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CONDITION MONITORING OF CABLES

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CONDITION MONITORING TECHNIQUES FOR ELECTRIC CABLES

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November 2009

BROOKHAVEN NATIONAL LABORATORY

Energy Sciences and Technology Department
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ABSTRACT

For more than 20 years the NRC has sponsored research studying electric cable aging degradation, condition monitoring, and environmental qualification testing practices for electric cables used in nuclear power plants. This report summarizes several of the most effective and commonly used condition monitoring techniques available to detect damage and measure the extent of degradation in electric cable insulation. The technical basis for each technique is summarized, along with its application, trendability of test data, ease of performing the technique, advantages and limitations, and the usefulness of the test results to characterize and assess the condition of electric cables.

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ABBREVIATIONS

ASTM . . . . .American Society for Testing and Materials
AWG . . . . American Wire Gauge
BNL . . . . .Brookhaven National Laboratory
CM . . . . Condition Monitoring
CSPE . . . . Chloro-Sulfonated Polyethylene (also known as Hypalon®)
DSC . . . . .Differential Scanning Calorimeter
EAB . . . . Elongation at Break
EMI . . . . .Electromagnetic Interference
EPDM . . . . Ethylene Propylene Diene Monomer
EPR . . . . Ethylene Propylene Rubber
EPRI . . . . Electric Power Research Institute
EVA . . . . Ethylene Vinyl Acetate
FTIR . . . . .Fourier Transform Infrared Spectroscopy
I&C . . . . .Instrumentation and Control
ICEA . . . . Insulated Cable Engineers Association
IEC . . . . .International Electrotechnical Commission
IEEE . . . . .Institute of Electrical and Electronics Engineers
INPO . . . . Institute for Nuclear Power Operations
IR (1) . . . . .Insulation Resistance
IR (2) . . . . .Infrared (imaging thermography)
ISO . . . . .International Organization for Standardization
LER . . . . Licensee Event Report
LIRA . . . . .Line Resonance Analysis
LOCA . . . . Loss of Coolant Accident
LV. . . . . Low Voltage
MV. . . . . .Medium Voltage
NPRDS . . . . Nuclear Plant Reliability Data System
NRC . . . . Nuclear Regulatory Commission
OITM .. . . Oxidation Induction Time
OITP . . . . .Oxidation Induction Temperature
OTDR . . . . .Optical Time Domain Reflectometry
PE. . . . . .Polyethylene
PI . . . . .Polarization Index
PM . . . . Preventive Maintenance
PVC . . . . .Polyvinyl Chloride
QA . . . . Quality Assurance
RES . . . . U.S. NRC, Office of Nuclear Regulatory Research
SR . . . . Silicone Rubber
SSC(s) . . . . .Structures, Systems, and Components
TDR . . . . Time Domain Reflectometry
XLPE . . . . .Cross-Linked Polyethylene
XLPO . . . . Cross-Linked Polyolefin

1. INTRODUCTION

1.1 Background

Electric cables are important nuclear power plant components that are used to supply electric power to safety-related systems and to interconnect the systems with their instruments and controls. The polymer materials used for the insulation and jacket materials for electric cables, cable splices, and terminations are susceptible to aging and degradation mechanisms caused by exposure to many of the stressors encountered in nuclear power plant service. Over time, the aging and degradation mechanisms caused by exposure to these stressors can result in degradation of the dielectric properties of a cable's polymer insulation material

The integrity and function of power and instrumentation and control (I&C) cables are monitored indirectly through the performance of in-service testing of the safety-related systems and components. Unfortunately, while these tests can demonstrate the function of the cables under test conditions, they do not verify their continued successful performance when they are called upon to operate fully loaded for extended periods as they would under normal service operating conditions or under design basis conditions. The results of instrument and control system calibration and functional surveillance tests, system and equipment performance tests, or other related technical specification surveillance testing and preventive maintenance program testing, can provide useful information and trends regarding the functional performance of a cable. However, specific information on the physical integrity and dielectric strength of the cable insulation and jacket materials is not revealed by this type of testing. Consequently, a cable with undetected damaged or degraded insulation could fail unexpectedly when called upon to operate under the severe stresses encountered during an emergency (i.e., fully loaded equipment, more extreme environmental conditions, extended operation in a heavily loaded state) or extended normal service operation at high load.

