at lower frequencies is indicative of aging effects that are closer to the surface. As a result, additional study is needed.

FTIR absorption spectra sensitively track chemical changes in material with thermal oxidation stress. Carbonyl chemical groups that form by reaction of thermally induced radicals in the material with oxygen present have characteristic absorption peaks. The presence and extent of these peaks is a key indicator of cable aging. Because absolute peak intensity can vary with sample geometry, it may be useful to determine internal references in the spectra. Ratios between peaks that change with aging and those that do not can then be used a metric of aging comparable between different cables.

The DMA has been determined to be a valuable tool for monitoring property changes over time. Future work with the DMA will be to run isothermal runs at different temperatures and monitor the changes in materials. The time-temperature-superposition method will be evaluated in predicting material changes relative to over time at different operating temperatures.

In contrast, the acoustic measurement methods need further study to determine if the sound speed (and potentially attenuation) may be an indicator of age that directly correlates with indenter modulus and EAB. Additional studies may also be needed to determine the viability of approaches that directly measure changes in polymer chemistry as a result of aging; these are planned for future phases of research.

5.0 Summary

The aging of cables is considered to be one of the factors that may limit the ability of light water reactors to continue operations beyond their licensed period (up to 60 years, depending on the specific plant). The most important requirement for cables (electrical or instrumentation) in NPPs is the ability to withstand a design-basis accident. Aging and subsequent degradation of insulation will impair the ability of cables to perform their function under all conditions, and there is therefore a need to assess the condition of cable insulation and estimate the corresponding remaining useful qualified life of the cable.

Several approaches to nondestructively measuring key indicators of cable aging and degradation are available, and include chemical, mechanical, and electrical measurements. Electrical and acoustic measurements are potential NDE approaches that may be capable of providing in-situ assessments of cable condition and remaining useful life.

The complex permittivity results using the high-temperature dielectric probe display promise for measuring a change in the real part of the dielectric constant and relating the change in this property to cable age. A total of 200 complex permittivity measurements were taken with cable samples exposed to 140°C for durations of 0–1200 hours. The real part of the dielectric constant was measured to have a nominal increase of 4.3% over the span of exposure times. Capacitance measurements performed on the cables below 100 MHz with an interdigital sensor did not exhibit the same type of trend observed in the 7-GHz datasets.

Using acoustic methods that can provide a direct relation to the elastic modulus of the cable material seems feasible. Preliminary baseline velocity measurements in EPR polymers are in line with published data. However, specimens of EPR rubber used for the measurements indicated some variability in baseline acoustic velocity. Additional measurements with aged specimens are being conducted and will be evaluated to determine the potential of acoustic measurements for aging characterization. The DMA has been determined to be a valuable tool for monitoring property changes over time. Further work can be done to optimize the ultrasonic transducers selected and analysis methods as well as provide a more reliable method for positioning and coupling them. Additional studies may also be needed to determine the viability of approaches that directly measure changes in polymer chemistry as a result of aging; these are planned for future phases of research.

6.0 Path Forward

Research going forward will focus on viability assessment of measurements of chemical, mechanical, and electrical key indicators that can provide data correlated to cable aging, and determine whether these diverse sets of measurements can provide synergistic information that can more effectively help in decisions on repair and replacement. Analysis of the viability will also require assessment of deployment challenges for the measurement methods employed for each of the key indicators. While most of the mechanical and electrical key indicator measurements may be performed on the complete cable system, issues such as variable thickness of the insulation, or the presence of shielding, may challenge the sensitivity of the measurement. Such issues will also be evaluated going forward.

6.1 Chemical Measurements

6.1.1 FTIR

Infrared spectroscopy is an informative method for investigating chemical bond content arising from polymer degradation. Oxidative damage indicators, such as carbonyl content, will be monitored in cable polymer samples and correlated with polymer mechanical and other properties. Chemical changes may be spatially located through sample thickness by, for instance, measuring the content of polymer slices taken throughout a cable cross section. In Figure 6.1, an anvil attachment is pictured holding an EPR cross-section slice in a Diamond Smart iTR™ attenuated total reflectance (ATR) attachment of a Thermo Scientific FTIR instrument. ATR is a surface technique that allows FTIR spectra of the first several micrometers of a sample near the interface. The spectrum in the figure has clearly visible absorbance peaks corresponding to the ethylene-propylene polymer in an EPR specimen. Specimens that have experienced diffusion-limited oxidation are expected to exhibit a graded profile of oxidation products through specimen thickness, which should be observable using ATR FTIR.

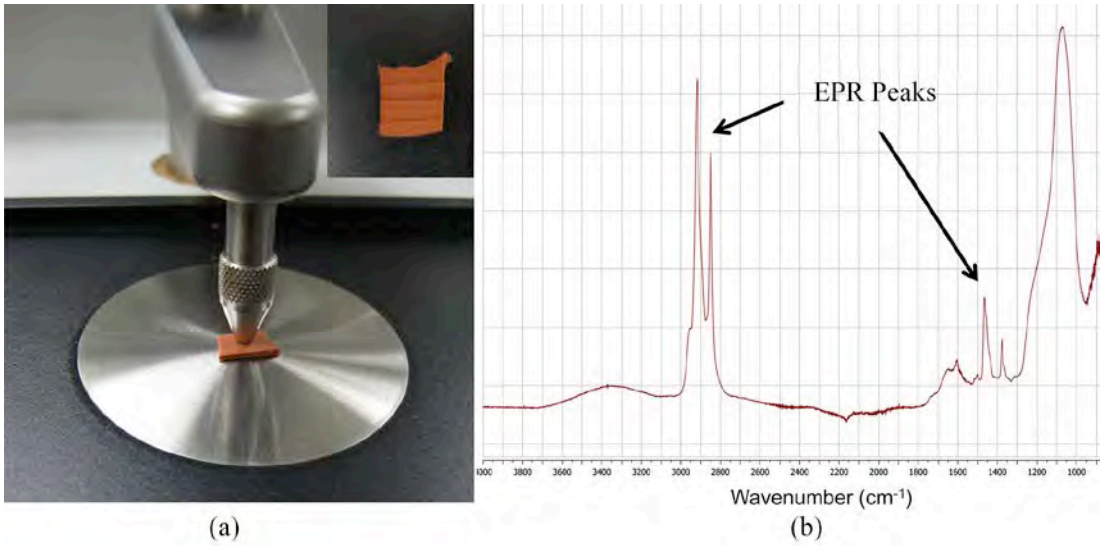


Figure 6.1. (a) Thermo Scientific Smart iTR™ Attenuated Total Reflectance Measurement of EPR Cross-section Slices. Inset: EPR cross-section sliced into layers. (b) FTIR ATR spectrum of EPR.

6.1.2 Differential Scanning Calorimeter

DSC will be used as a monitor of change in composition of cable polymer content. Changes in molecular weight from polymer chain scission and cross-linking will be reflected in changes in glass transition temperature. This data will be correlated with the sensitive change in glass transition measurable by dynamic mechanical analysis and to EAB. DSC will provide information on the effect of aging on the crystalline content of the cable polymer samples, which will also be correlated with mechanical properties and with density measurements.

6.1.3 Thermogravimetric Analysis

TGA investigation of insulation polymer material as a function of age will enable increased understanding of temperature stability effects of exposure damage. Increased oxygen content, chain scission, and cross-linking each result in changes to the mass loss profile with heating. This information will be correlated with changes in mechanical data and changes in other properties such as acoustic velocity and dielectric constant.

