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Light Water Reactor Sustainability Program

Evaluation of Localized Cable Test Methods for Nuclear Power Plant Cable Aging Management Programs

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SUMMARY

This Pacific Northwest National Laboratory milestone report describes progress to date on the investigation of nondestructive test methods focusing particularly on local measurements that provide key indicators of cable aging and damage. The work includes a review of relevant literature as well as hands-on experimental verification of inspection capabilities. As nuclear power plants consider applying for second, or subsequent, license renewal to extend their operating period from 60 years to 80 years, it is important to understand how the materials installed in plant systems and components will age during that time and develop aging management programs to assure continued safe operation under normal and design basis events (DBE). Normal component and system tests typically confirm the cables can perform their normal operational function. The focus of the cable test program, however, is directed toward the more demanding challenge of assuring the cable function under accident or DBE.

Most utilities already have a program associated with their first life extension from 40 to 60 years. Regrettably, there is neither a clear guideline nor a single non-destructive test (NDE) that can assure cable function and integrity for all cables. Thankfully, however, practical implementation of a broad range of tests allows utilities to develop a practical program that assures cable function to a high degree. The industry has adopted 50% elongation at break (EAB) relative to the un-aged cable condition as the acceptability standard. All tests are benchmarked against the cable EAB test. EAB, however, is a destructive test so the test programs must apply an array of other NDE tests to assure or infer the overall set of cable's system integrity. These cable NDE programs vary in rigor and methodology. As the industry gains experience with the efficacy of these programs, it is expected that implementation practice will converge to a more common approach. Generally speaking, however, these programs all include:

- A structured database of all cables within the plant and a specific subset of cables that are subject to regular testing.
- Visual walk-downs looking for visual indications of age-related degradation. This is the primary local cable test approach. The visual walk-down may be supplemented by examining the cables and cable environments with infrared cameras to identify higher temperature areas that may be subject to accelerated insulation aging.
- Bulk electrical tests (time domain reflectometry, monitored withstand, tan-delta, megger resistance, frequency domain reflectometry, time domain reflectometry, etc.) that confirm the electrical function of the cables and can provide early indications of degradation and, in some cases, even location of the degradation. These bulk measurements are not specifically addressed in this report but rather will be addressed in a subsequent report under this same project.
- Frequently apparent visual damage is limited to the external jacket, and the underlying insulation is still suitable for safely performing the required function. A number of other local tests are available and are being used to varying degrees to corroborate electrical and/or visual tests. In many cases, this allows the cable to remain in service until replacement can be conveniently scheduled.

This report assesses the range of local NDE cable tests that are or could be practically implemented in a field test situation. These tests include: visual, infrared thermography, interdigital capacitance, indenter, relaxation time indenter, dynamic mechanical analyzer, infrared/near-infrared spectrometry, ultrasound, and distributed fiber optic temperature measurement. The assessment criteria include a qualitative comparative evaluation of ease/cost of deployment, maturity, and correlation with EAB, plus suggested further research if required to allow the measurement to be implemented and accepted by the industry.

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CONTENTS

FIGURES

TABLES

ACRONYMS

AMP	Aging Management Program
CM	condition monitoring
DBE	design basis event
DMA	dynamic mechanical analysis
DOE	U.S. Department of Energy
EAB	elongation at break
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
FDR	frequency-domain reflectometry
FT-NIR	Fourier transform near infrared (spectroscopy)
FTIR	Fourier transform infrared (spectroscopy)
IAEA	International Atomic Energy Agency
IR	infrared
K	indenter relaxation coefficient
LOCA	loss-of-coolant accident
LWRS	Light Water Reactor Sustainability Program
N	Newton (unit of force)
NDE	nondestructive evaluation
NIR	near infrared
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
SLR	Subsequent License Renewal
TDR	time domain reflectometry
TGA	thermogravimetric analysis
XLPE	cross-linked polyethylene
σ	compression indenter modulus

Evaluation of Localized Cable Test Methods for Nuclear Power Plant Cable Aging Management Programs

1. OBJECTIVES

This Pacific Northwest National Laboratory (PNNL) milestone report describes progress to date on the investigation of nondestructive test methods focusing particularly on local measurements that provide key indicators of cable aging and damage. The work includes a review of relevant literature as well as hands-on experimental verification of inspection capabilities. This report specifically is targeted toward review and assessment of local measurement approaches against the following criteria:

- **Ease/cost of implementation:** Is it practical or could it be practical to deploy such a test in a power-plant environment and is or could the cost of the test be favorable compared to alternatives? Alternatives may be other tests or cable replacement. + = generally practical to implement and for relatively low cost. N = neutral: probably possible to implement cost competitively. – = unlikely to be cost-competitively field deployable.
- **Commercially available:** Can instruments or service contracts be purchased now? + = currently available. N = neutral: known commercial entities are actively exploring commercialization. – = no known current activity to commercialize.
- **Measurement correlation:** Does the measurement correlate with EAB or other age-related parameters? + = good correlation with EAB for a high percentage of components. N = neutral: correlation for some materials. – = weak correlation for most materials.
- **Quantitative measurement:** Can acceptance criteria be established such that it is possible to disposition a cable as good, marginal/needs further study, or definitely bad by comparing to existing guidelines/thresholds or guidelines/thresholds that could be established? + = yes and guidelines or thresholds are available. N = neutral: thresholds could likely be established but this work has not yet been done. – = only qualitative results are likely from this technique that will be difficult to use for cable dispositioning.
- **Additional R&D:** Are there major technical gaps that currently preclude the measurement approach from being fielded? + = little or no additional work needed for implementation or continued implementation. – = significant additional R&D needed for field implementation. Where possible, specific suggested additional work is noted.

PNNL has developed capabilities for thermal, radiation, and combined thermal and radiation aging of small cable sample sets. Details of the aging facility and general laboratory test capabilities have been reported elsewhere (Glass et al. 2015) so this information is only noted as it relates to characterizing the inspection methods. Moreover, inspection methods are focused on approaches that can be deployed in situ to nuclear power plants (NPPs). Some of the methods are currently laboratory-based, but it is expected that they could be customized for in-situ measurements in an NPP field environment if the laboratory results and business justification created a compelling case for such an evolution of the method.

The overall objectives of this project are to develop the technical basis for assessing the level and impact of cable insulation aging and degradation in NPPs. 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, including methods for nondestructively measuring the condition of aging cables. The project addresses the overall gaps that were identified at the workshop in FY2012 using a phased approach. This phased approach addresses the three areas identified from the workshop:

1. Determination of key indicators of cable aging. This has largely been addressed in earlier reports (Simmons et al. 2014; Fifield et al. 2015; Ramuhalli et al. 2015).
2. Characterize and advance current nondestructive evaluation (NDE) methods and develop new NDE methods by using insights from the determination of key indicators. This activity was generally addressed by Glass et al. (2015) describing the overall state of the art for both bulk electrical tests and local tests. This report focuses on local tests. A separate 2016 report is planned for bulk electrical tests.
3. Develop models that use the advances in key indicators and NDE methods to assist in predicting remaining life of cables-ongoing.

This report is submitted in fulfillment of deliverable M3LW-16OR0404022 – Evaluation of Localized Cable Test Methods for Nuclear Power Plant Cable Aging Management Programs.

2. REPORT ORGANIZATION

This document is organized as follows. The Summary includes a brief description of the material covered in the report focusing on significant observations and conclusions. Section 1 describes the report and research objectives; Section 2 explains the report organization. Section 3 provides an introduction and background to the topic specifically highlighting cooperation associated with this program. Section 4 reviews a global collection of cable Aging Management Program (AMP) guidelines. Section 5 reviews cable designs and categories. Section 6 summarizes PNNL's facilities for accelerated cable aging coupled with laboratory and in-situ condition monitoring and fundamentally addresses the material characteristic measurement capabilities. Sections 7.1–7.10 address local test approaches. Section 8 summarizes the qualitative assessments. Section 9 covers conclusions and future work recommendations and Section 10 addresses applicable and related standards. And finally, Section 11 chronicles the references used in the report.

3. INTRODUCTION AND BACKGROUND

As NPPs consider applying for second, or subsequent, license renewal (SLR) to extend their operating period from sixty-years to eighty-years it important to understand how the materials installed in plant systems and components will age during that time and develop AMPs to assure continued safe operation under normal and design basis events (DBE).

Degradation of the cable jacket, electrical insulation, and other cable components of installed cables within NPPs is known to occur as a function of age, temperature, radiation, and other environmental factors. Although system tests verify cable function under normal loads, concern remains over cable performance under exceptional loads associated with DBEs. The cable's ability to perform safely over the initial 40-year planned and licensed life has generally been demonstrated and there have been very few age-related cable failures (EPRI 2015; Mantey 2015). With greater than 1000 km of power, control, instrumentation, and other cables typically found in an NPP, replacing all the cables would be a severe cost burden. License renewal to 60 years and subsequent license renewal to 80 years, therefore, requires a cable AMP in accordance with regulatory guidance (NRC 2012) to justify cable performance under normal operation as well as accident conditions.

The aging of insulation and jacketing material in electrical and instrumentation 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 and 80 years, depending on the specific plant). The focus for cable SLR qualification is the continued ability to withstand a DBE. Aging and subsequent degradation of insulation will impair the ability of cables to perform their function under all environmental conditions. Methods to nondestructively assess the level of aging and degradation in cable insulation and jacketing materials are therefore needed. In addition to providing an estimate of the level of aging and degradation, such condition assessment or condition monitoring (CM) methods for cable insulation can also provide critical inputs into condition-based qualification approaches, assess corresponding remaining useful qualified life of the cable, and ensure that the cables do not exceed a qualified level of degradation.

The U.S. Nuclear Regulatory Commission (NRC) commissioned the U.S. Department of Energy (DOE) to perform a detailed analysis of NPP material aging in this context. The results of this analysis, the Expanded Materials Degradation Assessment (EMDA) have been published in five volumes. The first provides a summary of the analysis process and results. The second through fourth volumes focus on the aging of individual systems of concern including core internals and piping systems, reactor pressure vessels, and concrete and civil structures. The fifth volume (NRC 2013) considers the aging of cable and cable systems. It identifies age-related degradation scenarios that could be important to the use of NPP electrical cable components over an 80-year timeframe and identifies issues for which enhanced aging management guidance may be warranted.

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, including methods for nondestructively measuring the condition of aging cables. This workshop brought together subject matter experts from the NRC, DOE national laboratories, the Electric Power Research Institute (EPRI), universities, and cable manufacturers and inspectors. The workshop focused on identifying key research needs in the NDE of aging cable insulation in NPPs and the associated technical gaps. Identifying measurable quantities due to changes in chemical structure of insulating materials that would be a precursor to eventual failure of an aging cable, and the current state-of-the-art in NDE methods that could be applied to estimate the remaining life of the cable, were determined to be key to addressing the aging management challenge for nuclear cables. The development of new NDE methods or development of new measurement techniques using existing NDE methods that target these types of changes is of significant interest. Further, the ability to perform nondestructive tests 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. This cable aging management program is sponsored by

DOE under the Light Water Reactor Sustainability (LWRS) program to address knowledge and technique gaps to support the evolution of industry cable AMPs. Cable NDE methods comprise one topic of ongoing coordination and communication efforts on aging NPP cable research between the DOE, NRC, EPRI, and Iowa State University. Coordination of efforts helps to minimize duplication in research and to ensure that prioritized knowledge gaps are addressed.

Acceptance criteria that define the threshold for degradation below which cables may continue to be used are a challenge, because it is impractical to subject each cable system to loss-of-coolant accident (LOCA) or seismic simulation events following 40+ years of service. The report *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 elongation at break as a conservative practical end-of-life threshold for cables that may be stressed during maintenance or subjected to LOCA exposure. The report also discusses the basis for cautious continued use of cables beyond the 50-percent EAB threshold. EAB inherently compromises the in-service cable use as a destructive ex-situ test so the challenge is to develop NDE methods that can reasonably be correlated with EAB. Reliable NDE in-situ approaches are needed to objectively determine the suitability of installed cables for continued service. A variety of tests are available to assess various aspects of electrical and mechanical cable performance, but none of the available tests are suitable for all cable configurations nor does any single test assess all features of interest. Nevertheless, the complete collection of test possibilities offers a powerful range of tools to assure the integrity of critical cables.

Cable test technologies may generally be divided into:

1. Bulk electrical measurements (Tan δ [dissipation factor], time domain reflectometry, frequency domain reflectometry, partial discharge, and other techniques). These tests will not be addressed in this report as they are the focus of another 2016 report.
2. Local insulation measurements (visual or optical inspection, indenter, relaxing indenter, dynamic mechanical analysis, interdigital capacitance, infrared spectral measurement, etc.) that either can be applied in situ or could be adapted for an in-situ deployment if laboratory measurements justified instrument adaptations to an in-situ environment. This is the primary subject of this report.
3. Laboratory sample tests – these tests require samples from surrogate cables that may have been left in place but are no longer in service (rare) or a section of the cable may be sampled followed by a splice or termination repair. Such tests include EAB, oxidation induction time and temperature (evaluates loss of anti-oxidant compounds), insulation density measurement, temperature at maximum rate of weight loss and activation energy measurements using a thermogravimetric analyzer, swelling ratio and gel fraction measurements, atomic force microscope for micro-scale viscoelastic properties, nuclear magnetic resonance, and Fourier transform infrared spectroscopy. These tests are mentioned but are not addressed further in this report. Such tests can be useful to characterize general plant cable aging behavior, but their destructive nature and impracticality for field application makes them impractical for justifying continued use of in-service cables.

The LWRS Cable NDE program reviews the full range of techniques but focuses on promising test approaches most likely to be deployed in situ. The ultimate goal is to provide guidance for utilities and regulators leading to more robust cable aging management programs that can assure in-service cable integrity under the anticipated DBE (Glass et al. 2015).

4. CABLE AGING MANAGEMENT PROGRAM GUIDELINES

Cable safety factors offer significant margin for normal operation and consequently most cables can be expected to perform satisfactorily under normal loads. Cables are inherently tested as part of the regular system tests that are periodically performed on nuclear plant systems and active components. As emphasized in Regulatory Guide 1.218 (NRC 2012), cable aging management programs focus on the ability of cables to withstand the extreme stresses that may be experienced in a DBE and that may not be addressed with normal system tests. Degradation of electrical insulation and other cable components are key issues that are likely to affect the ability of currently installed cables to operate safely and reliably for another 20 to 40 years beyond the initial qualified operating life under a DBE. Although cable failures are rare, when they occur, the event can be dramatic; and if they involve critical safety systems, those systems are likely not to be available to the plant following cable failure.

Considering the extensive lengths, types, and integration of cables in a typical NPP, it would be a daunting undertaking to regularly inspect all of the cables. Licensees and regulators, however, are generally agreed that an aging cable management program can be developed to justify continued safe operation based on CM tests to reasonably assure the cables will perform their required function. Practical guidelines have been developed and are evolving in the United States and internationally that offer a manageable approach to sampling and screening cables based on accessibility, risk, history, and other factors. These include:

- NUREG/CR-7000, BNL-NUREG 90318-2009, *Essential Elements of an Electric Cable Condition Monitoring Program* (Villaran and Lofaro 2010)
- Regulatory Guide 1.218, *Condition-Monitoring Techniques for Electric Cables Used in Nuclear Power* (NRC 2012)
- NP-T-3.6, *Assessing and Managing Cable Aging in Nuclear Power Plants* (IAEA 2012)
- EPRI Low-Voltage Cable Aging Management Course (workbook) (updated 2015)[a]
- EPRI Technical Report 3002000557, *Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Revision 1* (Mantey and Toman 2013)
- *ADVANCE – Publishable Summary – Ageing Diagnostics and Prognostics of Low-Voltage I&C Cables*, Collaborative Project led by Electricity de France (ADVANCE 2013)
- Draft Regulatory Guide 1240, *Condition Monitoring Program for Electric Cables Used in Nuclear Power Plants* (NRC 2010)

Common themes from these reports include the following points:

- **CM assessment to estimate design margins under DBE**: The integrity and function of power, instrumentation, and control cables are monitored indirectly through the performance of in-service operability testing of safety-related systems and components. These tests can demonstrate the function of the cables under normal operating test conditions. However, such operability tests do not provide assurance that cables will continue to perform successfully when they are called upon to operate fully loaded for extended periods as they would under normal service operating conditions or under DBE conditions.
- **Multiple complementary test approaches**: A number of test approaches must be employed to reasonably assure the safe operation under the test condition and, by inference, safe operation under a DBE.

(a) EPRI. 2015. *Low-Voltage Cable Aging Management Course (workbook)*. Electric Power Research Institute, Palo Alto, California.