Condition monitoring inspections and tests can provide the means for evaluating the level of aging degradation of electric cables. The cables are exposed to a variety of environmental and operational stressors throughout their service life. Over time, the aging and degradation mechanisms caused by these stressors can eventually lead to early failure of the cable. These failures can result in multiple equipment failures, as described in US NRC Generic Letter 2007-01 [Ref. 1 – GL 2007-01]. It is therefore important that periodic condition monitoring inspection and testing of electric cables be considered. Severely damaged or degraded cable insulation can then be identified and repaired or replaced to prevent unexpected early failures while in service.

1.2 Objective

The objective of this report is to describe the technical basis supporting the use of various electric cable condition monitoring techniques to detect damage and measure the extent of degradation in electric cable insulation. For each of the CM techniques covered, information is presented on the application of the technique, trendability of test data, ease of performing the technique, advantages and limitations, and the usefulness of the test results to characterize and assess the condition of electric cables.

1.3 Scope

The condition monitoring techniques described in this report are applicable, in general, for nuclear power plant electric cable systems used for low-voltage (less than 1000Vac and 240Vdc) power and instrumentation and controls applications, and medium-voltage power cables up to about 38kV. The applicability of individual techniques to specific voltage classes is indicated in the description of the techniques. This is not intended to be a comprehensive list of all acceptable cable CM techniques but rather represents many of the most commonly used and effective techniques that are available for characterizing and monitoring the condition of electric cables.

Discussions and guidance regarding condition monitoring techniques for medium-voltage power cables are based on cables designed for operation below 38kV. Much of the medium-voltage cable information in this report can be adapted to higher voltage polymer-insulated power cables. However, due to the special construction, application, and hazards involved with higher voltage power cables, the aging and degradation mechanisms, inspection methods, condition monitoring techniques, and controlling procedures for higher voltage cables must be uniquely developed on an application-specific basis.

The boundaries of an electric cable system that are to be monitored in a cable CM program will typically include the electric cable, cable splices, and insulated connectors from their source terminals, electrical connectors, bushings, terminal blocks, or other electrical connection devices to their load terminals, electrical connectors, bushings, terminal blocks, or other electrical connection devices. Any miscellaneous cables, wiring, splices, or other connections contained within electrical power equipment, instrumentation, and controls enclosures or equipment cabinets are considered internal wiring that should be addressed under inspection, testing, and maintenance activities for that specific equipment.

Discussions, examples, and guidance regarding condition monitoring inspection and testing techniques are based on the assumptions that the cable electrical conductors are constructed from copper or aluminum, and the cable insulation and jacket materials are polymers, such as cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), silicone rubber (SR), and polyethylene (PE). These assumptions encompass nearly all of the cable conductors and more than 80 per cent of the polymer-insulated cables in nuclear plant service [Ref. 2 – SAND96-0344]. With minor variations, the guidance and discussions presented herein are also applicable to the other polymers used in nuclear plant cable insulation and jackets.

1.4 Organization of the Report

Section 2 of the report presents a basic overview of condition monitoring techniques used for aging of electric cable systems. The desired attributes for the “ideal” cable condition monitoring technique are presented along with a general discussion on the various properties of electric cable insulation that can be monitored to assess the condition of an electric cable and the dielectric integrity of cable insulation systems. This is followed by a discussion on some of the important factors that should be considered by the cable engineer when selecting the appropriate condition monitoring methods to characterize and monitor the condition of an electric cable system. A basic CM technique selection matrix is provided linking the various common techniques with the stressors and aging mechanisms they are best suited to detect and monitor.