6.2 Mechanical Measurements

As the study progresses, additional mechanical measurement techniques will be evaluated. These evaluations can be directly correlated to existing relevant data acquired by the indenter-type nondestructive tests as well as the elongation-at-break data that have been evaluated both in the laboratory and in the field on existing power plants.

- **DMA** – Future work with the DMA will be to run isothermal runs at different temperatures and monitor the changes materials. The time-temperature-superposition method will be evaluated in predicting material changes relative to over time at different operating temperatures. The DMA modulus data can be used to assist the ultrasonic testing methods in determining the effects on bulk velocity and surface wave measurements.
- **Ultrasonic Testing** – The acoustic method used in the initial investigation will be further evaluated using the thin sheet specimens that are thermally aged. These data can then be compared to the DMA and other indenter type tests as well as to the breaking elongation data.

  Development efforts for FY2015 include optimization of a transducer (diameter, angle, frequency) and arrangement (location, size, coupling) for repeatable velocity and attenuation measurements on NPP cables. Appropriate mechanical fixtures will be developed to provide consistent application of ultrasonic energy to the cable specimens. In addition, the feasibility of measurement over longer segments of cables will be explored through the application of guided acoustic wave approaches.

6.3 Electrical Measurements

As the study progresses, additional electrical measurement methods will be investigated. These methods will be assessed on the test apparatus and evaluated as possible methods for further exploration. Some of the methods currently being considered are:

Electrical Permittivity – The electrical permittivity measurements (using the coaxial probe and capacitance probe) that were initially investigated will be further explored using additional specimens (including other insulation materials).

Line Resonance Analysis – Line resonance analysis, or LIRA, is an electrical measurement technique that has been shown to detect changes in electrical impedance along a cable. These changes are generally due to changes in dielectric properties. Challenges in this area include determining the condition of the cable from LIRA measurements, and applying this diagnostic technique for remaining life estimation.

Complex permittivity measurements performed in FY2014 demonstrated the ability to measure a change in the real part of the dielectric constant of the cable insulation in relation to cable aging. Considerations for this measurement technique are repeatability of data, physical geometry of the cable and the sample size requirements of the dielectric probe, calibrated repeatable pressure applied for each sample set, the frequency band used to isolate and monitor the change in the real part of the dielectric constant, and whether this type of measurement can be performed remotely and in real-time as the cable is being exposed to temperatures representative of the cable aging.

Development efforts for FY2015 include studies with additional specimens of aged EPR and XLPE cables to quantify the effects of aging on permittivity and insulation resistance. In parallel to the efforts on quantifying changes in electrical properties, initial work will begin on examining other measurement techniques such as the line resonance analysis will also be explored.

7.0 References

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Appendix A

Real Component of the Complex Permittivity Measurements for Aged Cable Samples, 200 MHz–20 GHz

Appendix A

Real Component of the Complex Permittivity Measurements for Aged Cable Samples, 200 MHz–20 GHz