- **Continued operation based on condition monitoring**: The basis for justifying aged cables should be periodic condition testing. This is commonly referred to as monitoring and normally does not mean continuous monitoring. This is a practical way to assure cables are performing as designed, thereby justifying leaving them in service after their initial planned useful life.
- **Bulk and local tests**: Bulk end-to-end testing of a cable is preferred, but it is possible and even likely that cable condition can be locally masked by splices, blind spots at termination ends, etc. Test tools can and should include both bulk and local tests.
- **Localization of damage**: Localization of areas of concern is important because practical management of areas of degradation may involve local tests, cable splices, and repair rather than replacement of a full cable length.
- **Structured program for aging cable management**: Although the same basic program elements are recommended from most of the above documents, NUREG/CR-7000 (Villaran and Lofaro 2010) outlines a clear nine-step aging management condition-based qualification approach.

5. CABLE DESIGN, CLASSIFICATION, AND LAYOUT

NPP cable designs typically include a conductor to carry power, instrumentation or control signals, and an insulating cover layer to isolate the conductor (Figure 5.1). They may include more than one insulated conductor within a bundle. Other components typically associated with the overall cable design include a semiconductor screen, a shield over each conductor and/or over all conductors, binder tape, and a jacket. While the insulation provides electrical isolation, in jacketed cable configurations the jacket mainly serves to provide mechanical protection during installation and sometimes fire or moisture resistance depending on the cable construction. The materials for cable components are chosen based on the use environment, such as wet, dry, radiation, or sunlit conditions, and the application such as for power or instrumentation. Conductors, made from copper, aluminum, or tin, are relatively insensitive to age and related damage. Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) compose the vast majority of insulation materials in the nuclear industry, with silicone rubber also being of interest. The most significant jacket materials are chlorosulphonated polyethylene (CSPE – also known as Hypalon®, registered trademark of DuPont), polychloroprene, and polyvinyl chloride (PVC). While installed cables with intact insulation may well be able to continue to provide safe operation with degraded jacket material, the tendency of jacketing materials to degrade more readily than insulation materials enables their use as lead indicators for local stress prior to insulation degradation and failure.

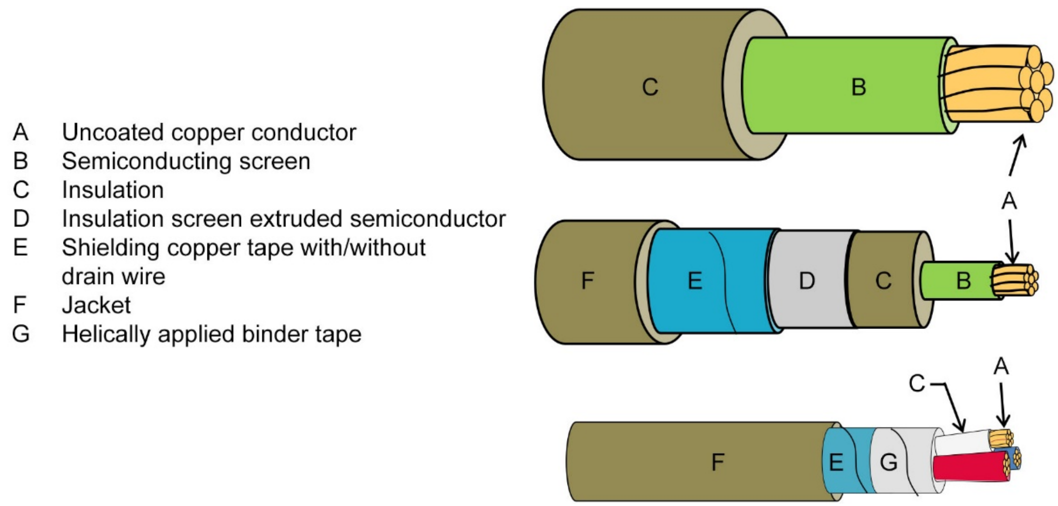


Figure 5.1. Configurations of typical cable designs used in NPPs.

A survey performed by EPRI in the mid-1990s established a representative distribution of insulation materials within the U.S. nuclear fleet (EPRI 1994) (see Table 5.1). Note that over 70 percent of the materials are XLPE or EPR.

Table 5.1. A Sort of Insulation Material for U.S. NPPs (from EPRI 1994)

Insulation Material	Database Entries	Percent of Total (%)	Insulation Material	Database Entries	Percent of Total (%)
XLPE	439	36	ETFE	39	3
EPR	434	36	Flame retardant	36	3
Silicone Rubber	63	5	CSPE	28	2
Kerite	61	5	Butyl rubber	20	2
Polyethylene	52	5	All others		Each ≤ 1%

Numerous standards have been developed over the years to group and categorize cables based on application, voltage, environment, and basic design type (Table 5.2). Exactly what grouping is used depends on the application but for cable aging management, generally the nuclear industry has focused on medium- and low-voltage cables. Low-voltage cables constitute the majority of NPP cables but many safety-critical cables exposed to moisture are medium-voltage cables. Most plants have a rigorous program to test and verify performance of safety-critical medium-voltage cables. Cable CM programs are encouraged through NRC's Draft Regulatory Guide 1240 (NRC 2010) with particular emphasis on medium-voltage cables citing examples of cable failures particularly for wet environment cables. Although this is not currently a required program, it is encouraged by the NRC "*to promote discussion between staff and licensees when a facility's operating experience indicates cable failure or degraded cable performance as a causal factor. The NRC staff will use this guidance to evaluate compliance with the Maintenance Rule*."

Table 5.2. Categories of Cable Grouping

Application	Voltage	Environment	Design
Power Control Instrument Thermocouple Communication Specialty Configuration Safety Related Non-Safety Related	Low (≤2 KV) Medium (≤2–46 KV) High (>46 KV)	Normal operating temperature High temperature Fire/flame retardant High radiation Submerged – water Aggressive solvents	Single/multi-conductor Triplex Thermocouple alloys Coaxial Shielded/unshielded (and shield type – tape, braid, …) Special jacket Conductor/shield material (copper, tinned copper, aluminum, …) Insulation/jacket material (XLPE, EPR, PVC, …)

Cable termination and splice kits also represent sensitive sites for cable system failure. Designs include screw-clamp or crimp-clamp connections between the conductor and the solid metal part of the splice or terminations usually coupled with an insulating shrink-wrap or tape to seal and electrically isolate the metal parts. With respect to wet or dry aging, splices and terminations are expected to have very long lives if they are made in accordance with manufacturers recommended procedures. This means that crimps and bolted connections have been made properly and that the tapes have been properly applied to the correct thickness and with the appropriate tension, or that heat-shrink materials have been properly applied and completely shrunk in place. Given that no voids exist, the splice and termination insulation is thicker than that of the cable and generally has ratings equal to or greater than the cable insulation. Generally when splices or terminations fail, it is because of an installation error. Such errors include inadequate removal of semiconducting layers, cuts to the insulation under the splice, voids from inadequate taping or heat-shrink practices, and/or the presence of dirt in the splice layers. If mechanical metal-metal connections are not made properly, the connections can loosen over time thereby increasing the connection resistance due to vibration and/or corrosion-based contact-force loss. Many of these workmanship-related failures do not occur on initial energization and may take years to manifest themselves in a cable failure.

This aspect of the cable design has been studied and these junctions have been subjected to aging and LOCA performance tests (Lofaro and Villaran 2002) similar to the full tests. In fact, some form of termination must be included in the full cable tests. In addition, these cable terminations are subject to workmanship-based performance issues and are carefully considered as potential failure points during periodic CM activity. As a practical matter, whenever cables need to be de-terminated for testing, new termination kits are frequently applied. Because of the bulk of larger diameter cables and practical reel size limitations, splices may be necessary for long cable runs. The main concern for power connections is that a high-resistance connection does not occur. Infrared (IR)-camera thermographic-aided visual inspections are frequently employed to determine if problems (hot spots) exist. Such overheating can cause the insulation and connection tape or heat-shrink to degrade or the connection to burn open over time.

Cable layout is not designed to facilitate access and inspection of much of the cable lengths. Cable trays and conduits are designed to protect the cables from environmental stresses as well as accidental damage from workers and equipment that may be moving either inside containment, auxiliary buildings, or control buildings. While cable ends are generally accessible at termination boxes and control panels, many cables are grouped together with other cables in trays that do not necessarily follow personnel access pathways, pass through penetration pipes and conduits that may be buried in concrete, underground, or even passing through areas that may be flooded (Figure 5.2).

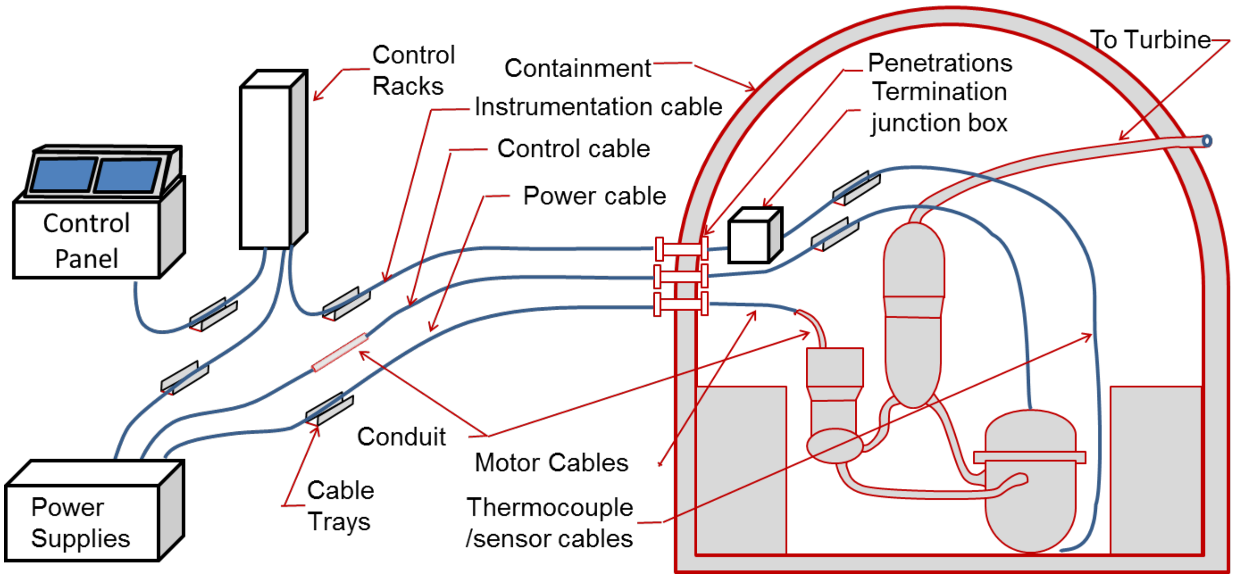


Figure 5.2. Typical cable layout allows access at control racks and termination junction boxes but much of the cable is protected within cable trays and conduit thereby limiting access for local inspections.

6. AGING AND ACCELERATED AGING

Stressors leading to cable degradation can generally be divided into three groups (Lindsay and Benson 2012):

- Environmental: radiation, heat, moisture, chemical, etc.
- Operational: high voltage, electrical transients, ohmic heating, flexing/vibration, mechanical damage, etc.
- Error-induced damage from inappropriate design/selection for the given environmental or operational stressors above, manufacturing, or maintenance deficiencies.

When CM techniques are being applied to evaluate cable condition, consideration of the stressors can be important to point out where to look and what to look for, but the tests are sensitive to changes in the cable material characteristics. These changes can generally be considered as follows:

- Various insulation and jacket polymers (XLPE, EPR, PVC) subject to elevated temperature and/or radiation are prone to embrittlement, cracking, decrease in dielectric strength, increased leakage current, reduction in structural integrity, and susceptibility to intrusion of moisture or contaminants.
- PVCs (mostly related to jackets) are also subject to hydrogen chloride (HCl) evolution and salt formation resulting in wet environments that can reduce dielectric strength and increase leakage currents. Because PVCs are rarely used for insulation however, this may be only a cosmetic issue limited to the jacket.
- Various insulation and jacket polymers are also subject to wetting and moisture intrusion in the form of "water trees" resulting in decreased dielectric strength and increased leakage currents.
- Copper conductors subjected to wetting may experience corrosion resulting in increased electrical resistance and corresponding ohmic heating that may accentuate the corrosion process.
- Various insulation and jacket polymers are subject to handling, physical contact abuse during maintenance, operation, or testing that may result in crushing, cracking, scuffing, cutting, bending deformation, etc. and may result in visually observed damage, reduced dielectric strength, and increased leakage current.

PNNL has developed (Glass et al. 2015):

- extensive capabilities for controlled accelerated aging of cable samples
- laboratory measurements of cable and particularly insulation characteristics, and
- a collection of laboratory and in-situ techniques that may be applied to cable CM assessment.

The principal concerns for adverse environments experienced by polymer-insulated/jacketed electrical cables in the NPPs are elevated temperature, gamma radiation exposure, and the presence of moisture or other chemical environmental stress. Typical NPP temperatures and dose environments allow the cable to operate for 40+ years before material degradation is of sufficient concern to warrant specific tests and repair or replacement if necessary. Because it is not practical to wait 40+ years for suitably aged samples, the ability to accelerate aging is essential to the program. A series of aging ovens has been acquired with room to house either racks of samples inside or support pass-through intact cables. In addition, PNNL has a Co-60 gamma radiation facility that can subject samples to up to 1 kGy/hr. The facility can also combine the ovens and the radiation test source for combined thermal and radiation aging. The capability to specify both temperature and dose rate during sample enables PNNL to address knowledge gaps in the understanding of degradation from combined exposure including synergistic effects and inverse temperature effects. These facilities have been used to generate the representative aged samples where PNNL and PNNL collaborators have performed verification or demonstration CM measurements.

7. LOCAL MEASUREMENTS

7.1 General Discussion

Bulk electrical measurements examine the entire cable and in some cases, as with frequency domain reflectometry (FDR) and time domain reflectometry (TDR), can identify the location of cable anomalies including insulation weaknesses. Evaluation of the actual area of weak or degraded insulation requires local measurements. In many cases, the location of the weakness is not readily available or must be inferred from a priori knowledge of the cable environment (proximity to hot pipes or vessels, exposure to high radiation sources, moisture or chemical exposure, tight bend radius within cable tray, cable hanger support, etc.). Much can be learned from careful observation of cable jackets and insulation through careful informed walk-downs of the visibly accessible areas. Plant operators and EPRI have developed training modules that emphasize what to look for and where to look for cable damage as part of their aging cable management programs (low-voltage training).[a] Qualitative indications of cable degradation, however, are insufficient for many NPP programs where a quantitative indication of cable condition is desired. Local measures of cable condition include the following methods (Table 7.1), each of which is discussed in more detail in subsequent sections.

Table 7.1. Available Common Techniques for Local Cable Inspection/Monitoring

Method	Advantage	Disadvantage
Visual walk-downs	Simple and low cost	Not quantitative
IR thermography	Easily implemented at distance Quantitative	Sensitive to specific component load Requires line of sight view
IR/NIR spectroscopy	Sensitive to chemical changes on the jacket and outer surface	May over-predict jacket or surface damage not indicative of full volume condition. Also sensitive to surface condition.
Indenter	Simple test that is broadly accepted	Does not work well for harder cables like XLPE
Dynamic mechanical analysis (DMA)	Promising and potential for broader application than indenter	Although it could be adapted to in-situ test, currently a laboratory approach
Interdigital capacitance	Promising and seems to have broad application	Not fully commercial
Ultrasound velocity	Works well for some materials, particularly jacket materials	Not easily adapted to in-situ field measurement and does not work well for some materials
Distributed Fiber Optic Temperature Sensing	Could be an easy test as a leading indicator of damage	Difficulty to retroactively install in existing cable systems

Advantages and disadvantages of local tests vs. bulk electrical tests include:

- Local tests address specific locations.
- Cables may not need to be disconnected to perform the test.
- Low-voltage cables may not need to be de-energized to perform tests although many plants may have administrative protocols that require de-energization for any test that requires the cable to be manipulated. (Note—all medium-voltage cables should be de-energized before any tests requiring manipulation.)

(a) http://www.cvent.com/events/low-voltage-cable-aging-management-training/event-summary-929b0753ee1a4613a0923cf10877c643.aspx

- If the cable-damaged area is accessible and confirmed, the cable may be suitable for a local splice/repair.

Disadvantages include:

- If test is to be nondestructive, the test must only touch the exterior cable layer (usually overwrapping jacket) and must assess insulation and jacket together.
- Knowing the most degraded location of a cable is challenging in most field situations because a large percentage of the cable is not easily accessible.
- Many mechanical tests are highly temperature-dependent.