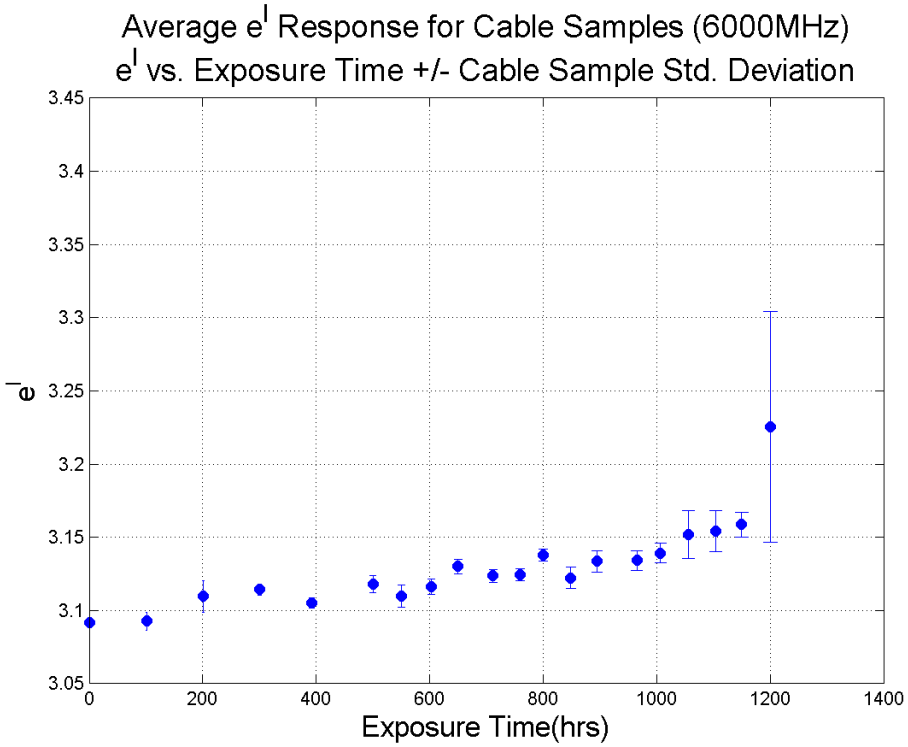

Figure A.1. Averaged ε' vs. Exposure Time ± Standard Deviation at 6000 MHz

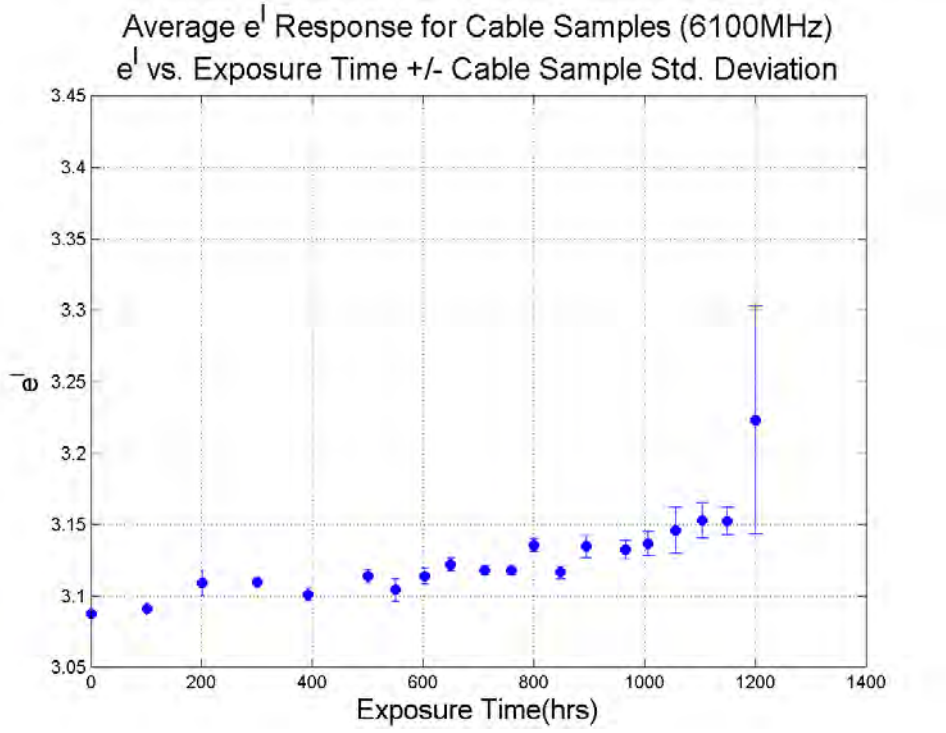

Figure A.2. Averaged ε' vs. Exposure Time ± Standard Deviation at 6100 MHz

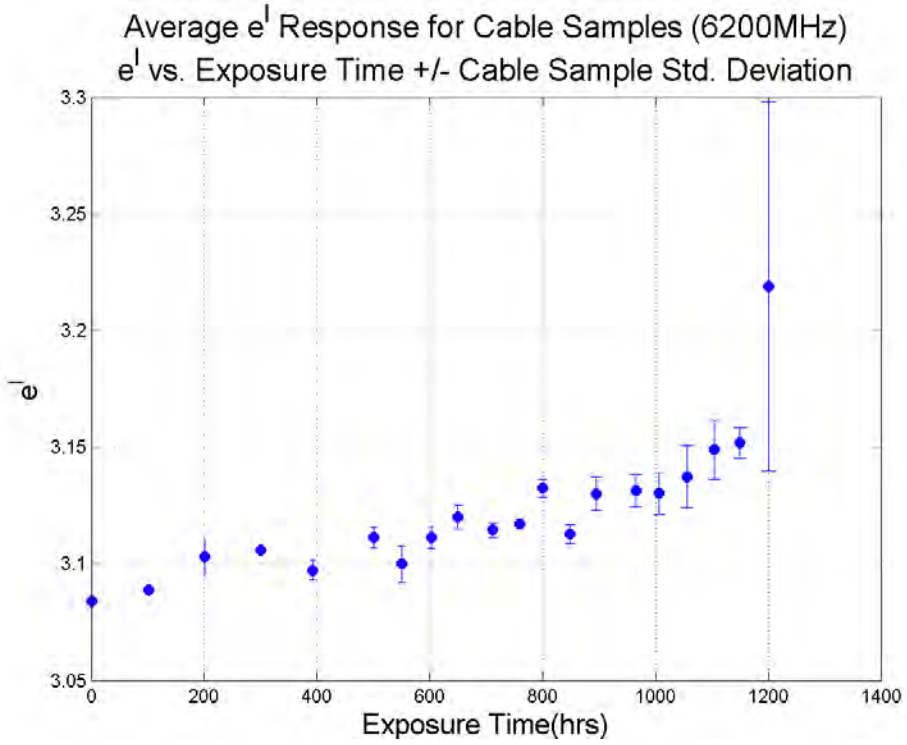

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Figure A.3. Averaged ε' vs. Exposure Time ± Standard Deviation at 6200 MHz