One of the principal goals of this report is the qualitative assessment of the various test methods. The following criteria were applied to each of the methods and overall results are summarized

- **Ease/Cost of implementation:** Is it practical or could it be practical to deploy such a test in a power-plant environment and is or could the cost of the test be favorable compared to alternatives? Alternatives may be other tests or cable replacement. + = generally practical to implement and for relatively low cost. N = neutral: probably possible to implement cost competitively. – = unlikely to be cost-competitively field deployable.
- **Commercially available:** Can instruments or service contracts be purchased now? + = currently available. N = neutral: known commercial entities are actively exploring commercialization. – = no known current activity to commercialize.
- **Measurement correlation:** Does the measurement correlate with EAB or other age-related parameters? + = good correlation with EAB for a high percentage of components. N = neutral: correlation for some materials. – = weak correlation for most materials.
- **Quantitative measurement:** Can acceptance criteria be established such that it is possible to disposition a cable as good, marginal/needs further study, or definitely bad by comparing to existing guidelines/thresholds or guidelines/thresholds that could be established? + = yes and guidelines or thresholds are available. N = neutral: thresholds could likely be established but this work has not yet been done. – = only qualitative results are likely from this technique that will be difficult to use for cable dispositioning.
- **Additional R&D:** Are there major technical gaps that currently preclude the measurement approach from being fielded. + = little or no additional work needed for implementation or continued implementation. – = significant additional R&D needed for field implementation. Where possible, specific suggested additional work is noted.

7.2 Visual Observation

One of the primary methods for cable inspection is a plant walk-down and visual inspection. It may be difficult to view a high percentage of the cables length because of the practice of running cables in trays and conduit where they are protected from accidental damage and therefore difficult to view. Such viewing and inspections may be aided by:

- Pole-mounted or drone-mounted video cameras providing viewing access without ladders or scaffolding
- Consideration of severe environment areas along cable run (thermal hot spots, high radiation areas, moisture areas, areas where maintenance has occurred and potentially damaged cable, areas where splices have previously been made, locations of tight bends, etc.)
- IR cameras can illuminate cable insulation hot-spots and areas subject to closer investigation

- FDR and TDR measurements that can localize regions of the cable run to pay particular attention to.

Visual inspections only allow evaluation of the cable outside surface. This largely limits viewing to the cable jackets, which may be made of different material than the primary insulation (like Hypalon or PVC) that are known to be more susceptible to thermal, radiation, and moisture damage than the most common insulations such as XLPE and EPR. Cable jackets are known to discolor in response to thermal and radiation stresses. This is most observable with yellow or other light-colored jacketed cables and color change can serve as a leading indicator of insulation damage. Interpretation of discoloration and/or cracking of cable jackets, however, should be made with consideration of the actual jacket material with appreciation that insulation damage may not be as severe as the jacket damage may indicate.

Guidance for visual walk-downs is provided in numerous industry and vendor training materials. One resource with a rich collection of images that teach what to look for is the EPRI cable harvesting guideline,[a] as well as the EPRI courses on low-voltage[b] and medium-voltage cable aging management.[c] Additional images were requested from utility and cable inspection vendors as examples of noteworthy visual inspection observations. Example images are shown in Figures 7.1 through 7.23.

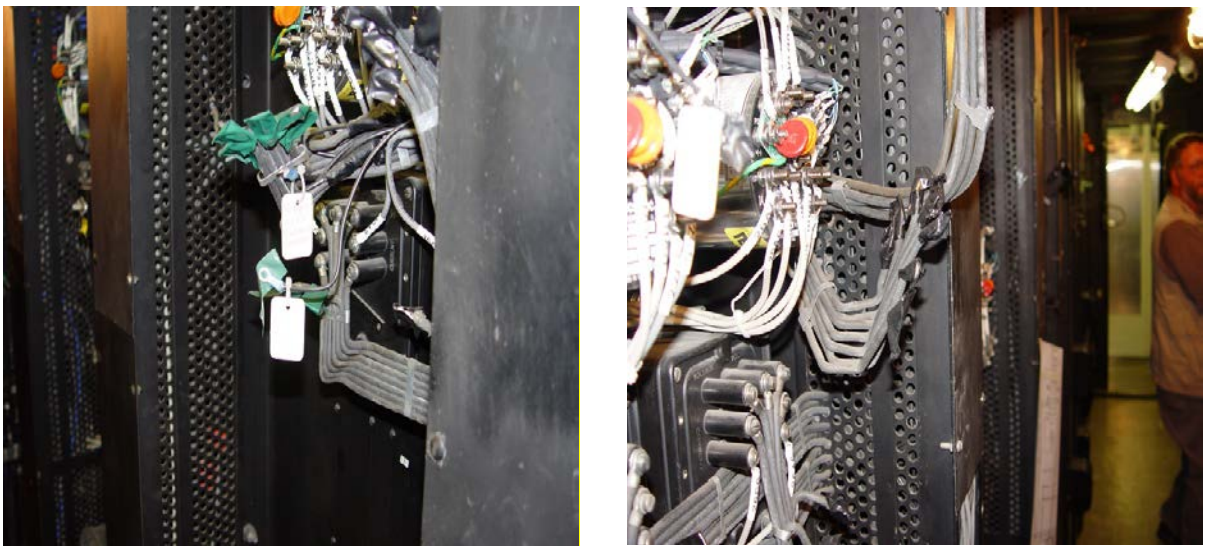


Figure 7.1. Abandoned cable ends. Photos courtesy of EPRI.

(a) EPRI. 2015. *Cable Harvesting Guide*._Electric Power Research Institute. Palo Alto, California. Available at http://cableharvest.epri.com/ (last updated March 2015). You must be an EPRI member to access this website.

(b) http://www.cvent.com/events/low-voltage-cable-aging-management-training/event-summary-929b0753ee1a4613a0923cf10877c643.aspx

(c) http://www.cvent.com/events/epri-medium-voltage-cable-course-university-of-wisconsin-/event-summary-2a91a43d9c5344cfbfe42d6692d64e63.aspx

Figure 7.2. Full cable trays can make extraction of a single cable difficult and subject adjacent cables to damage. Photo courtesy of EPRI.

Figure 7.3. Cracked butyl jacket. Photo courtesy of EPRI.

Figure 7.4. Cable contact along sharp edge. Photo courtesy of EPRI.

Figure 7.5. Severely bent cable. Photo courtesy of EPRI.

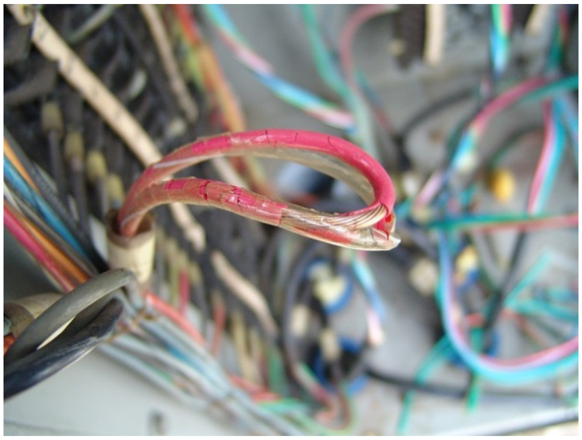


Figure 7.6. Cracks in jacket and insulation. Photo courtesy of EPRI.

Figure 7.7. Unsupported cables outside of tray. Photo courtesy of EPRI.

Figure 7.8. Excess cable tie tension. Photo courtesy of EPRI.

Figure 7.9. Kinked conductors. Photo courtesy of EPRI.

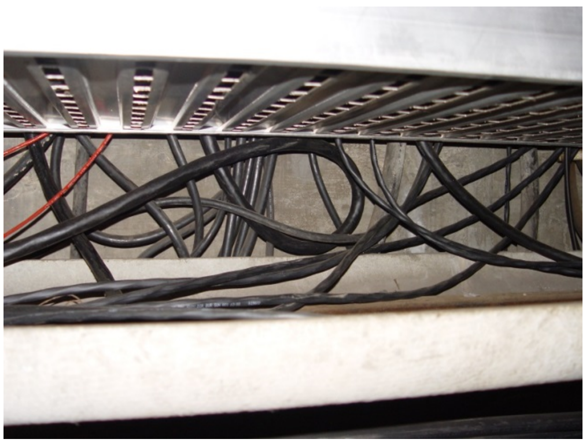


Figure 7.10. Tight bend radius. Photo courtesy of EPRI.

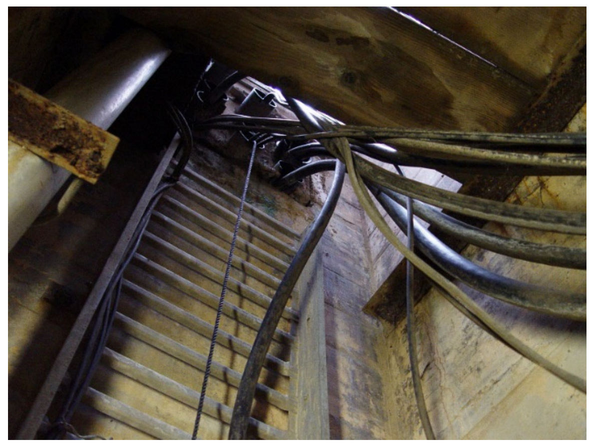


Figure 7.11. Poorly supported vertical runs. Photo courtesy of EPRI.

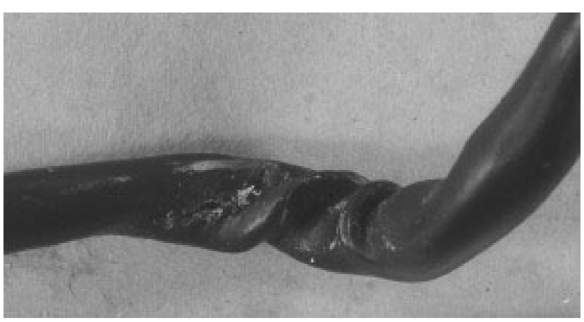


Figure 7.12. Pull-in twist. Photo courtesy of EPRI.

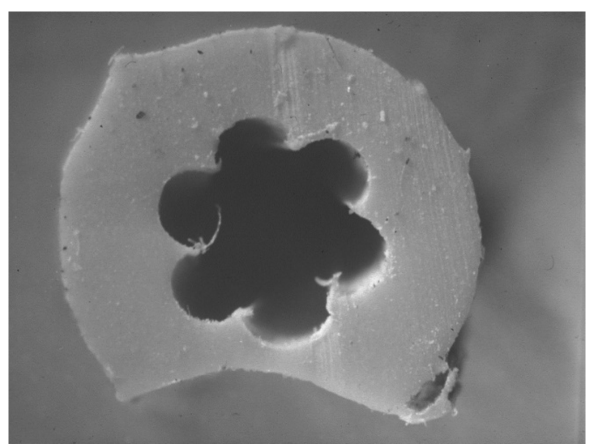


Figure 7.13. Pull rope burn. Photo courtesy of EPRI.

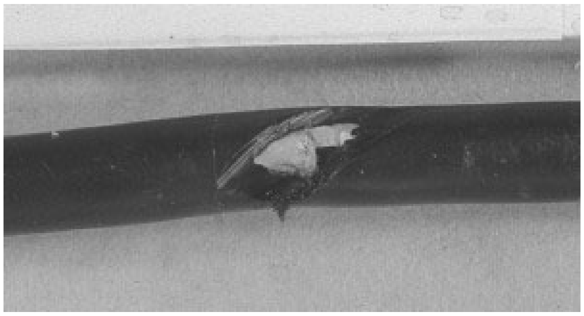


Figure 7.14.Sharp edge pull-over. Photo courtesy of EPRI.

Figure 7.15.Cable ties constricting jacket and insulation. Photo courtesy of EPRI.

Figure 7.16.Twisted cable. Photo courtesy of EPRI.

Figure 7.17.Contacting conduit edge. Photo courtesy of EPRI.

Figure 7.18.Cable short – exposed conductor. Photo courtesy of EPRI.

Figure 7.19.Contact with broken bushing. Photo courtesy of EPRI.

Figure 7.20. Very bent conduit entering a fitting near condensate polishing mixing bed service.

Figure 7.21. Ripped seal-tight on conduit on RCB chiller.

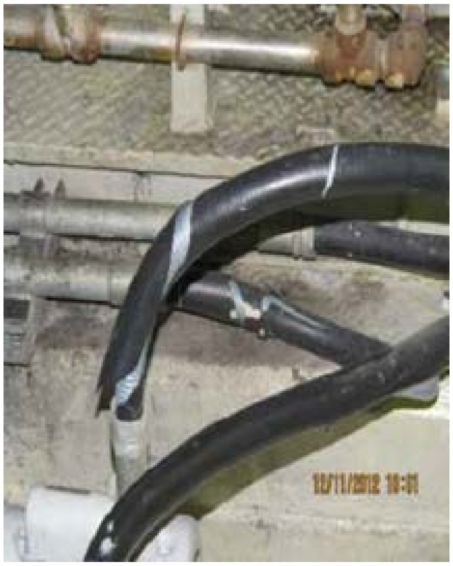


Figure 7.22. Ripped seal-tight on conduit near polyacrylic acid supply tank.

Figure 7.23. Bird feces on cables in trays.

Plant walk-downs will continue to be one of the most widely employed approaches to assess cable condition. Its weaknesses include difficulty of viewing a high percentage of cables and the inherent qualitative nature of the approach. As computer image comparison methods become more common-place, some quantitative comparisons of current vs. reference original images may become more common but this will likely still fall short of definitive guidance for dispositioning a cable except perhaps to flag the cable location for scrutiny or additional tests. The visual qualitative tabular assessment is shown in Table 7.2.

Table 7.2. Qualitative Relative Assessment of Cable Visual Assessment through Plant Walk-Downs.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Visual walk-downs	+	+	N	– (1)	+	1
Comment 1: Although visual tests are not quantitative, digital images may be archived and checked for subtle indications of degradation or worsening of conditions. IR camera images are quantitative but only for temperature, which is not directly relatable to insulation damage. Technology to enhance computer-based image comparisons is expected to mature and advance during the next decade.						

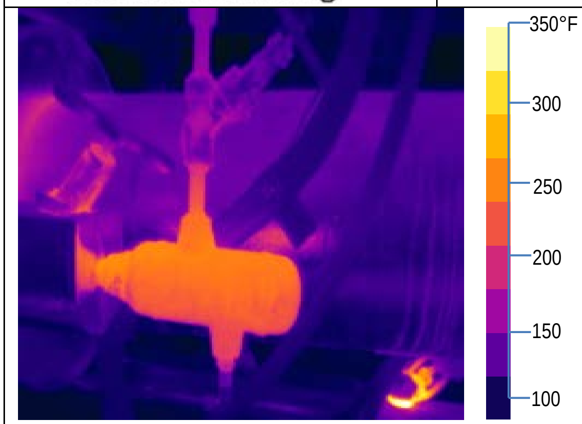
7.3 Infrared Thermography

Infrared thermography can be used as a supplemental tool to support plant walk-downs. Although IR thermography is often listed as a CM technique, this is not entirely accurate. IR thermography does not provide a direct indication of cable condition (resistance, capacitance, insulation integrity, etc.); however, it may be used to screen the cable environment and identify hot spots that may accelerate cable aging effects and locate regions for additional local inspection. Thus, IR thermography may be claimed as part of the overall CM program of the cable AMP. It is a nondestructive, nonintrusive tool that can be practically incorporated into the cable program because most plants already have a thermography program to monitor many aspects of the plant including transformers, motors, and valves. Reasonably priced portable IR cameras are available that are accurate and repeatable to fractions of a degree. Particular concerns include power cable splices and terminations, which may be subject to ohmic heating, plus adjacent heat sources such as steam lines and motors that may raise ambient temperatures. Ohmic heating can also raise the temperature of the cable itself. It is important that cables are energized and heat sources are in their "hot" condition for these types of surveys to be meaningful. As with other structured nuclear plant programs, measurements should be planned and performed such that images are stored for comparison with historical data (Figure 7.24). Examples of IR images are shown in Figures 7.25 through 7.33.