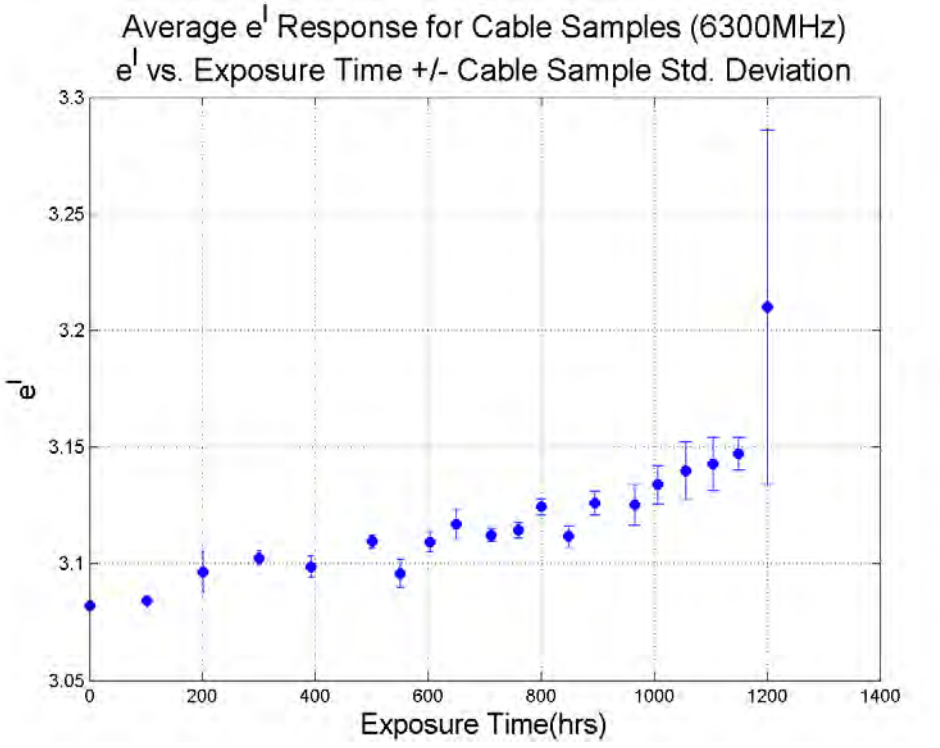

Figure A.4. Averaged ε' vs. Exposure Time ± Standard Deviation at 6300 MHz

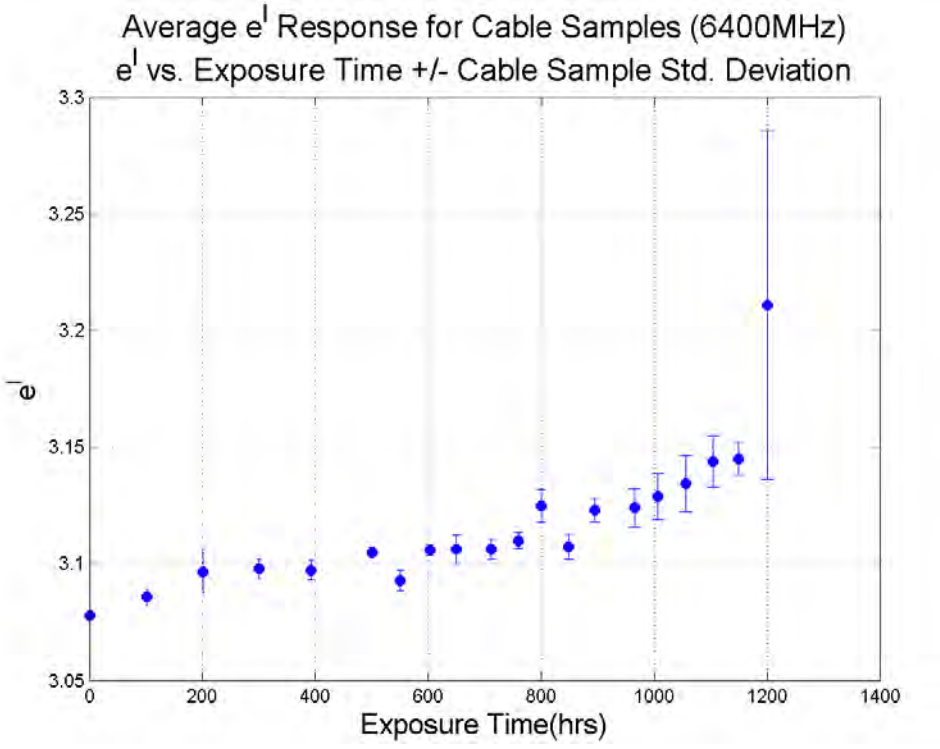

Figure A.5. Averaged ε' vs. Exposure Time ± Standard Deviation at 6400 MHz

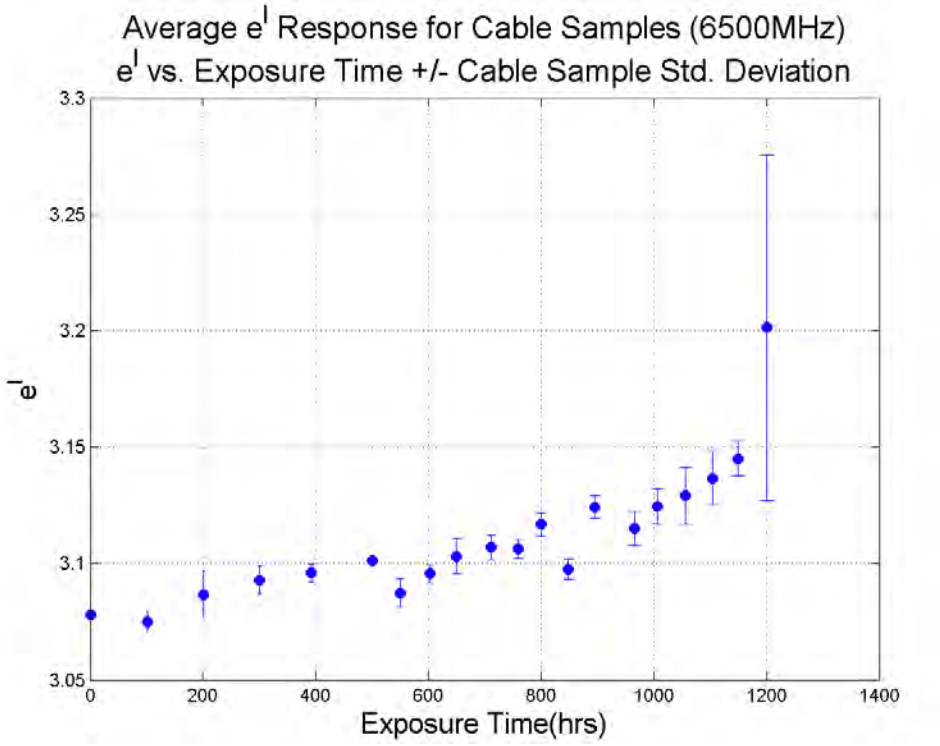

Figure A.6. Averaged ε' vs. Exposure Time ± Standard Deviation at 6500 MHz

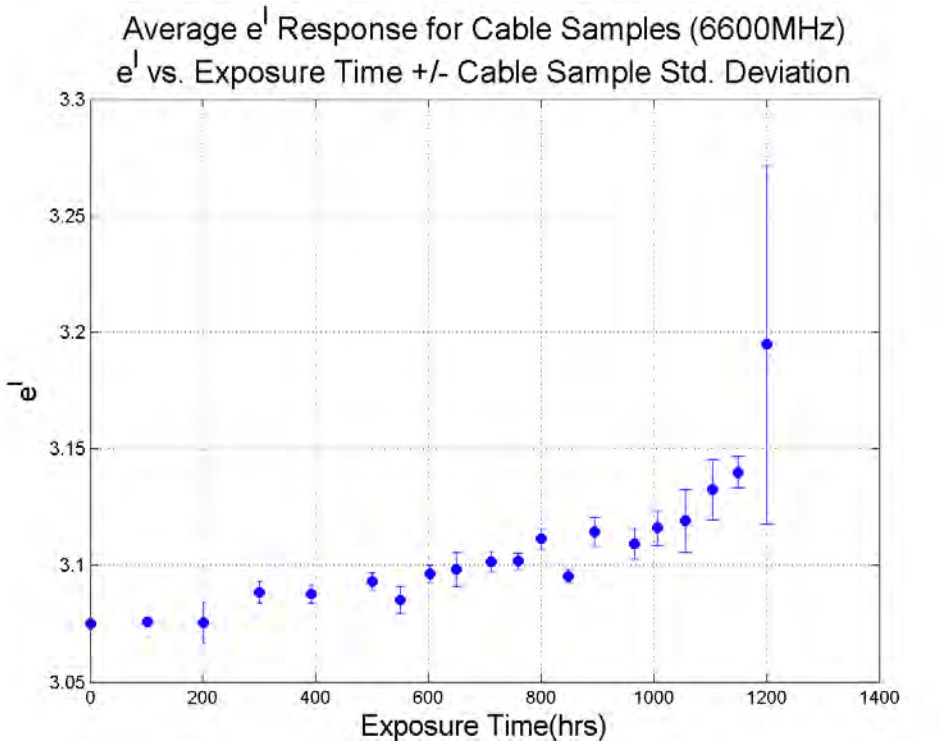

Figure A.7. Averaged ε' vs. Exposure Time ± Standard Deviation at 6600 MHz