3JMTNHV0329C**MOTORX	03-E-MTF-0014, s3	3E-MT14-NC-3KA	3/C #10	839	90°C
		3E-MT14-NC-3RA	12/C #14	A87	90°C
3JEDNLSH0880**IBISSW	03-E-EDF-0008, s3	3E-ED08-NC-2RF	1/C #12	B18	200°C
3JEDNLSH0860**IBISSW	03-E-EDF-0008, s3	3E-ED08-NC-2RH	1/C #12	B18	200°C
3JMTNLSH0379A**IBISSW	03-E-MTF-0035, s1	3E-MT35-NC-1RP	1/C #12	B18	200°C
3JMTNLSH0379B**IBISSW	03-E-MTF-0035, s1	3E-MT35-NC-1RQ	1/C #12	B18	200°C
3JMTNLSH0379C**IBISSW	03-E-MTF-0035, s1	3E-MT35-NC-1RR	1/C #12	B18	200°C
3JMTNHV0327H**MOTORX	03-E-MTF-0013, s8	3E-MT13-NC-8KA	3/C #10	839	90°C
		3E-MT13-NC-8RA	12/C #14	A87	90°C
3JMTNPV0352**VALVOP	03-E-MTF-0011, s6	3E-MT11-NC-8RA	2/C #16 S	CE6	90°C
3JMTNUV0330D**MOTORX	03-E-MTF-0011, s4	3E-MT11-NC-4KA	3/C #10	839	90°C
		3E-MT11-NC-4RA	12/C #14	A87	90°C
3JMTNHV0327G**MOTORX	03-E-MTF-0013, s7	3E-MT13-NC-7KA	3/C #10	839	90°C
		3E-MT13-NC-7RA	12/C #14	A87	90°C
3JMTNUV0328D**MOTORX	03-E-MTF-0013, s8	3E-MT15-NC-4KA	3/C #10	839	90°C
		3E-MT15-NC-4RA	12/C #14	A87	90°C
		3E-MT15-NC-4RD	4/C #14	A47	90°C
		3E-MT15-NC-4RE	2/C #16 S	CE6	90°C
3JMTNHV0329D**MOTORX	03-E-MTF-0014, s4	3E-MT14-NC-4KA	3/C #10	839	90°C
		3E-MT14-NC-4RA	12/C #14	A87	90°C
3JMTNLSH0235B**IBISSW	03-E-MTF-0035, s1	3E-MT35-NC-1RJ	1/C #12	B18	200°C
3JMTNTE0237**IXMITR	03-MTB-0037	3E-MT37-NC-2YE	2/C #16 S	FE6	90°C
3JMTNHV0327C**MOTORX	03-E-MTF-0013, s3	3E-MT13-NC-3KA	3/C #10	839	90°C
		3E-MT13-NC-3RA	12/C #14	A87	90°C
3JMTNHV0327D**MOTORX	03-E-MTF-0013, s4	3E-MT13-NC-4KA	3/C #10	839	90°C
		3E-MT13-NC-4RA	12/C #14	A87	90°C
3JMTNHV0329B**MOTORX	03-E-MTF-0014, s2	3E-MT14-NC-2KA	3/C #10	839	90°C
		3E-MT14-NC-2RA	12/C #14	A87	90°C

Figure 7.24. IR thermography inspection plan and database courtesy of Palo Verde Nuclear Station.

U3 TB 176 FT	Work Order ALE Walkdown	Thermographer: Dan Obrien
Component Name (If Necessary):		
Condensing Pot for 3JMTNFT0337**IXMITR (Iso. Vlv. 3PMTNV136 on left)		



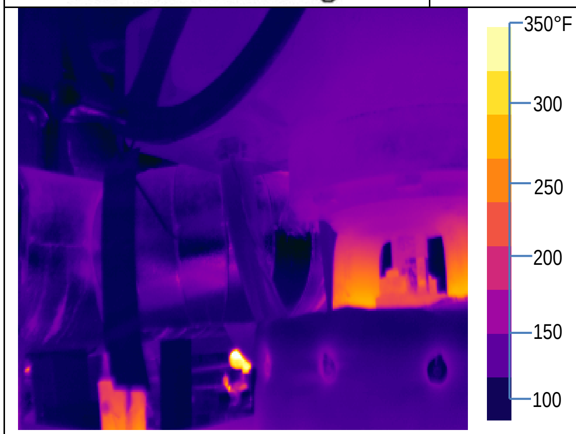
Emissivity	0.95
Ar1 Max. Temperature	269.8°F
Ar2 Max. Temperature	151.5°F
Ar3 Max. Temperature	122.6°F

Date	1/26/2016
Image Time	2:47:45 PM
File Name	FLIR0905.jpg
Image Camera Type	FLIR T450 sc
Image Camera Lens	FOL10

Comments:
Thermal Adverse Local Environment (ALE) – Flex conduit temperatures exceed 150 Deg. F.
Reference Dwg. -03-E-EDF-0005,sh.3

Figure 7.25.Example thermal IR image from plant cable walk-down noting flex conduit temperatures exceeding 150°F. Courtesy of Palo Verde Nuclear Station.

U3 TB 176 FT	Work Order ALE Walkdown	Thermographer: Dan Obrien
Component Name (If Necessary):		
3JMTNHV0329C**MOTORX		



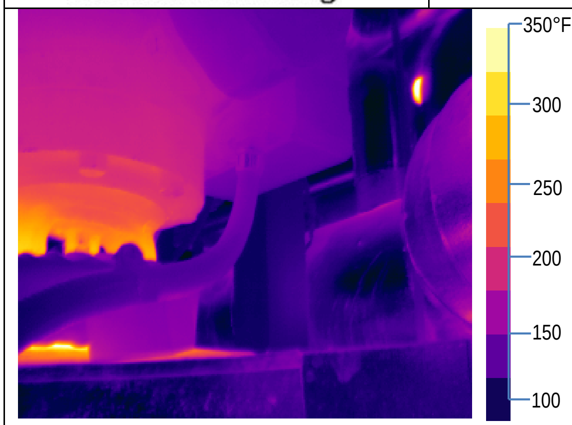
Emissivity	0.95
Ar1 Max. Temperature	275.3°F
Ar2 Max. Temperature	147.1°F
Ar3 Max. Temperature	154.8°F

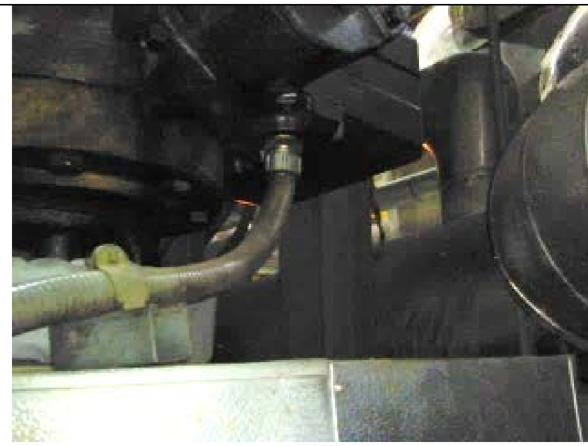
Date	1/26/2016
Image Time	2:47:45 PM
File Name	FLIR0905.jpg
Image Camera Type	FLIR T450 sc
Image Camera Lens	FOL10

Comments:
Thermal Adverse Local Environment (ALE) –
Component housing temperatures exceed 150 Deg. F.
Location Drawing - 13-E-ZTC-0026

Figure 7.26.Thermal adverse local environment (ALE) – component housing. Temperatures exceed 150°F. Courtesy of Palo Verde Nuclear Station.

PALO VERDE Condition Monitoring	U3 TB 176 FT	Work Order ALE Walkdown	Thermographer: Dan Obrien
	Component Name (If Necessary):		
	3JMTNHV0329B**MOTORX		





Emissivity	0.95
Ar1 Max. Temperature	156.9°F
Ar2 Max. Temperature	156.2°F

Date	7/29/2015
Image Time	10:13:06 AM
File Name	FLIR0673.jpg
Image Camera Type	FLIR T450 sc
Image Camera Lens	FOL10

Comments:
Thermal Adverse Local Environment (ALE) – Flex conduit temperatures exceed 150 Deg. F.
Location Drawing - 13-E-ZTC-0025

Figure 7.27.Thermal ALE – flex conduit temperatures exceed 150°F. Courtesy of Palo Verde Nuclear Station.

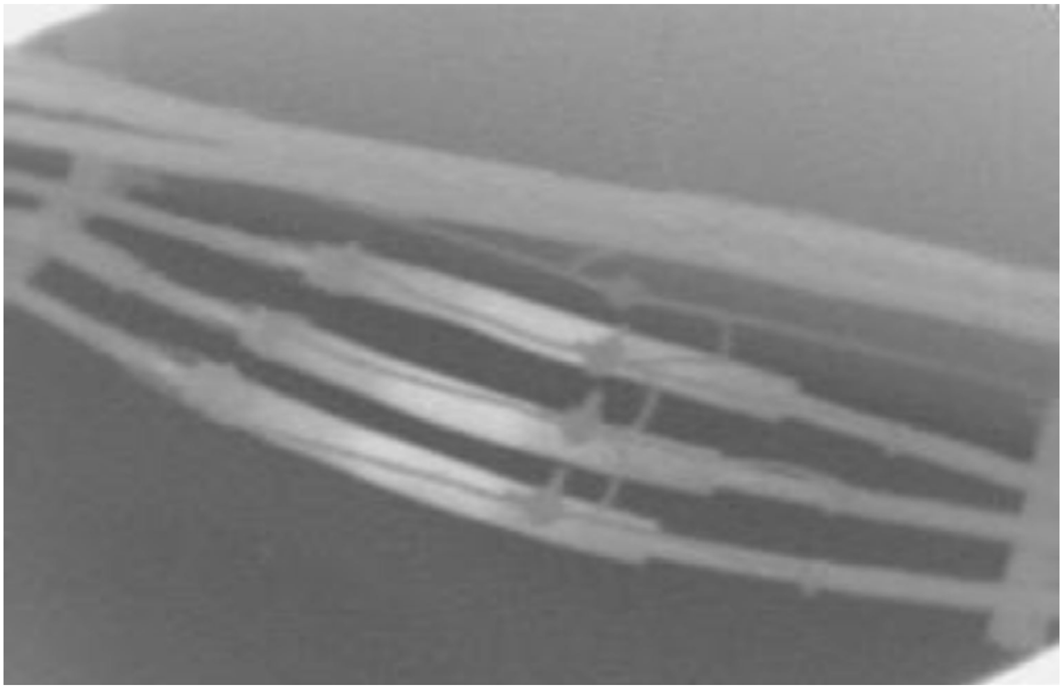


Figure 7.28.IR image – joints with hot cable connectors. Image courtesy of and credited to © Hydro-Québec.

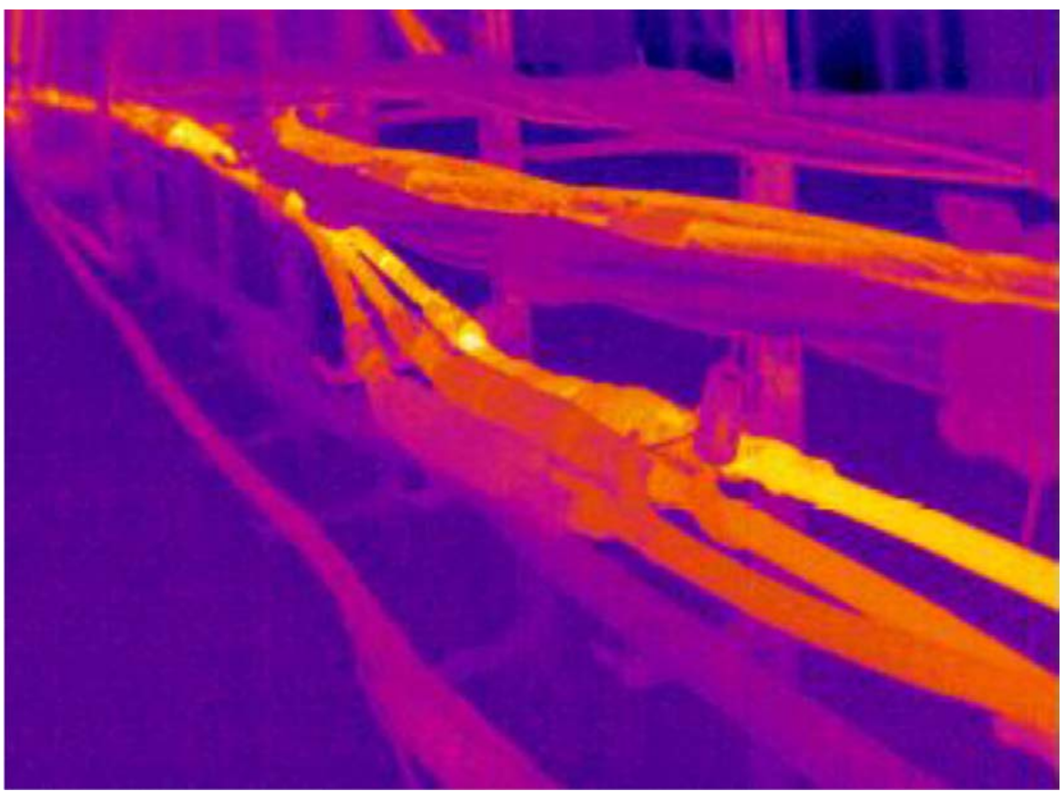


Figure 7.29.IR image – One cable and joint hotter than adjacent cables. Image courtesy of and credited to © Hydro-Québec.

Figure 7.30.IR image – Hot spot in the bulk of insulation of a joint body (pattern 1). Image courtesy of and credited to © Hydro-Québec.

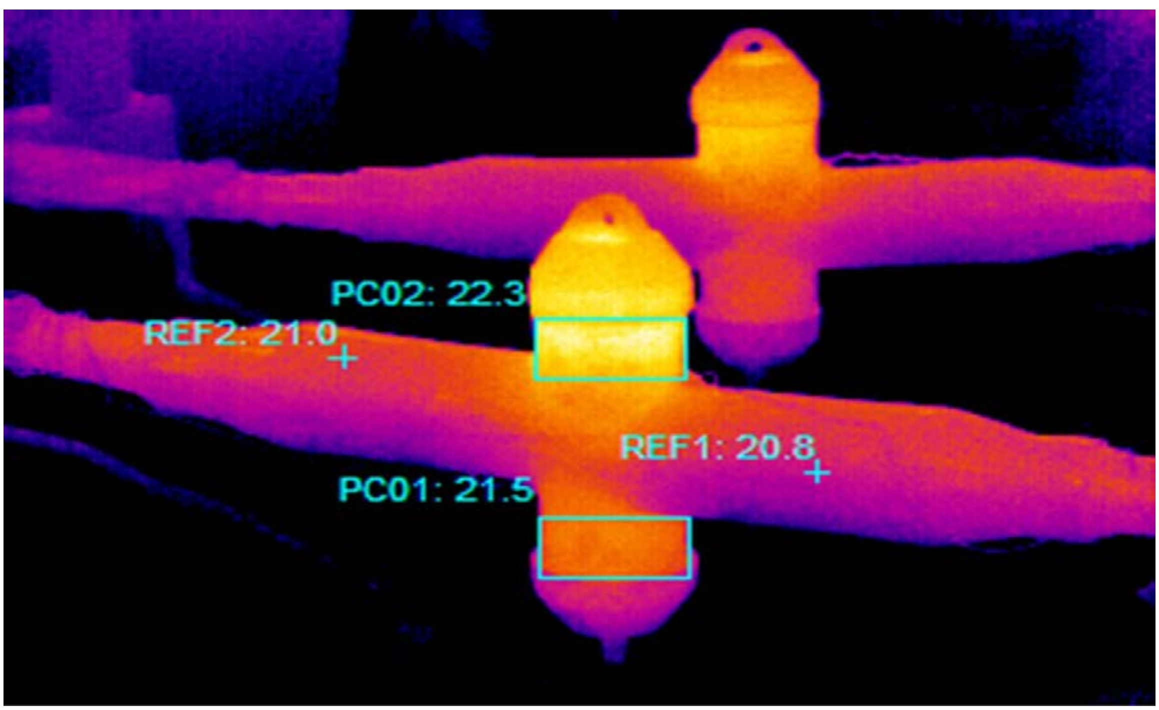


Figure 7.31. IR image – Hot spot in the bulk of insulation of a joint body (pattern 2). Image courtesy of and credited to © Hydro-Québec.

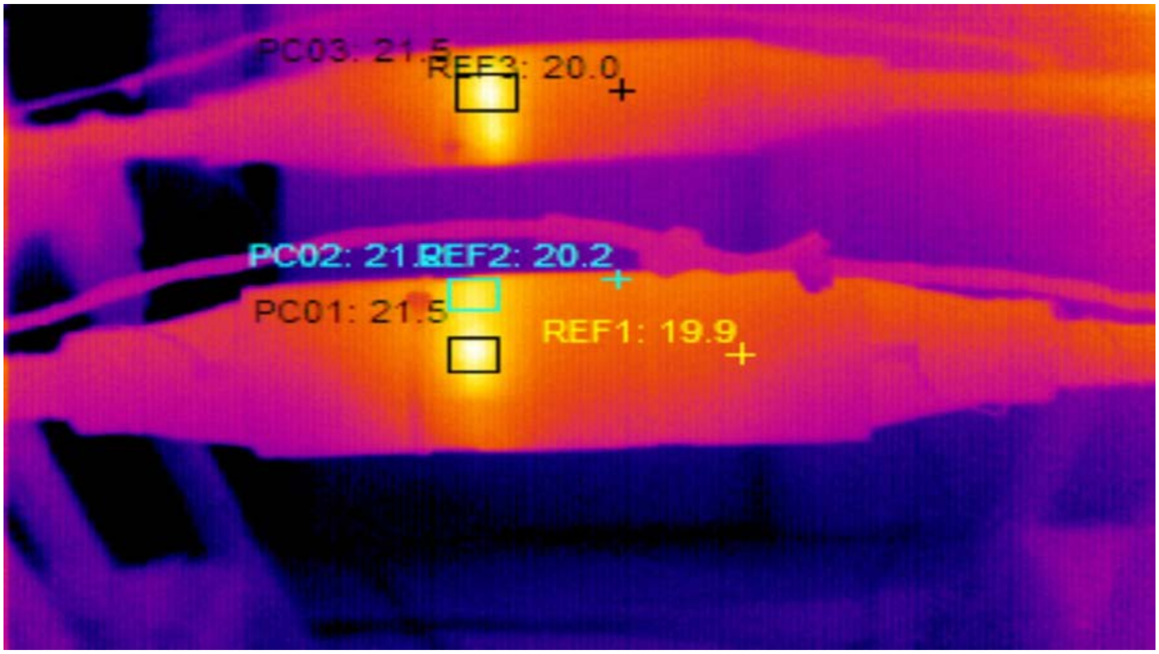


Figure 7.32. IR image – Hot spot in the bulk of insulation located at center of a cable splice. Image courtesy of and credited to © Hydro-Québec.

Figure 7.33. IR image – Hot spot in the bulk of insulation located on left side of cable splice. Image courtesy of and credited to © Hydro-Québec.

More and more plants will probably incorporate IR images into their cable AMP as the technology becomes more widely available and if this becomes part of specific guidance for cable AMP programs. Clear and notable weaknesses of relying on an IR inspection for cables is that many cable areas are not man-accessible during at-power operation when temperatures are of concern. A qualitative assessment of an IR camera supplement is provided in Table 7.3.

Table 7.3. Qualitative Relative Assessment of Cable IR Thermography Inspections

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
IR camera	N (2)	+	–	N (2)	+	2
Comment 2: IR cameras can measure temperature at the time the image is captured. Many cable locations—particularly inside nuclear containments however—are not man-accessible during operation when the bulk of the cables exposure to elevated temperature occurs. Permanently installed IR camera arrays or robotically piloted IR cameras could address this issue in future plants, but this is currently not being actively investigated.						

7.4 Indenter

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 general concept is addressed in an IEC/IEEE international standard (IEC/IEEE 62582-2 2011). Largely due to ease of use and positive reviews by the IAEA (2012) and EPRI (2005), an indenter instrument commercially distributed by a U.S. firm (AMS 2013) has become a broadly accepted industry standard test for cable aging that correlates well with EAB for many materials (Figure 7.34). This indenter is a portable instrument that can readily be taken into NPPs for in-situ local measurements of the cable jacket and insulation combined. The compression indenter modulus (σ) is simply a ratio of the change in force (ΔF) divided by the displacement (ΔX) where the displacement of the instrument probe is delivered at a carefully controlled speed (typically 5.08 mm/min.).

$$\sigma = \frac{\Delta F}{\Delta X} \tag{1}$$

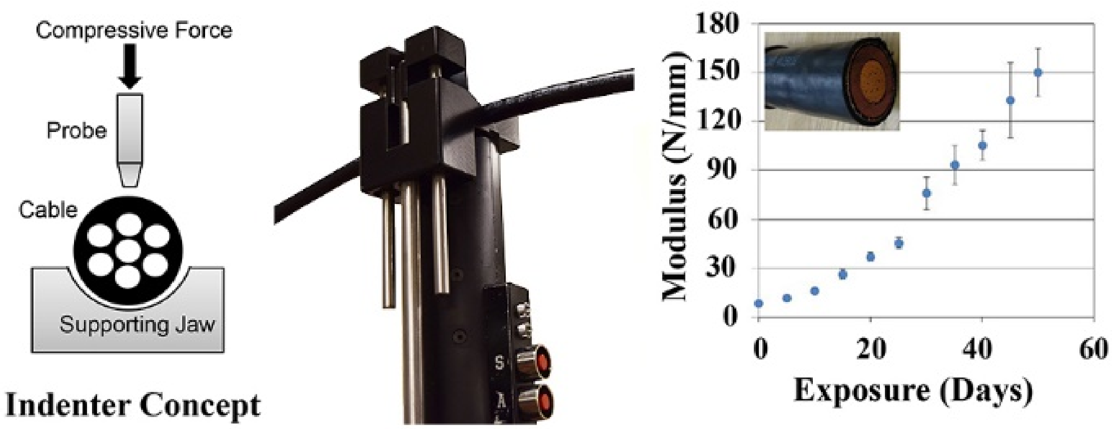


Figure 7.34. Probe, supporting jaw, and cable cross-section (*left*), instrument photo (*center*), and EPR cable modulus vs. exposure time (*right*).

Care must be taken when using the indenter measurement to compensate for temperature changes if the room is not at nominal room temperature (20°C). Compensation approaches are discussed in the IEEE standard and in the user's guide for measurements significantly different from the nominal room temperature reference. Variability of measurements as a function of circumferential and axial position are also of concern. The recommended measurement sequence calls for at least nine measurements around the circumference and along the axis where the high and low values are discarded and the recorded elastic modulus is the average of the remaining values. This measurement produces a simple value that can be evaluated against reference values for new and aged material. Typical programs, however, include logging of the indenter modulus values for trending analysis.

The indenter is also significantly more sensitive to the jacket condition than to underlying insulation. Frequently nondestructive access to the jacket-covered insulation is impractical. Thus, if the jacket is significantly degraded and hardened but the jacket is a different material than the underlying insulation, the underlying insulation may be in a significantly different condition than data from an indenter test of the outer jacket may indicate.

For most cable materials and particularly softer materials such as EPR, silicone rubber, and Hypalon jacket materials, the indenter modulus increases with aging and correlates well with changes in EAB (Figure 7.35). The method is less appropriate, however, for harder materials such as XLPE, some PVC formulations, or polyethylene that show smaller change in modulus with aging (IAEA 2012) or do not change significantly until the EAB is significantly degraded (EPRI 2011).

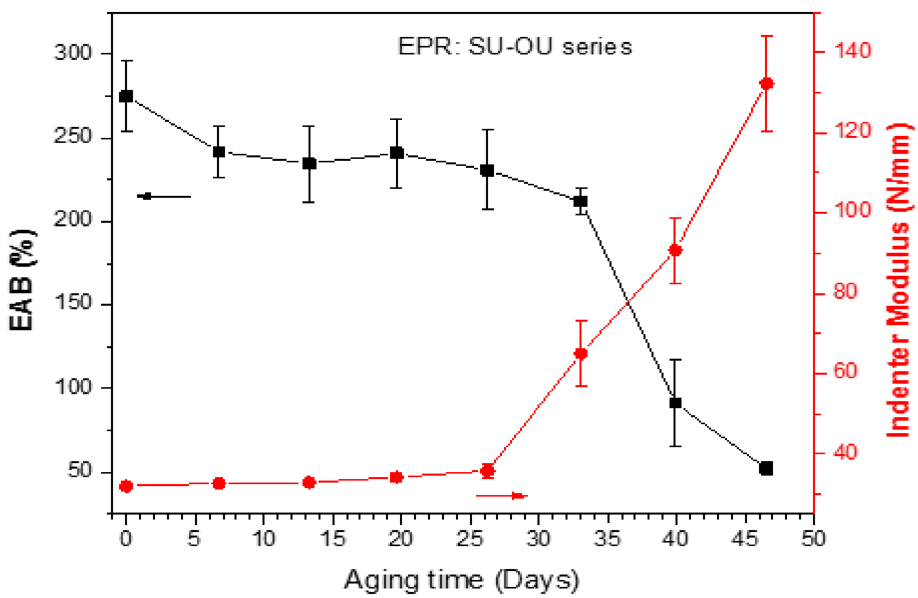


Figure 7.35.Typical EPR cable showing indenter modulus and %EAB with 1 standard deviation error bars. Note that the inflection point of both %EAB and indenter modulus occurs at the 25–30 day point, and thereafter both slope absolute values increase. Also note that %EAB is referenced to the initial sample length, not the unaged EAB.

The EPRI/AMS indenter also includes a feature and instructions for measuring a force relaxation constant (K) as defined by:

$$K = \frac{t_1 - t_2}{\ln\left(F_1/F_2\right)} \tag{2}$$

where: K = Force relaxation constant
t_1 = Time 1 (typically set at 2 seconds)
t_2 = Time 2 (typically set at 5 seconds)
F_1 = Force at t_1
F_2 = Force at t_2

The indenter probe is driven to a predetermined force limit where it is held at a fixed position for a period of time (typically 2 seconds) to allow the force to start to stabilize and this force (F_1) is recorded.

With time (typically 3 seconds later), the material relaxes further and a second force (F_2) is recorded. The relaxation constant K is then calculated as in Eq. (2). The force relaxation constant (K) is rarely reported or recorded compared to the indenter modulus (σ), but this option was exercised for one EPR sample to compare σ, K, and %EAB (Figure 7.36). As in Figure 7.35, the indenter modulus σ corresponds to the inverse of the EAB%. The relaxation constant K starts to match the %EAB except for the last value where %EAB is degraded to ~20% of the unaged value yet K reverses it's trend upward thereby degrading it's correlation with EAB.

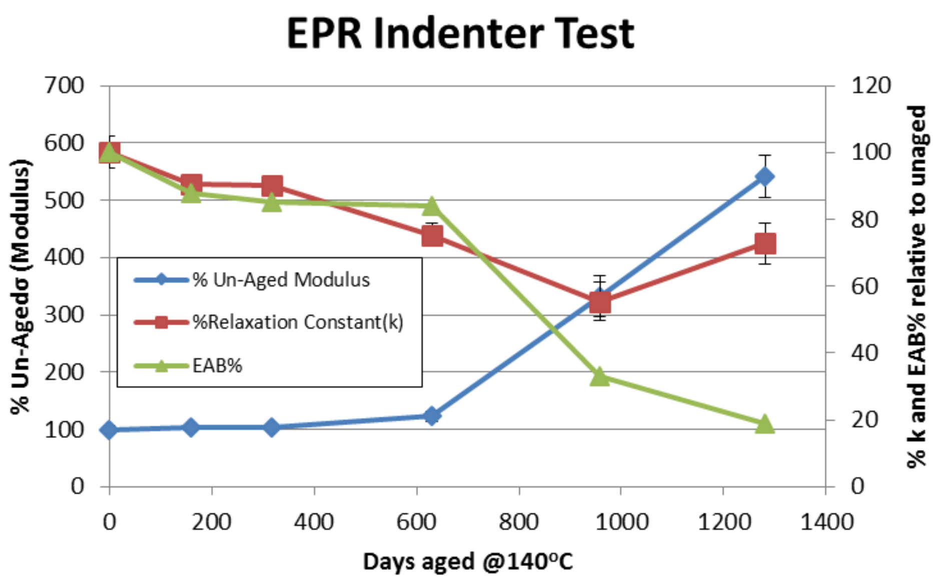


Figure 7.36. Normalized indenter modulus (left axis), plus relaxation constant (k) and %EAB all normalized to the unaged values; i.e., each data point at 0 days =100%.

The overall assessment of the indenter technology applied to indenter modulus is shown in Table 7.4. Indenter modulus is the most commonly applied local test behind the visual inspection walk-downs. Although some materials demonstrate age-related affects earlier and more strongly than others, indenter modulus has been broadly demonstrated to generally correlate to cable aging. This is well documented in numerous cable studies so the value of additional corroboration research may add little to the indenter knowledge base. Indenter is expected to continue to be an important technique for cable assessment until improved techniques are identified and demonstrated.

Table 7.4. Qualitative Relative Assessment of Cable Indenter Test.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Indenter	+	+	+	+	+	3
Comment 3: Indenter is the most widely used local test technique. Practically, its primary drawback is that for jacketed insulation; nondestructive access is only available to the jacket.						

7.5 Recovery Time Indenter

The EPRI indenter primarily focuses on the compressive indenter modulus. More recently, research by Canadian Nuclear Laboratories – Chalk River has been published indicating that the recovery time of an "indented" cable jacket and insulation material is indicative of the viscous behavior of indented viscoelastic materials and provides additional information that correlates better to EAB cable aging than simple compression modulus data (Guerout and Boor 2015). A test instrument has been developed and is under license to SNC-Lavalin. The measurement sequence includes three phases—indentation, force relaxation, and recovery (Figure 7.37). The indentation phase compresses the cable as with the EPRI indenter and the compression modulus is measured similarly based on the Δ Force/Δ Position feedback. The force relaxation phase consists of holding the indenter at the maximum depth reached at the end of the indentation phase. The reaction force typically peaks immediately upon completion of the indentation phase then decreases over time. This maximum depth position is held for 60 seconds to allow for relaxation of a large portion of the force initially generated. This phase is a conditioning step prior to the deformation recovery phase that occurs upon rapid retraction of the probe tip. The recovery phase starts with rapid indenter probe retraction—typically 50%–90% of the indentation depth (depending on the material tested) and measures the time required for the cable viscoelastic material to catch up to and contact the probe tip. At this point in time, a force is again detected by the load cell. This time interval is defined as the polymer deformation recovery time. At the time of this publication, the recovery time indenter is not commercially available; however, a commercial version of the tool is under development at SNC-Lavalin.

To evaluate the relative performance of recovery time (RT) compared to indentation modulus (S), and EAB, the measured and normalized terms of EAB/EAB(0), S/S(0), and RT/RT(0) were plotted. Generally the recovery times showed a stronger response to aging and closer correlation to EAB than the indentation modulus. An example of this response is shown (Figure 7.38) below for irradiated XLPE insulation. This is a material with a notoriously weak age vs. indenter response.

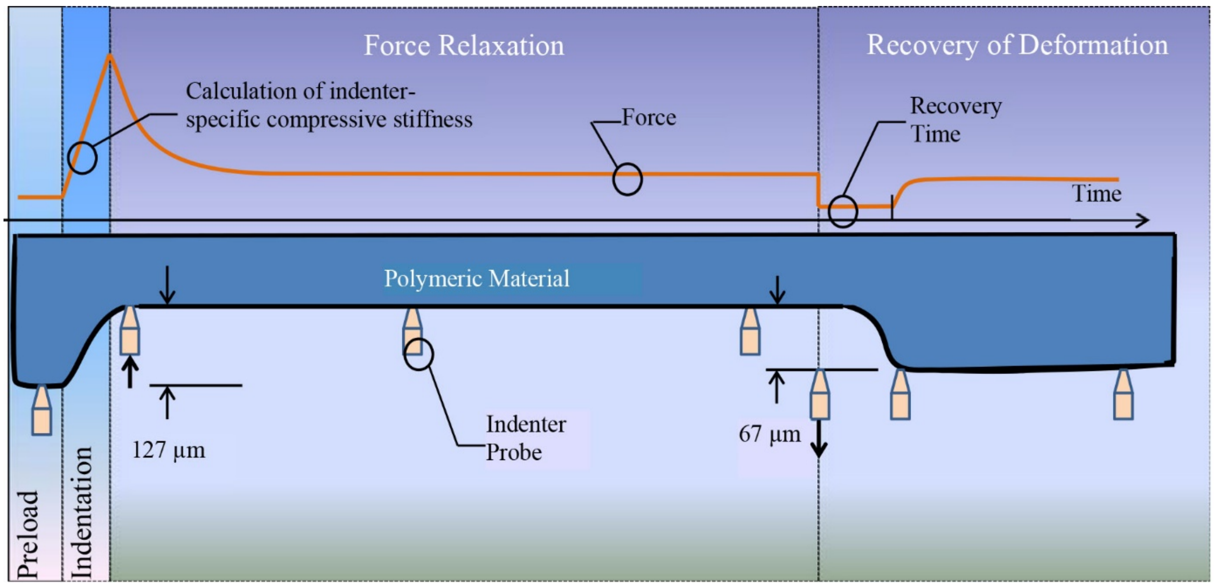


Figure 7.37. A typical test sequence showing the preload, indentation, force relaxation, and deformation recovery phases. The recovery phase is shown following a probe retraction equal to 50% of the initial indentation depth. Figure courtesy of Canadian Nuclear Laboratories.