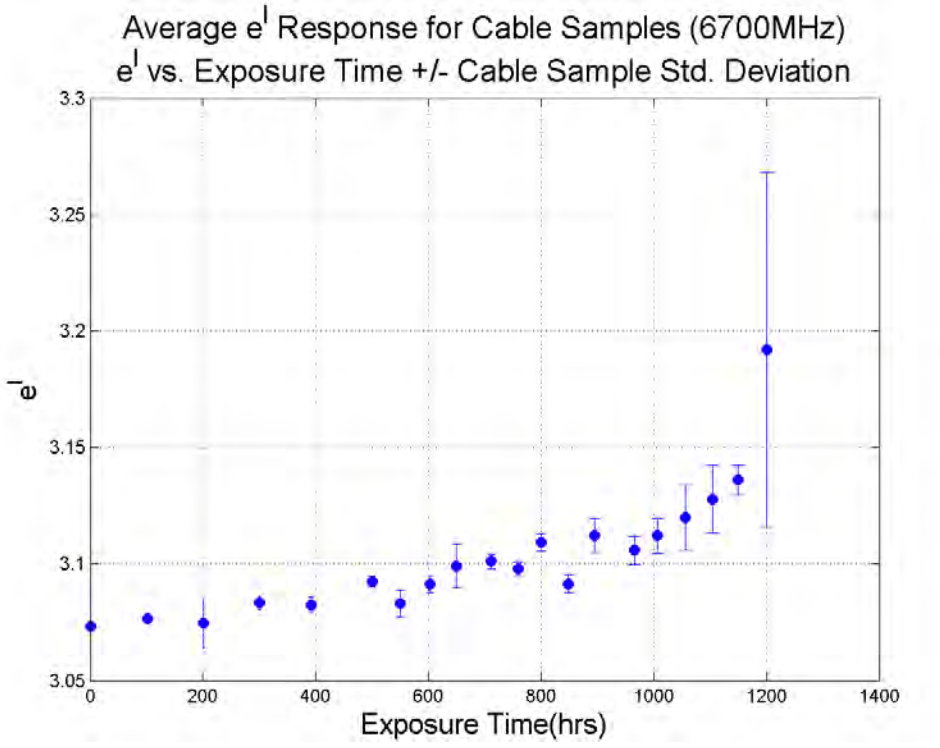

Figure A.8. Averaged ε' vs. Exposure Time ± Standard Deviation at 6700 MHz

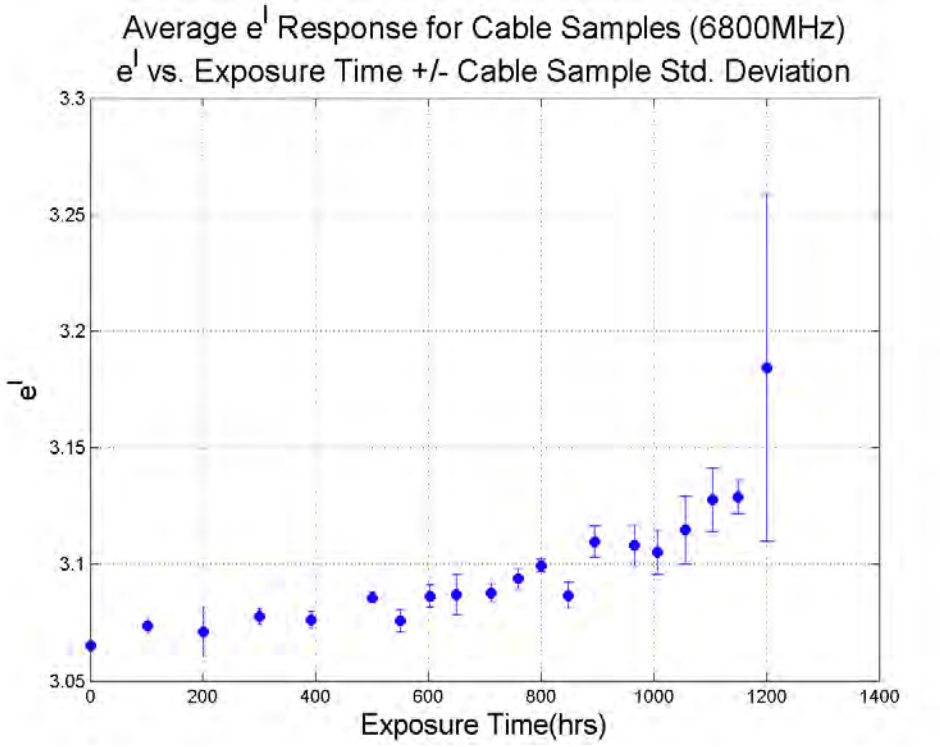

Figure A.9. Averaged ε' vs. Exposure Time ± Standard Deviation at 6800 MHz

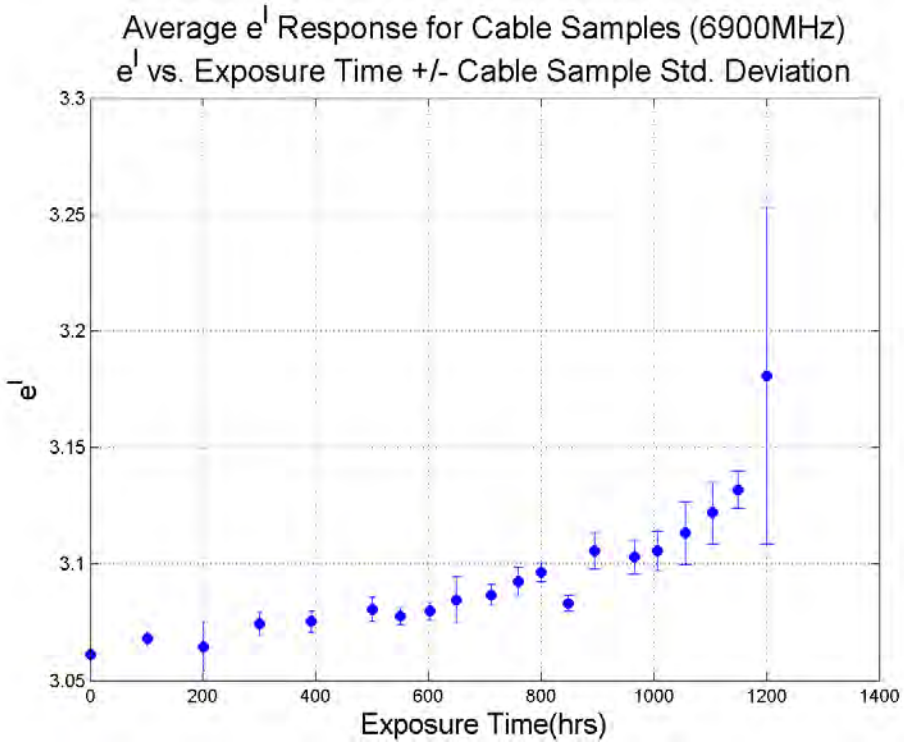

Figure A.10. Averaged ε' vs. Exposure Time ± Standard Deviation at 6900 MHz

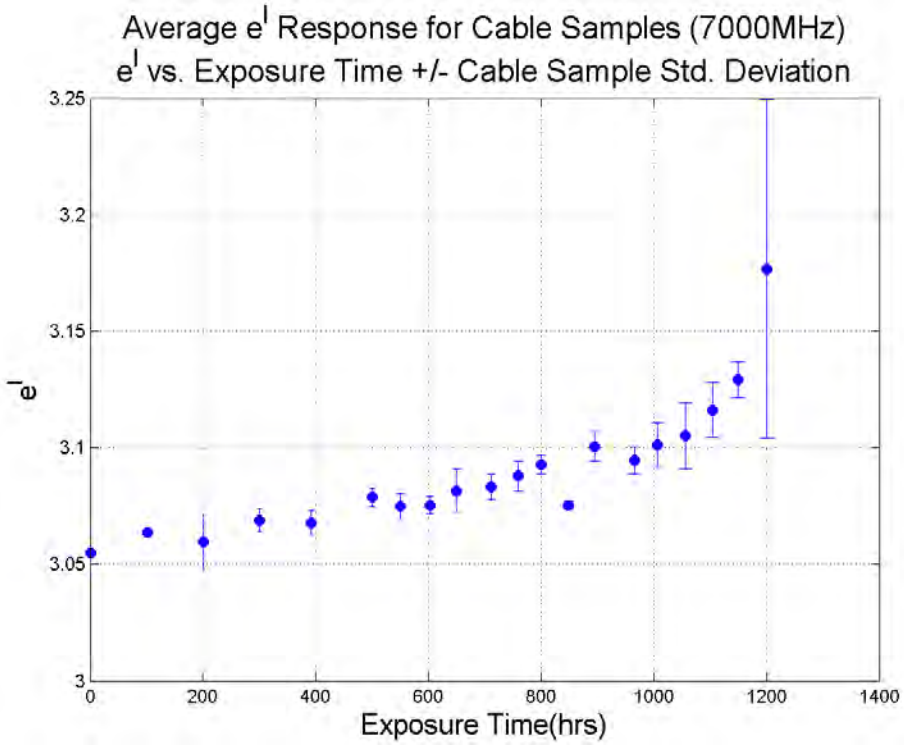