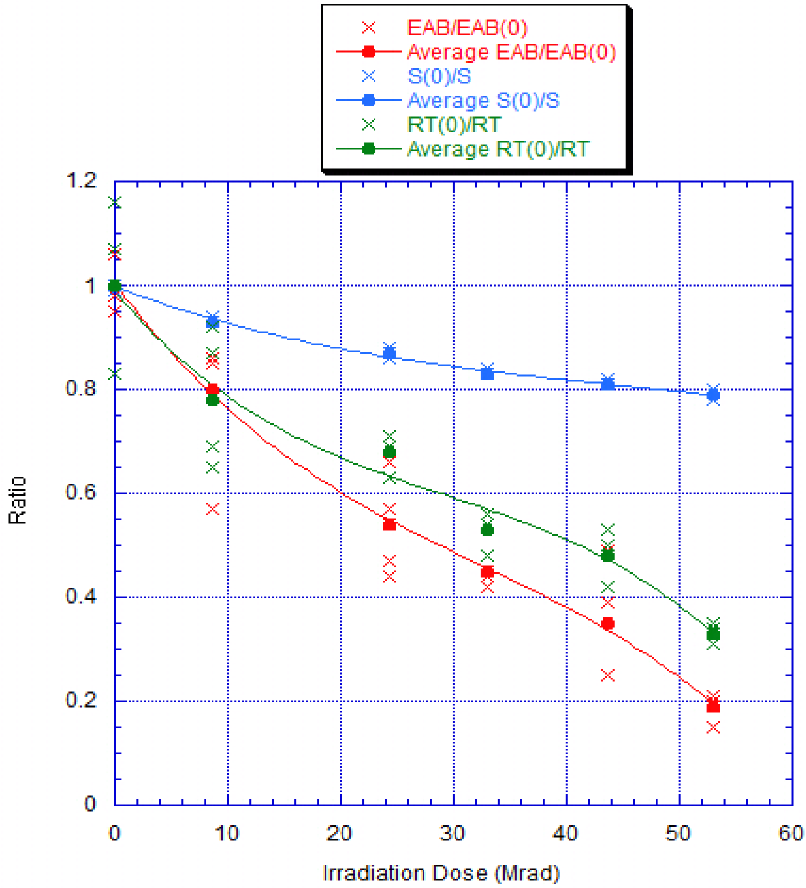


Figure 7.38. EAB and indentation results for irradiated XLPE insulation. Figure courtesy of Canadian Nuclear Laboratories.

The overall assessment of the relaxation time indenter technology is shown in Table 7.5.

Table 7.5. Qualitative Relative Assessment of Relaxation Time Indenter.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Recovery time indenter	+	N (4)	+	+	N (4)	4
Comment 4: Recovery time indenter has been developed and evaluated to date as a laboratory experimental device. Limited data indicates stronger correlation between relaxation time and EAB, but available data is limited compared to the indenter modulus. Some further development is anticipated by any commercial entity prior to offering as a commercial instrument.						

7.6 Dynamic Mechanical Analysis

PNNL used an advanced measurement system from TA Instruments and a technique known as dynamic mechanical analysis to explore if a broad frequency range could provide additional information about the insulation material's mechanical behavior. DMA measurements are known to be sensitive to polymer transitions, levels of crystallinity, chain scission, and crosslinking (Sepe 1998) but are typically plotted as a function of temperature. Figure 7.39 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, measurement of energy dissipation in the material, is the tan δ. This can be thought of as a complex number and can be plotted as the absolute modulus magnitude and phase. The DMA was used to measure the material response to a mechanical swept-frequency stimulus from 1 to 100 Hz. A sample plot of this amplitude and phase DMA frequency response is shown in Figure 7.40 for an EPR cable that has been aged to an EAB less than 50% of its unaged condition. Note that the phase angle is quite low (9°–16°) placing the cable primarily in the elastic range. Moreover, there is no discernable trend or correlation for the phase variation with aging. The modulus however does seem to correlate with progressive cable thermal aging.

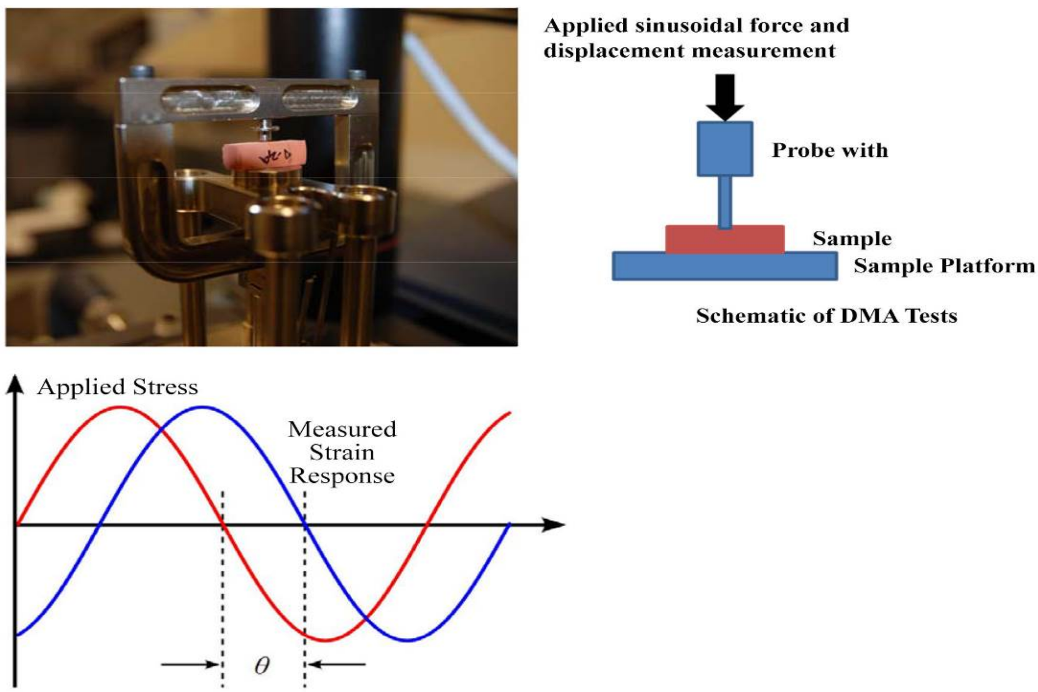


Figure 7.39.Image of the DMA instrument with compression tip for shear modulus and an illustration of a simple schematic and input/output waveforms for analysis.

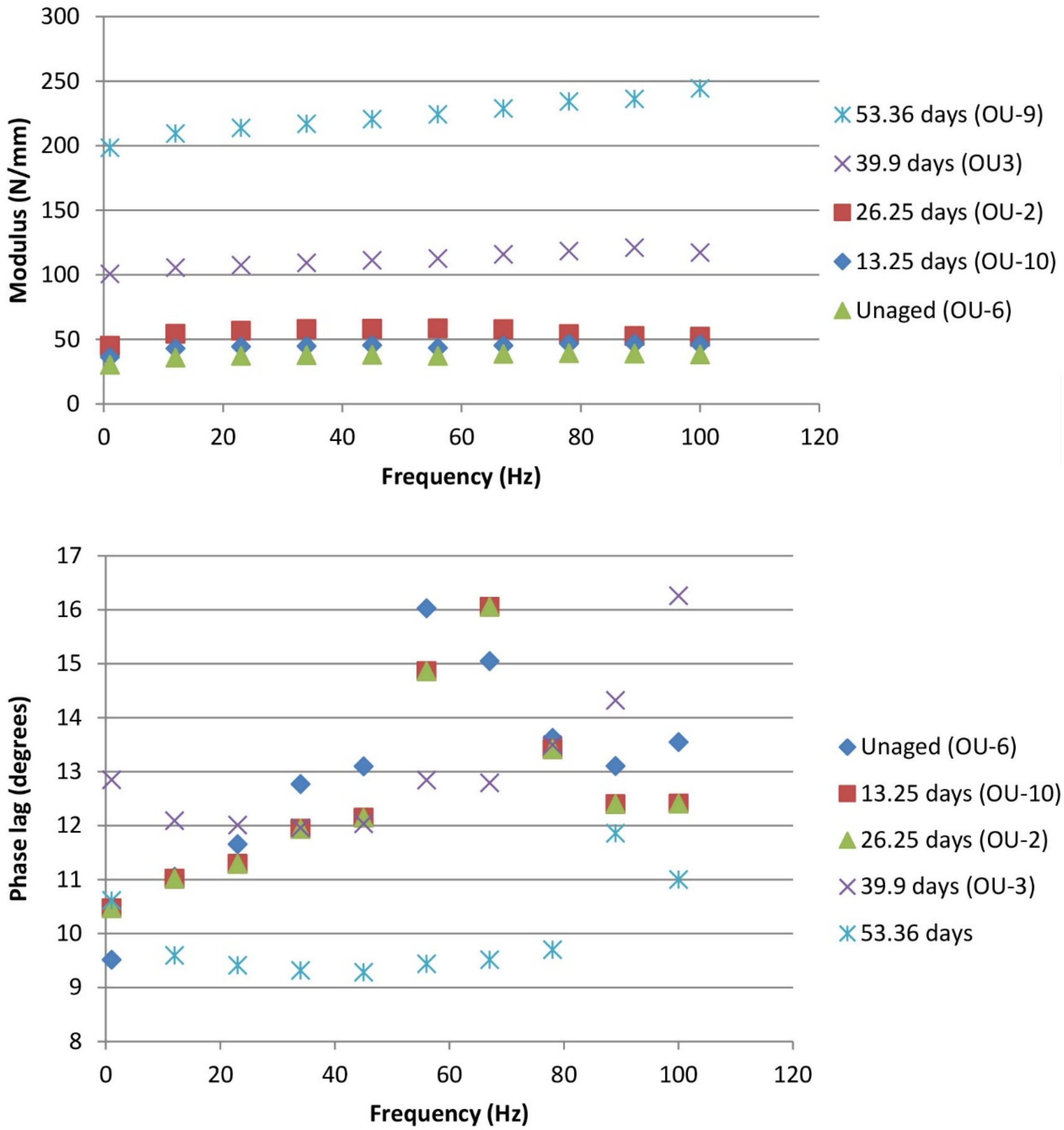


Figure 7.40. DMA modulus (*top*) and phase (*bottom*) frequency response measured for different degrees of cable aging from 0 to 53 days, which corresponded to an EAB reduction to <50% of the unaged condition.

Note that the DMA modulus units are the same as the indenter modulus, σ. Moreover, the low frequency data is not substantially different from the higher frequency data. The change in both the indenter and DMA moduli are shown in Figure 7.41. Both instruments show a similar trend with the cable age. There are some differences in the phase angles particularly in the 45–65 Hz range and the 100 Hz range but these differences are still relatively small. There may be some additional information in the multi-frequency DMA test, but the difficulty of performing a field measurement with the laboratory DMA is far greater than with the indenter that was designed for field applications.

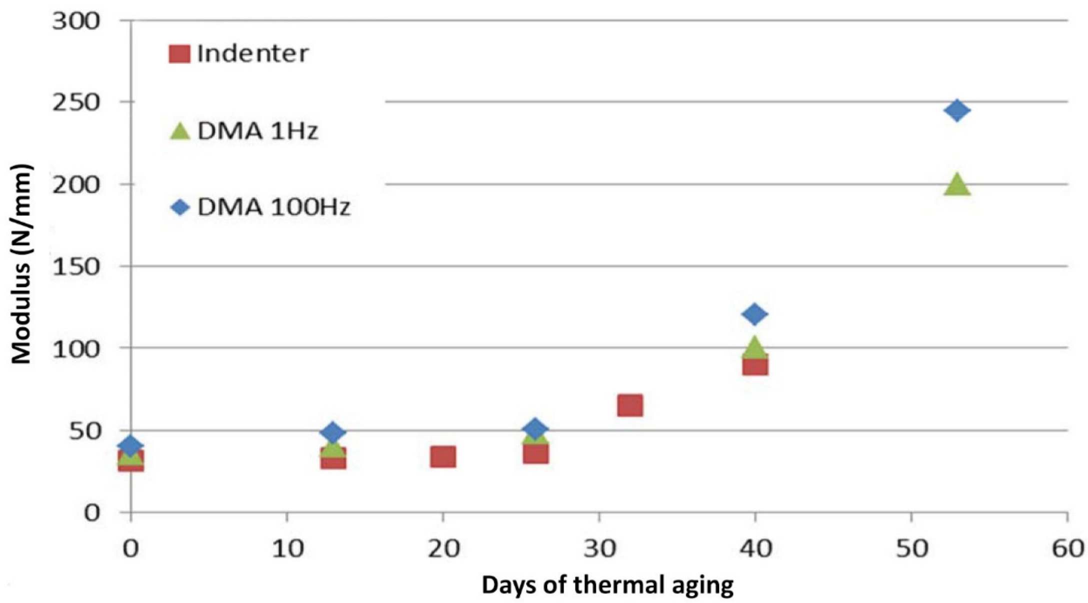


Figure 7.41. Indenter modulus plus the 1 Hz and 200 Hz DMA responses for thermally aged EPR cable at 140°C from 0 to 53 days, which corresponds to >50% reduction in %EAB.

A qualitative assessment of the DMA technique is shown in Table 7.6.

Table 7.6. Qualitative Assessment of DMA Cable Aging Test.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
DMA	–	+	–	N	–	5
Comment 5: Although DMA modulus correlates well with indenter and there may be some additional information within the phase and/or change with respect to frequency, additional age-related behavior is not obviously evident. The rating was N for correlation because the additional information over and above indenter did not correlate well with aging. R&D effort and industrial commercialization would be required to field-package the instrument and implement DMA field tests and this is not necessarily recommended by the data.						

7.7 Fourier Transform Infrared and Fourier Transform Near Infrared Spectroscopy

Fourier transform infrared (FTIR) spectroscopy and Fourier transform near infrared (FT-NIR) spectroscopy are spectroscopic tests that measure energies absorbed or transmitted by a material proportional to the infrared absorption or emission of a solid, liquid, or gas. IR wavelengths are generally from 4 to 14,000 cm^{-1} with wavelengths from 4–4000 cm^{-1} characterized as mid-infrared and 4000–14000 cm^{-1} categorized as near infrared. These absorption frequencies can yield information about specific chemical bonds within the materials. FT-NIR is becoming more widely used for quality and process control for qualitatively characterizing products without using reagents or solvents, because photons in this band can be energetic enough to excite molecular overtones and combinations of vibrations to higher energy levels and the FT-NIR generally penetrates farther into a sample than mid-infrared radiation.

Oxidation and crosslinking of cable insulation polymers such as EPR and XLPE inherently introduce new chemical bonds within the material, including C=O carbonyl and C=C carbon-carbon bonds, that have unique light-excited vibrational frequencies. One important FTIR peak occurs at 1730 cm^{-1} and is indicative of the presence of carbonyl (C=O) bonds (Villaran and Lofaro 2010). This peak is a direct indication of polymer oxidation and that carbonyl bonds are being generated. Other wavelengths can also show aging as evidenced in Figure 7.42. This is an extreme example FTIR spectrum of aged and unaged pink EPR material. The EPR cable insulation material was milled into a powdered, particulate form and aged in a circulating air oven at 140°C to investigate chemical property changes in a form of the material easier to characterize than fully intact 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 also provided. These changes in infrared absorption with cable aging provide a method to assess the extent of cable degradation. In-situ results would be less dramatic as the influence of oxidation would be sensitive to surface proximity; however, the technique's sensitivity to chemical changes in the material is dramatically demonstrated in this example.

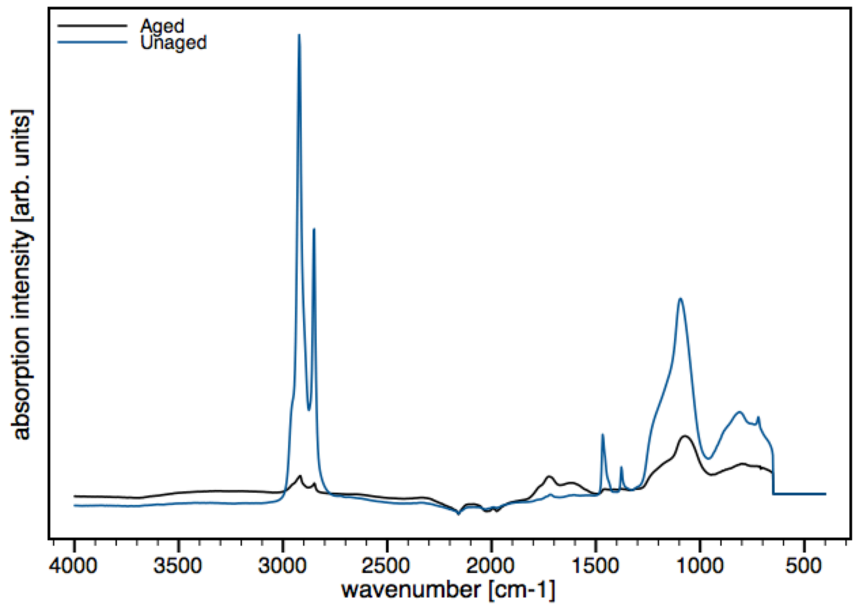


Figure 7.42. FTIR spectra of aged and un-aged EPR.

FT-NIR instruments have been developed and demonstrated to be practical for portable field cable measurements (Figure 7.43). The equipment includes a spectrometer unit connected to a non-metallic probe via a fiber optic cable. Research has demonstrated sensitivity to thermal and radiation damage to cable jackets and insulation, and the approach has been adopted into some Canadian nuclear plants' cable AMP (Azizian and Benson 2008). This FT-NIR test offers several advantages over other methods including:

- Unlike classic laboratory-based FTIR through-transmission analysis, measurements may be made directly on the material surface based on reflected energy without grinding material into a powder and/or suspending material in a solution. The technique is readily deployed as a field NDE test.
- Sensitivity to chemical changes like observing the presence of HCl and conductive salts that would be invisible to other tests.
- No manipulation required. The test is "non-contact," requiring only that the probe is in near proximity to and pointed at the material to be tested.
- With a recorded "database," FT-NIR can unambiguously identify cable types based on their FT-NIR reference signature spectrum.

Some Canadian plants have largely used these instruments on PVC or XLPE yellow-jacketed or light-colored cable materials. Unambiguous cable material identification was established based on a reference database of materials. FT-NIR data was taken on the outer jacket and/or on the exposed insulation at the cable ends within junction boxes near the termination connectors. Data was also taken on similar cable that had been exposed to both thermal and radiation accelerated aging. These cable samples were also EAB tested. These investigations showed strong correlations between FT-NIR and EAB. Based on these results, some Canadian plants have adopted FT-NIR testing into their cable AMP. The approach offers a clear indication of age-related chemical change in the cable jacket and the insulation.

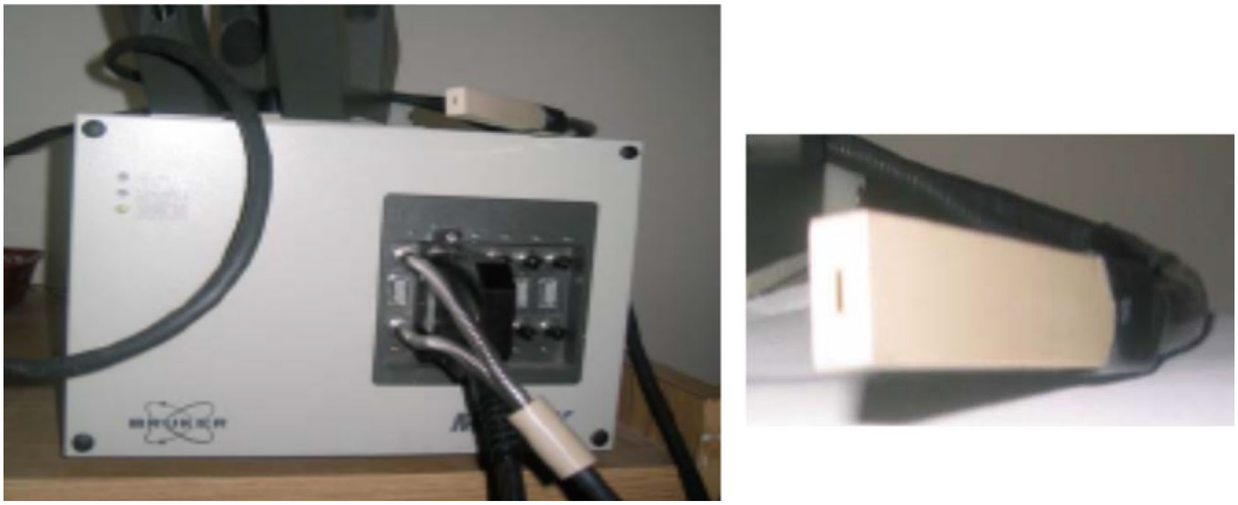


Figure 7.43. FT-NIR spectrometer (inset: the cable insulation probe). Image courtesy of NIR Technologies Inc.

Limitations to this approach of note are:

- Only accessible cable surfaces may be tested. For most of the cable, this means only the jacket material. In some cases, the jackets are made of different material than the insulation. If the jacket is PVC or Hypalon, this material may show indications of aging well before XLPE or EPR insulation damage occurs.
- Neither FTIR, nor FT-NIR works well with black material. Black material typically has carbon fillers that reflect or transmit too little light for spectral analysis.

FTIR and FT-NIR can be performed in field settings with portable instruments so that in-situ tests can be envisioned. Taking such expensive instruments into nuclear containments presents logistics problems (difficulty of decontamination, need to calibrate permanently contaminated instruments, controlled environment in-containment housing of sensitive instruments, etc.); however, these issues may be managed as indicated by the ongoing Canadian inspection of yellow-jacketed cables. Alternatively, FTIR and FT-NIR tests require a very small sample (a few mm^3) and so one could consider taking an insulation sample then repairing (tape or heat-shrink) the cable where the sample was removed. Such an approach is much more practical for cable jackets or relatively large unjacketed cables with exposed insulation than jacketed multi-conductor cables. Although such a sampling program seems technically feasible, obtaining utility/industry acceptance may be an issue.

Extensive quantitative correlations of FTIR with EAB or other aging indicators for light-colored jacket and insulation materials not been reported in the literature as has the FT-NIR work. The value of such an activity seems questionable given the available FT-NIR data. The limitation of black material would be severe issues for U.S. plants because a high percentage of their cables have black insulation. The qualitative assessment of FTIR and FT-NIR is shown in Table 7.7.

Table 7.7. Qualitative Assessment of FTIR and FT-NIR Cable Aging Test.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
FTIR	N	+	N	N	–	6, 7
FT-NIR	N	+	N	N	–	7
Comment 6: Despite some logistics issues, current FTIR and FT-NIR systems could be deployed into plants but for meaningful measurements to occur, many/most cables must be replaced with light-colored material. A sample/repair approach could circumvent some of the above issues if additional R&D showed significant promise to the technique but this would face plant resistance. Thus, the Ease/Cost column is evaluated as N. FT-NIR and FTIR limitations for black or dark cable are a severe limitation for U.S. plants. More research and data from a number of light-colored material samples with confirmed correlations to EAB would be necessary for a meaningful quantitative program to displace other tests in most U.S. plants. Thus, the R&D needed is evaluated as –.						
Comment 7: FT-NIR is being commercially applied in Canadian plants for yellow or light-colored cable. It does not work for black or dark cable. This is a severe limitation for U.S. plants.						

7.8 Interdigital Capacitance

Recent work has been published on the design of interdigital sensors that was begun for NDE of aircraft wire insulation dielectric properties to detect material degradation (Sheldon and Bowler 2014) and extended for application to cable aging management in NPPs. The idea is that the insulation material dielectric constant is affected by both thermal and radiation aging similarly to the mechanical properties that are measured by EAB and indenter modulus. Because the capacitance of the electrode in contact with the cable insulation is proportional to the material dielectric constant and independent of the applied test voltage, this type of test seems to be an approach that could be easily implemented for field testing. The test uses low-voltage excitation so no high-voltage precautions need be made prior to or during the test. Field test equipment could be made sufficiently portable to take inside a nuclear containment facility. Testing would be relatively quick for each location. PNNL has performed some laboratory validation tests using an impedance analyzer that could operate at multiple frequencies. Only single-side access to the cable is required. Although the clamp shown goes fully around the cable, the wire sensor spans less than 180° around the cable circumference Figure 7.44.

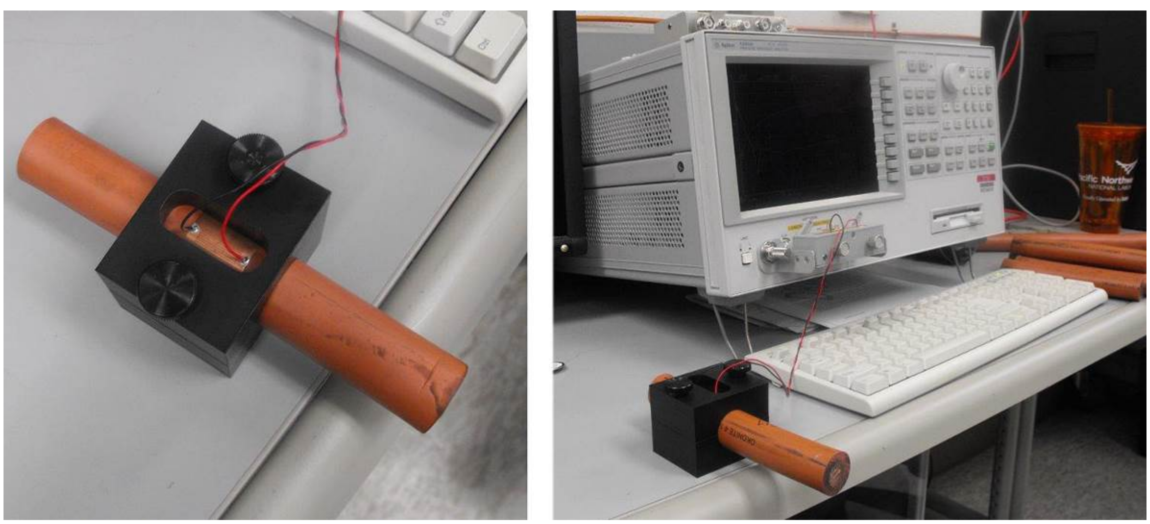


Figure 7.44. Experimental configuration for capacitance measurements showing impedance analyzer and clamshell fixture used to wrap the sensor onto the outer surface of the cable.

The interdigital sensor shown in Figure 7.44 consists of a 15-digit capacitor printed on a thin flexible polyimide substrate with an approximate width of 13 mm and length of 25 mm. Separation between the capacitor digits was 1 mm (0.004 in.). The diameter of the Okoguard 15 kV cable is approximately 25 mm (1 in.) and the capacitor was in direct contact with the EPR insulation. There was no jacket. Figure 7.45 shows the simulation model of the sensor wrapped onto the cable insulation and the electric field distribution 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 are performed over a frequency range of 10–100 MHz. Measurements were conducted with the laboratory impedance analyzer measuring both capacitance (F) and capacitive dissipation factor (D) where D is defined as the tangent of the difference of the phase angle between capacitor voltage and current caused by dielectric losses within the capacitor.

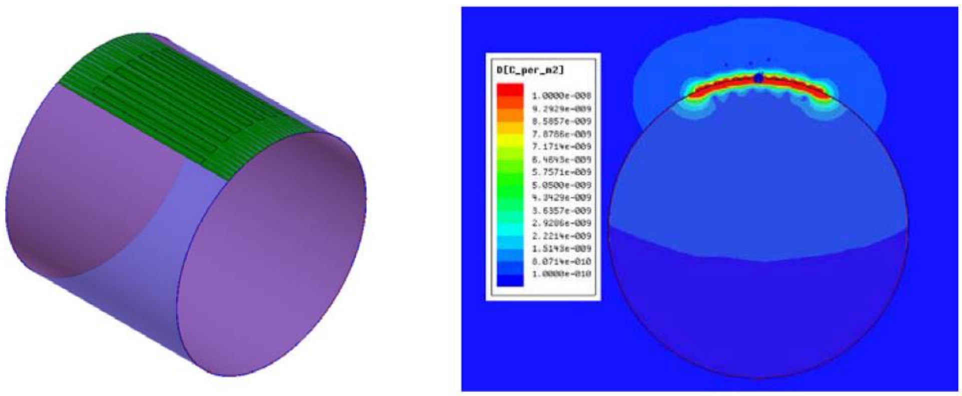


Figure 7.45. Electrostatic field simulation model of interdigital capacitive sensor and electric flux distribution inside cable insulation.

A similar arrangement was applied by researchers at Iowa State University to correlate EAB and indenter measurements with capacitance (F) and dissipation factor (D) (Arvia et al. 2014). One sample set of measured results versus thermal aging is shown in Figure 7.46. Good correlations for both indenter modulus and EAB were shown for EPR cable insulation, although these correlations vary with material, insulation color, and excitation frequency. Practical implementation of the interdigital capacitance test does not separate the effect of the jacket and the insulation, although this may be possible with further development. As of the publication date of this report, this capacitance measurement technique has not been commercialized as a field-deployable system.

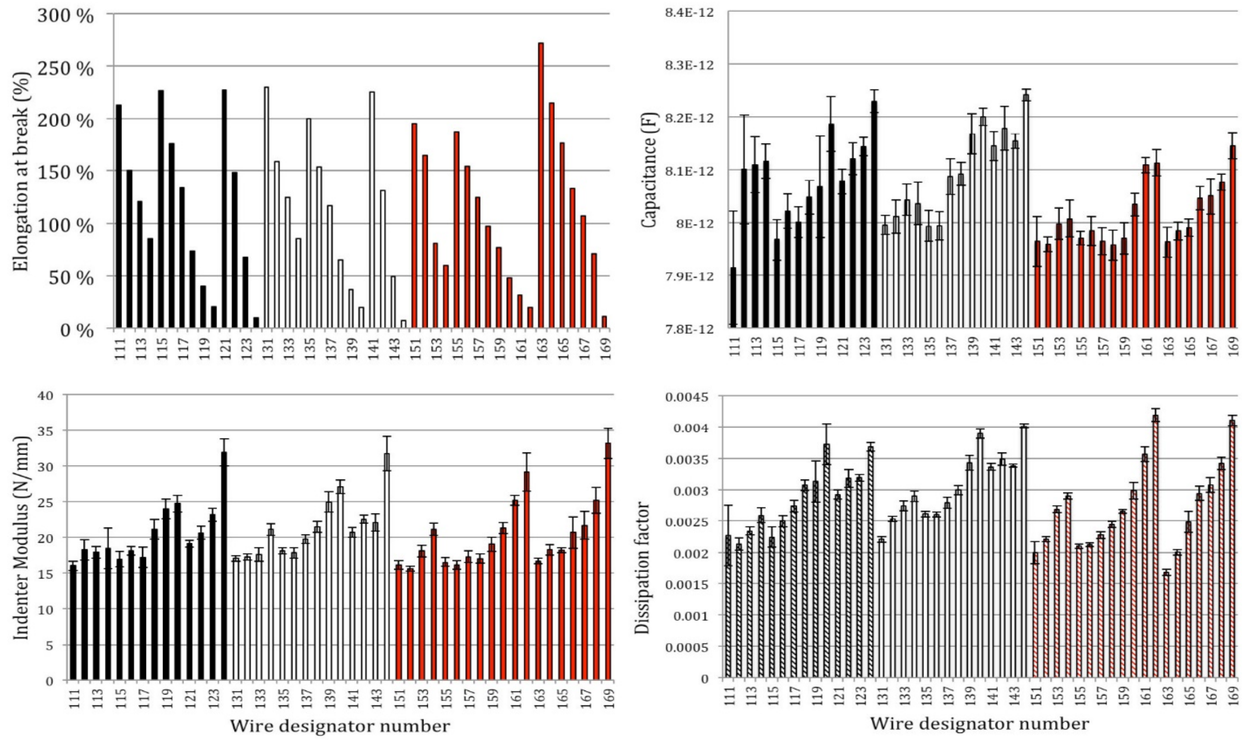


Figure 7.46. EPR accelerated aging cable test response for EAB: indenter modulus (σ), capacitance (F), and dissipation factor (D) (Arvia et al. 2014) © 2014 IEEE. Reprinted with permission.

Interdigital capacitance seems like a possible preferred alternative to indenter or other local tests. Although measurements to date have been based on laboratory instruments, a field-packaged unit could be developed that would be customized for in-plant cable testing. Published results show good correlation with indenter and EAB mechanical property measurements. Interdigital capacitance however measures an electrical property that may relate as well or better to withstand results which are more closely related to the function the insulation is designed to perform. The test is low-voltage and non-destructive. This test also has possibility of assessing insulation through jacket material. Two limitations are limited corroborative R&D showing correlations with aging for a variety of materials and absence of a commercially available product. The qualitative assessment is shown in Table 10.