Figure A.11. Averaged ε' vs. Exposure Time ± Standard Deviation at 7000 MHz

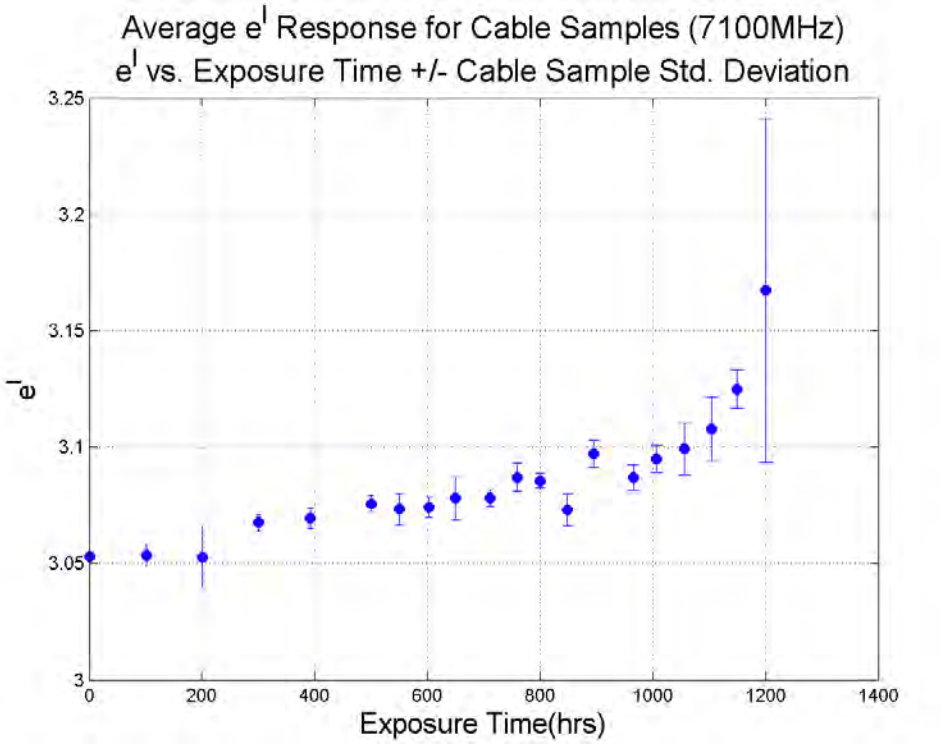

Figure A.12. Averaged ε' vs. Exposure Time ± Standard Deviation at 7100 MHz

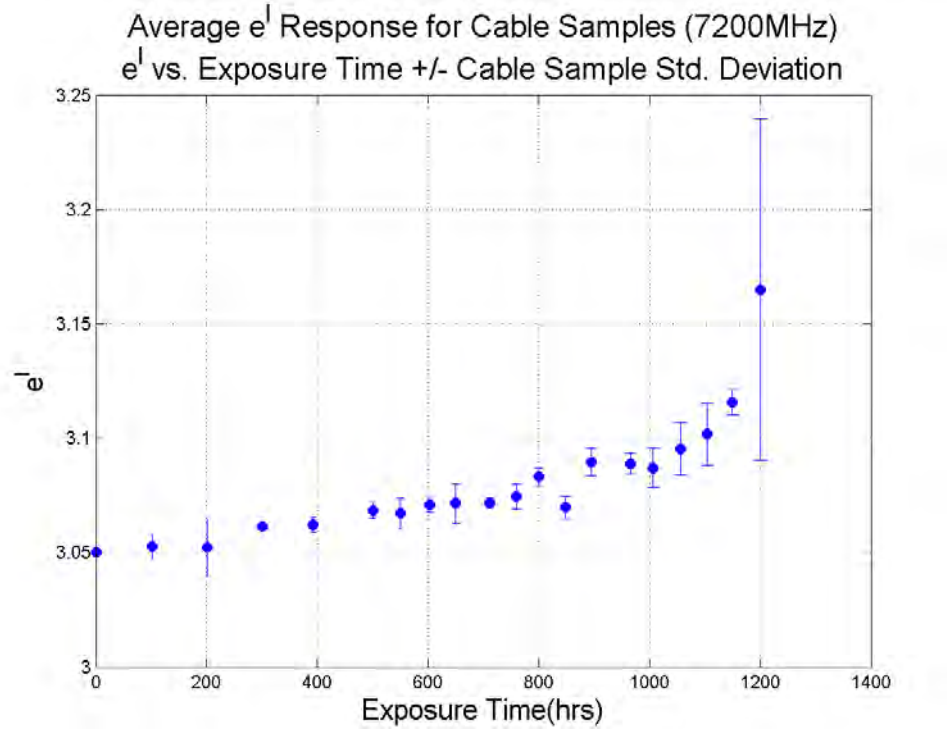

Figure A.13. Averaged ε' vs. Exposure Time ± Standard Deviation at 7200 MHz

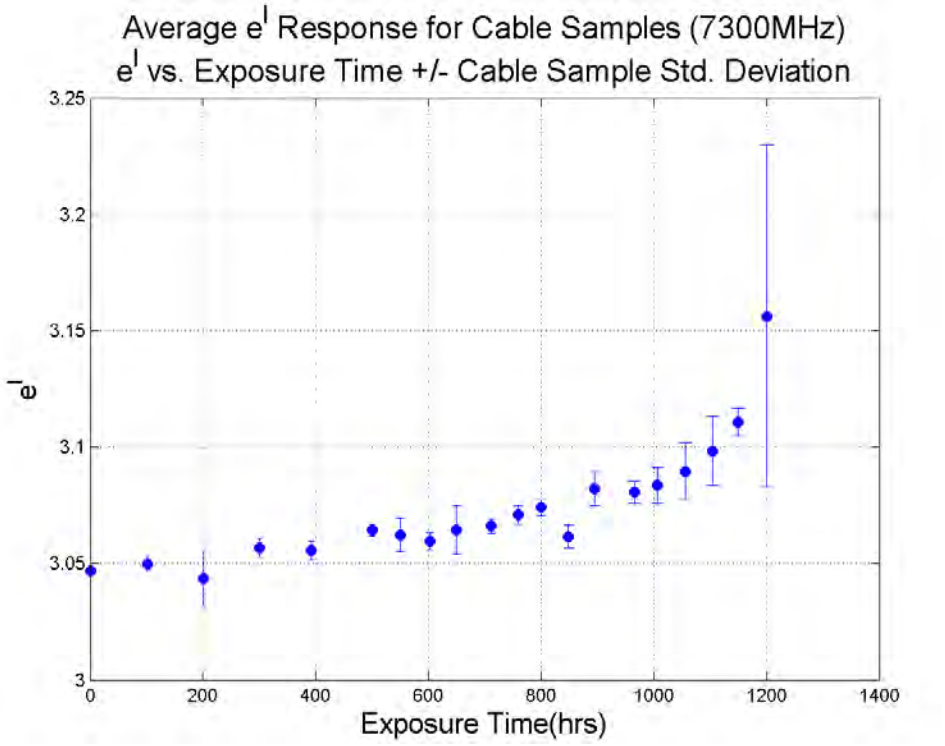

Figure A.14. Averaged ε' vs. Exposure Time ± Standard Deviation at 7300 MHz