Table 7.8. Qualitative Assessment of Interdigital Capacitance Cable Aging Test.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Interdigital capacitance	+	N	+	+	–	8
Comment 8: Two limitations are the limited corroborative R&D showing aging correlation with a wide variety of materials and absence of a commercially available product. The commercial column is N because commercialization discussions are ongoing.						

7.9 Ultrasonic Velocity

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):

$$c_l = \sqrt{\frac{E}{\xi}\frac{1-\mu}{(1-\mu)(1-2\mu)}} \tag{3}$$

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):

$$p = \xi c_l \omega\zeta = Z\omega\zeta \tag{4}$$

where Z is the acoustic impedance.

These two relations indicate that sound speed measurements may be a proxy to measuring the elastic modulus. Several studies have shown a strong correlation between aging jacket material and speed of sound for PVC sheaths and jacket material (Ikehara et al. 1998). PNNL tried to use these techniques on EPR cable samples with limited success. The EPR samples are relatively soft material with strong sound attenuation and due to signal distortion along the sound path, some variability of the sound velocity measurement was observed. To counter this, the cable was scanned as shown in Figure 7.47.

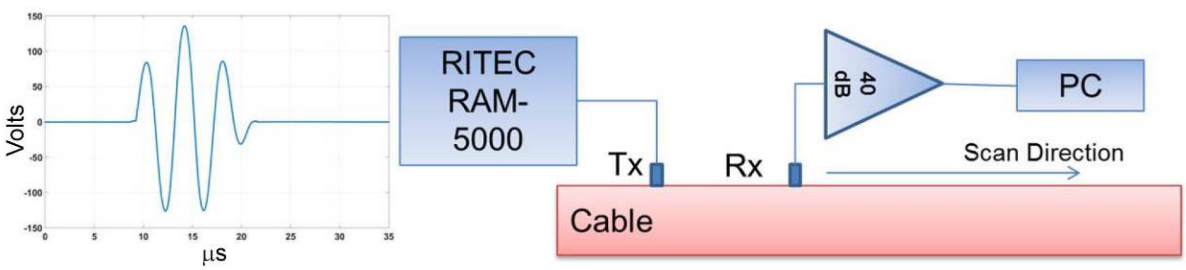
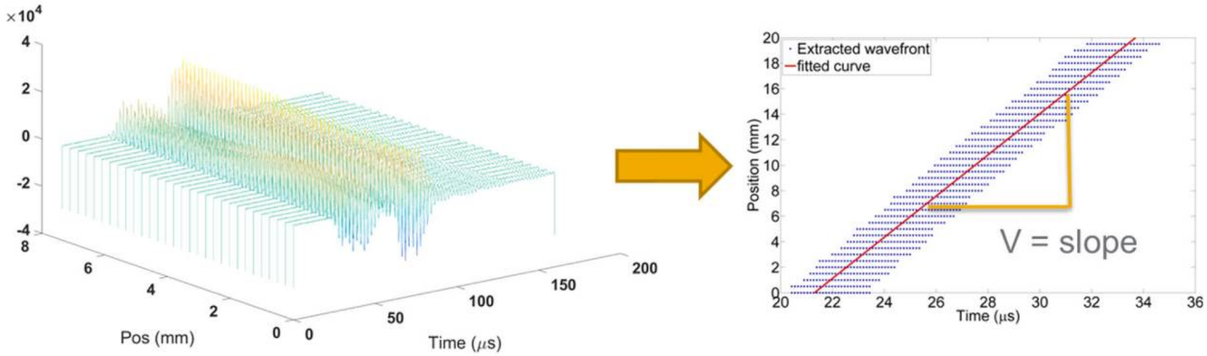


Figure 7.47. UT velocity measurement setup for EPR cable.

The arrival time of the transmitted waveform was difficult to pinpoint. Several advanced algorithms were attempted including auto-correlation, spatial-temporal 2-D Fourier transforms, and scanned least-squares fit regression analysis of the constant phase demarcation of the first-arrival wave packet. The regression analysis produced the most reliable repeatable velocity measurements (Figure 7.48).



(a) (b)

Figure 7.48. Waveforms at each scan location (a) are discretized for first arrival wave-packet. This position/time plot is then subject to a regression analysis for more consistent velocity measurement (b).

This approach was used to measure the sound velocity in a set of EPR samples exposed to up to 1200 hrs. (50 days) at 140°C (Figure 7.49).Such a period of thermal aging would be expected to reduce the EAB to below 25%. Transducer excitation frequencies of 250 kHz, 500 kHz, and 750 kHz were used. Significantly higher frequencies were rejected due to material attenuation, which limited sound propagation beyond a few inches. There was still some spread in the data but most of the measurements were relatively consistent. The sound velocity results, however, showed poor correlation with the EPR sample's thermal exposure time.

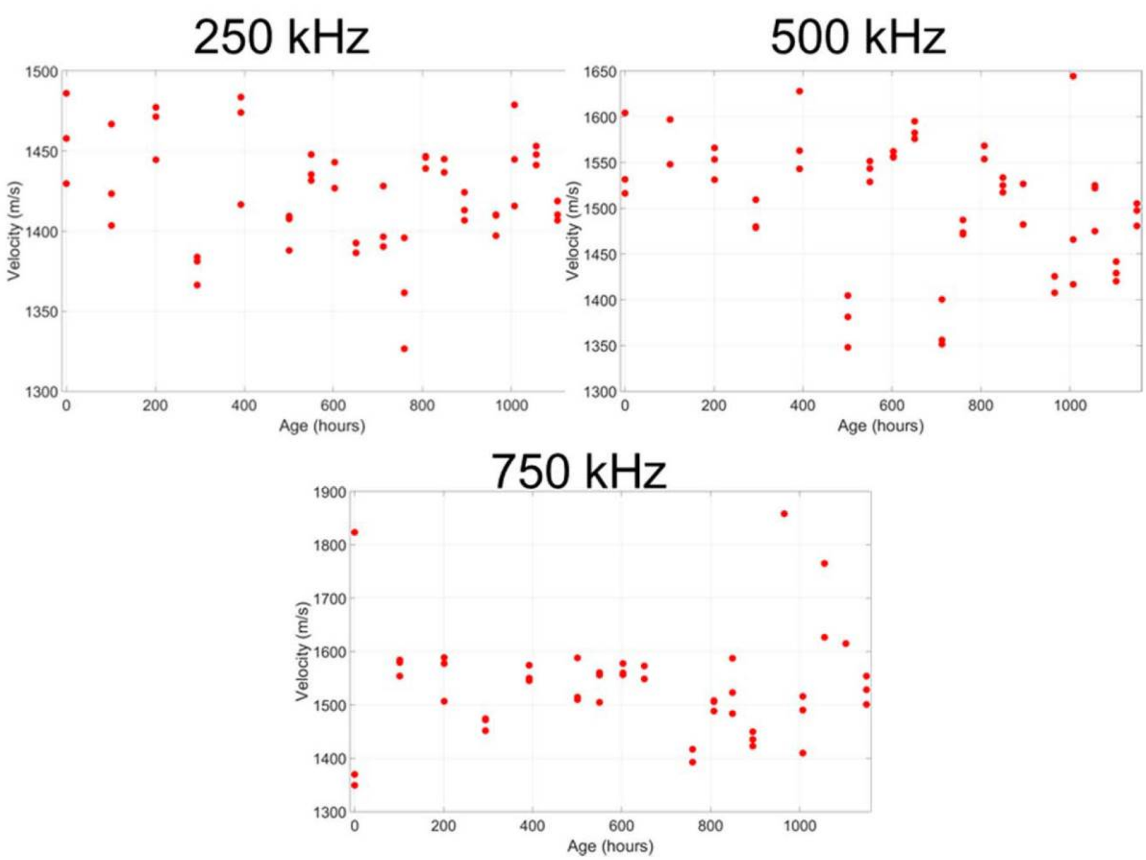


Figure 7.49. EPR ultrasound velocity as a function of accelerated thermal at 140°C aging shows poor correlation.

Although other work has shown some correlation between thermal aging and ultrasonic velocity (Anastasi and Madaras 2005), this poor correlation between thermal aging versus laboratory ultrasonic velocity measurements does not encourage development of a field-deployable in-situ measurement approach. Although such an in-situ system could be envisioned, other techniques seem to have better correlation to the parameter of interest and would be easier to implement for in-situ tests within NPPs. The qualitative assessment of ultrasonic velocity is shown in Table 7.9.

Table 7.9. Qualitative Assessment of Ultrasonic Velocity Cable Aging Test.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Ultrasound velocity	–	–	–	–	–	9
Comment 9: PNNL's ultrasonic velocity correlation results with aging were poor; however, others have reported better correlations. Regardless of the correlation results, ultrasound velocity would require investment to produce an easily field-deployable instrument and the correlation with other cable aging indication does not necessarily recommend such an investment.						

7.10 Distributed Fiber Optic Temperature Sensing

Although not a direct local measurement of cable condition, distributed fiber optic sensing can provide meaningful temperature profiles that can be indicative of likely areas for accelerated cable aging. This approach is analogous to the IR thermography; however, it is not limited to time periods when the cable is people-accessible. The concept is to include a sensing optical fiber alongside critical cables where temperature profiles are of interest. The fiber is interrogated taking advantage of the quantum Raman effect to achieve a temperature profile along the fiber length. Any hot-spot location may be identified for analysis of expected accelerated aging and/or corroborative local inspection. Although implementations have been limited, the approach has been used for transmission and distribution systems, underground and underwater cable systems, transformer systems, and large motor systems (Ukil et al. 2012).

The qualitative assessment of distributed fiber optic temperature sensing is shown in Table 7.10. Having detailed profiles of temperature exposure could support predictions of the actual cable condition; however, research would be required to justify cable dispositions. This approach would also require adding an instrument to interrogate and log the temperatures along the fiber. This may be a challenge to add to existing nuclear plants.

Table 7.10. Qualitative Assessment of Distributed Fiber Optic Temperature Sensing for Cable Aging.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Fiber optic temperature sensing	– (10)	+	N	N	–	10
Comment 10: Distributed fiber optic temperature sensing requires adding fiber to monitored cable trays and connecting it to a permanently installed instrument. This is may be a difficult plant modification to justify simply for temperature readings. The temperature indication is quantitative but not directly related to cable condition.						

8. COLLECTIVE QUALITATIVE ASSESSMENT

One of the principal goals of this report is the qualitative assessment of the various test methods. The individual method assessments have been assembled in Table 8.1.

Table 8.1. Qualitative Relative Assessment of Local Cable NDE Inspection Methods¶Green (+) is good, yellow (N) is neutral, and orange (–) is poor compared other approaches. More detailed discussion of evaluation criteria is shown under 1.0 Objectives.

Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed	Comments
Visual walk-downs	+	+	N	– (1)	+	1
IR Camera	N (2)	+	–	N (1,2)	+	1, 2
Indenter	+	+	+	+	+	3
Recovery time Indenter	+	N(4)	+	+	N(4)	4
DMA	–	–	N	+	–	5
FTIR	N	+	N	N	–	6, 7
FT-NIR	N	+	N	N	–	7
Inter-Digital Capacitance	+	N	+	+	–	8
Ultrasound velocity	–	–	–	–	–	9
Fiber-Optic Temperature Sense	– (10)	+	N	N	–	10

Comments:

1. Although visual tests are not quantitative, digital images may be archived and checked for subtle indications of degradation or worsening of conditions. IR camera images are quantitative but only for temperature, which is not directly relatable to insulation damage. Technology to enhance computer-based image comparisons is expected to mature and advance during the next decade.
2. IR cameras can quantitatively measure temperature at the time the image is captured. Many cable locations—particularly inside nuclear containments—however are not man-accessible during operation when the bulk of the cables exposure to elevated temperature occurs. Permanently installed IR camera arrays or robotically piloted IR cameras could address this issue in future plants but this is currently not being actively investigated. This is why N is assigned to Quantitative and Ease/Cost.
3. Indenter is the most widely used local test technique. Its primary drawback is that for jacketed insulation, non-destructive access is only available to the jacket.
4. Recovery time indenter has been developed and evaluated to date as a laboratory experimental device. Limited data indicates stronger correlation between relaxation time and EAB, but available data is limited compared to the indenter modulus. Some further development is anticipated by any commercial entity prior to offering as a commercial instrument.
5. Although DMA modulus correlates well with indenter and there may be some additional information within the phase and/or change with respect to frequency, additional age-related behavior is not obviously evident. The rating was N for correlation because the additional information over and above indenter did not correlate well with aging. R&D effort and industrial commercialization would be required to field-package the instrument and implement DMA field tests and this is not necessarily recommended by the data.

6.	Despite some logistics issues, current FTIR and FT-NIR systems could be deployed into plants but for meaningful measurements to occur, many/most cables must be replaced with light-colored material. A sample/repair approach could circumvent some of the above issues if additional R&D showed significant promise to the technique but this would face plant resistance. Thus, the Ease/Cost column is evaluated as N. FT-NIR and FTIR limitations for black or dark cable are a severe limitation for U.S. plants. More research and data from a number of light-colored material samples with confirmed correlations to EAB would be necessary for a meaningful quantitative program to displace other tests in most U.S. plants. Thus, the R&D needed is evaluated as –.
7.	FT-NIR is being commercially applied in Canadian plants for yellow or light-colored cable. It does not work for black or dark cable. This is a severe limitation for U.S. plants.
8.	Interdigital capacitance seems like a possible preferred alternative to indenter or other local tests. It is likely to be easy to deploy, correlates well with indenter and EAB, measures an electrical property that is likely to relate to withstand results, is low-voltage and non-destructive. This test also has the possibility of assessing insulation through jacket material. Two limitations are the limited corroborative R&D showing aging correlation and absence of a commercially available product.
9.	PNNL's ultrasonic velocity correlation results with aging were poor; however, others have reported better correlations. Regardless of the correlation results, ultrasound velocity would require investment to produce an easily field-deployable instrument and the correlation with other cable aging indication does not necessarily recommend such an investment.
10.	Distributed fiber optic temperature sensing requires adding fiber to monitored cable trays and connecting it to a permanently installed instrument. This is may be a difficult plant modification to justify simply for temperature readings. The temperature indication is quantitative but not directly related to cable condition.

9. CONCLUSION AND FUTURE WORK

Although there is no single test for condition monitoring of nuclear power plant cables, a powerful set of tests exist and practical programs are being implemented to evaluate cable condition and justify continued NPP safe operation. The strategy generally includes: (1) trending of CM results within a structured database of select cables, (2) applying bulk electrical tests, (3) locating suspected weak points for focused local measurements, and (4) evaluating signs of cable degradation or damage so repair or replacement can be planned and cost-effectively managed.

A number of local cable test approaches are available to assess the cable's integrity for operation as well as extreme service that may be called for under DBE conditions. A qualitative relative assessment of the local techniques is presented focusing on research required to support new or continued field implementation.

Visual observation through walk-downs is the most prevalent approach, and the industry has a rich history of reference examples of compromised cable conditions that can be recognized. These visual observations may be supplemented with IR images to identify hot spots where accelerated insulation damage may be suspected. A significant percentage of nuclear plant cables, however, is not readily observable and unless one is specifically focused on inspecting the cable system, degraded conditions may not be observed. The structured database of cables with inspection schedules aids utilities to examine and document cable systems for conditions of concern. These databases include consideration for where the cable is run and if there are any particular locations where the cable could be subjected to elevated temperatures, radiation, water, or other environmental stresses.

Cable jacket material may be different from the underlying insulation. Observed damage or degradation of the cable jacket may over-predict damage to the underlying insulation. If that insulation is accessible either at a damaged jacket location or via abandoned cables that have been exposed to similar environmental stresses, alternate approaches can be applied to assess the cable. The indenter is the most commonly used instrument for this local measurement. It is commercially available and there is laboratory and field experience supporting its use as one input to disposition cable for service or maintenance/repair/replacement. Other approaches are being developed and show promise but are less widely applied by the industry.

This work has highlighted research gaps that are targeted for future activity because they seem promising and because near-term gains are likely to be achieved with modest effort. One particularly promising technique that could offer an easier and lower-cost test compared to indenter is the interdigital capacitance test. This approach is appealing because it tests electrical characteristics of the cable that may be more indicative of electrical performance. It is also the only test with some promise of testing some underlying insulation and neglecting influence of an external cable jacket. This capability however is yet to be demonstrated and additional research is required to bring this technique to the field.

Another promising technique is FTIR and FT-NIR. This is being used in some plants for yellow or light-colored cable but has severe limitations for black insulation, which constitutes the bulk of the U.S. plant cables. Improved techniques to overcome black material limitations coupled with new or additional EAB research here could also pave the way for a viable quantitative field-test alternative.

10. APPLICABLE AND RELATED CABLE TEST STANDARDS

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