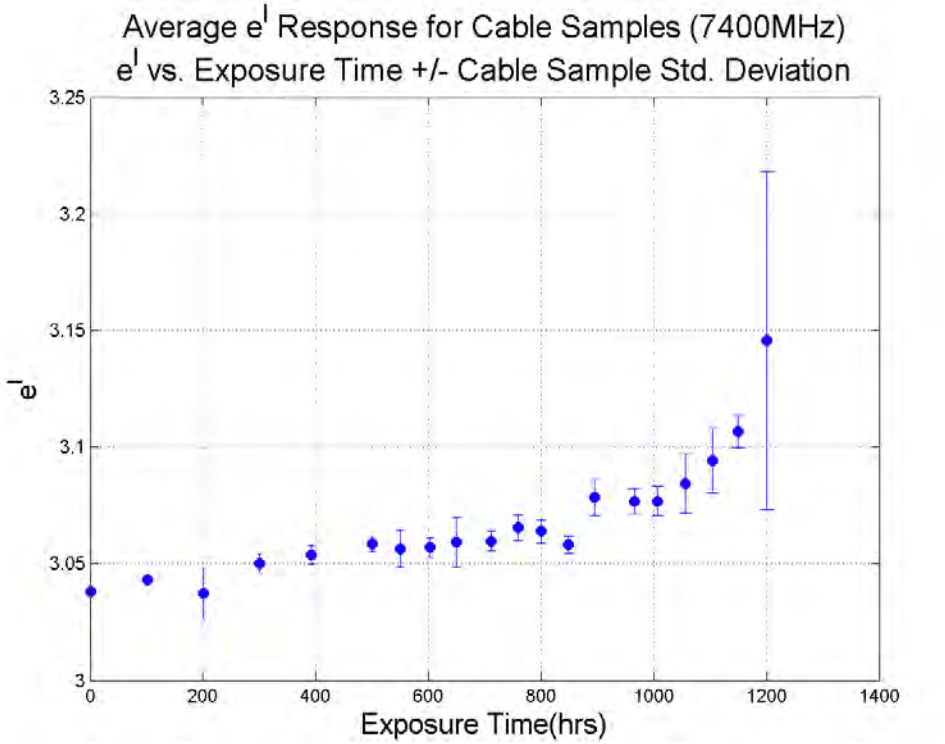

Figure A.15. Averaged ε' vs. Exposure Time ± Standard Deviation at 7400 MHz

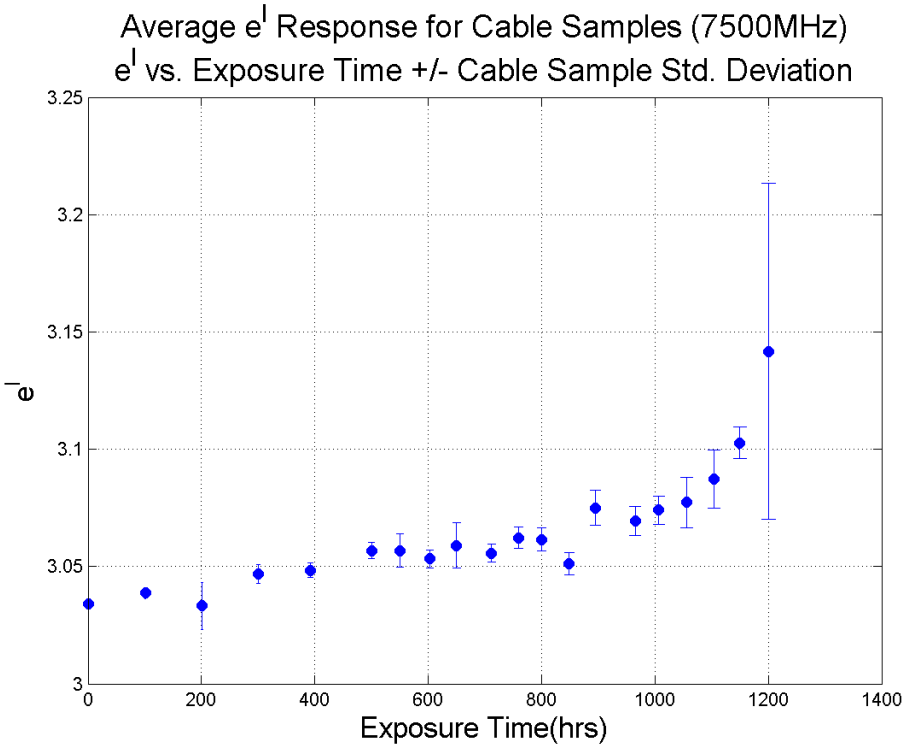

Figure A.16. Averaged ε' vs. Exposure Time ± Standard Deviation at 7500 MHz

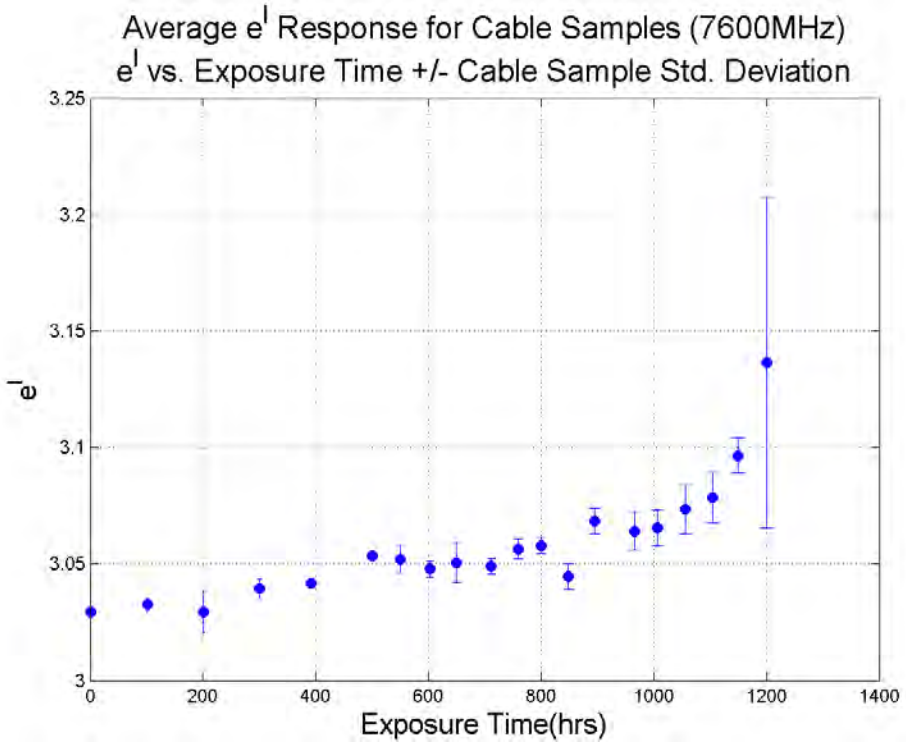

Figure A.17. Averaged ε' vs. Exposure Time ± Standard Deviation at 7600 MHz

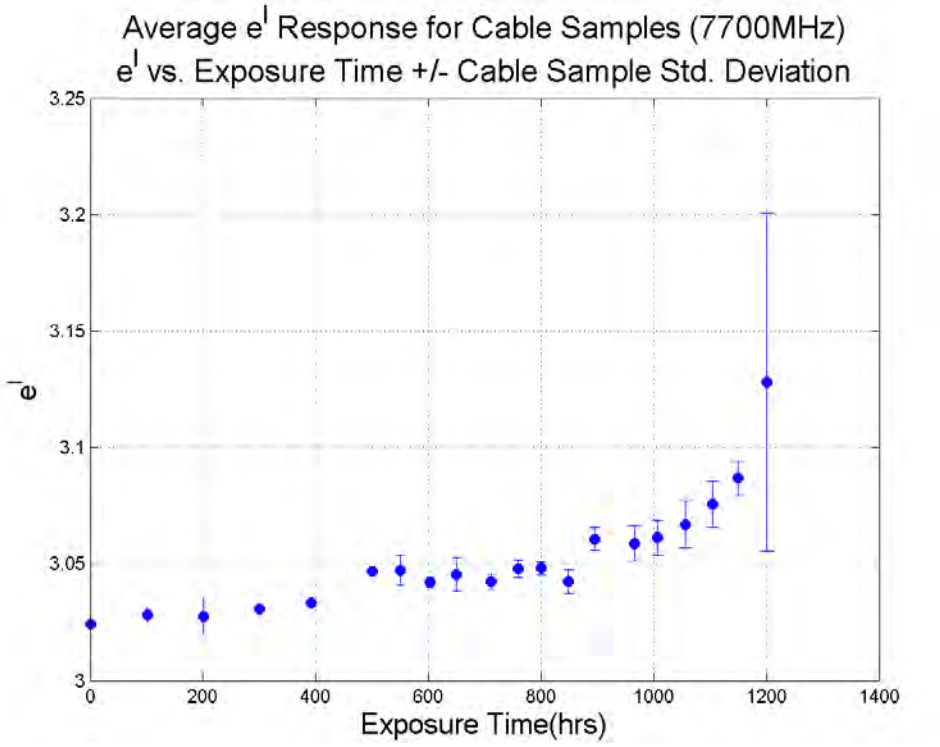

Figure A.18. Averaged ε' vs. Exposure Time ± Standard Deviation at 7700 MHz

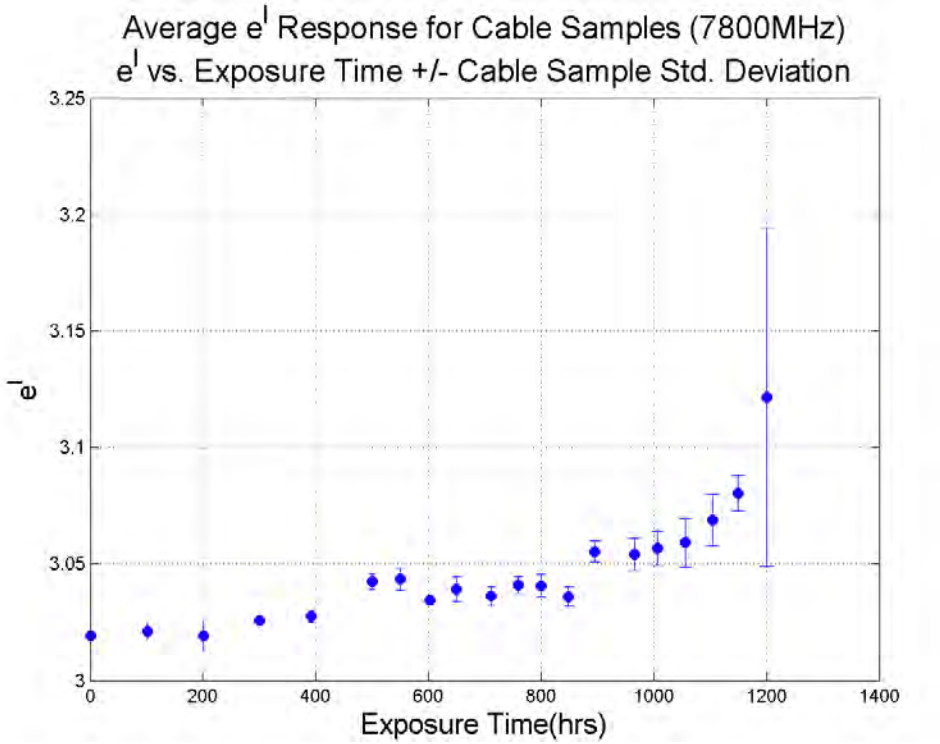

Figure A.19. Averaged ε' vs. Exposure Time ± Standard Deviation at 7800 MHz

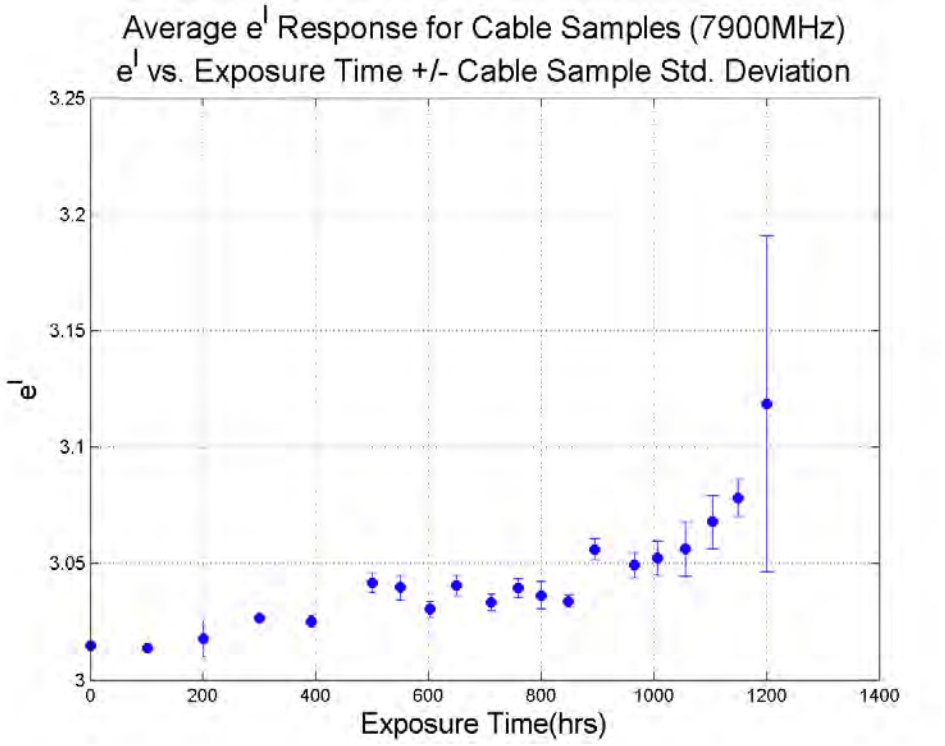

Figure A.20. Averaged ε' vs. Exposure Time ± Standard Deviation at 7900 MHz

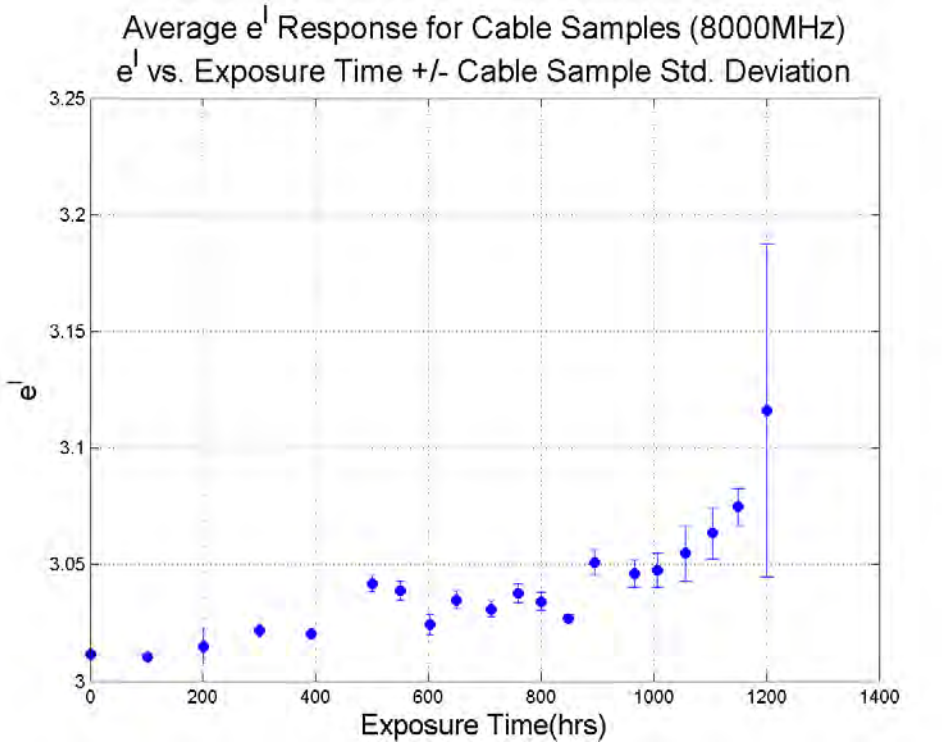

Figure A.21. Averaged ε' vs. Exposure Time ± Standard Deviation at 8000 MHz

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