Section 3 of this report describes many of the common CM testing methods available for measuring the performance parameters and properties of electric cables. A brief general description for each method is provided along with discussions on the applicability, features, special equipment and training requirements, test results, advantages and limitations for each technique, and applicable standards and technical references that may be consulted for further details on applying each technique for cable condition monitoring.

Section 4 presents a brief summary on the use and application of in situ and laboratory-type cable condition monitoring techniques in an overall plant program for electric cable condition monitoring.

2. SELECTION OF CABLE CM TECHNIQUES

Condition monitoring for electric cable systems involves inspection and measurement of one or more indicators, which can be correlated to the condition or functional performance of the electric cable on which it is applied. Furthermore, it is desirable to link the measured indicators with an independent parameter, such as time or cycles, in order to identify trends in the condition of the cable. Ideally, condition monitoring data and trends in cable performance indicators can guide the cable engineer's decisions to effectively manage the aging and degradation in electric cables, cable splices, or other accessories in a cable system before they reach the point of failure or degraded performance that may adversely affect the safe and reliable operation of the associated components and systems.

2.1 Desired Attributes for Cable CM Techniques

In a research program sponsored by the NRC, the attributes of an ideal CM technique for electric cables were identified in NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables" [Ref. 9 – NUREG/CR-6704], Volume 2, Section 3, as the following:

• non-destructive and non-intrusive (i.e., does not require the cable to be disturbed or disconnected),
• capable of measuring property changes or indicators that are trendable and can be consistently correlated to functional performance during normal service,
• applicable to cable types and materials commonly used in existing nuclear power plants,
• provides reproducible results that are not affected by, or can be corrected for the test environment (i.e., temperature, humidity, or radiation),
• inexpensive and simple to perform under field conditions,
• able to identify the location of any defects in the cable,
• allows a well defined end condition to be established,
• provides sufficient time prior to incipient failure to allow corrective actions to be taken,
• available to the industry immediately

The most useful condition monitoring would provide information that can be used to determine the current ability of a cable system to perform within specified acceptance criteria, as well as to make predictions about its future functional performance and accident survivability. To predict future performance, it is desirable to have a trendable indicator and a well-defined end point. A trend curve can then be used to estimate the time remaining before the end point is reached. However, research and experience has shown that no single, non-intrusive, cost effective currently available CM method alone can be used to predict the survivability of electric cables under accident conditions. A plant cable circuit may traverse a number of different environments and localized conditions along its length. Many condition monitoring techniques are localized indicators of condition at the specific location along a cable circuit where the measurement is made. The criteria used to define cable functional condition or accident survivability for a particular circuit are application-specific. Consequently, engineering judgments concerning the integrity and soundness of an electric cable must be made by experienced personnel based upon the results of several condition monitoring tests, including visual, electrical, physical, and chemical techniques. A suite of such condition monitoring tests, with periodic measurements referenced to baseline values may then be used to make cable condition assessments and predict cable survivability. [Ref. 9 - NUREG/CR-6704]

2.2 Electric Cable Properties

Since no single CM technique alone can be used to effectively monitor and assess all aspects of a cable's condition, multiple CM inspection and testing techniques must be chosen to best accomplish the tasks of detection of degradation, assessing the state of degradation, and monitoring the progress of degradation processes, for a given cable application. By evaluating test and performance data on the whole range of cable properties and functions, an informed assessment of the cable system can be made.

Several different groups of cable CM test techniques may be performed to measure and assess various electric cable properties as follows:

- *electrical properties* (such as insulation resistance/polarization index, voltage withstand, dielectric loss/dissipation factor, time domain reflectometry, partial discharge),
- *mechanical properties* (such as hardness, elongation-at-break, compressive modulus/polymer indenter test),
- *chemical/physical properties* (such as density, OITM, OITP, and FTIR),
- *physical condition/appearance*, or
- *functional performance* (technical specifications calibration & functional surveillance tests, system/component operating tests, preventive maintenance functional tests)

The electrical properties of a cable generally provide a global measurement of the overall condition of the cable insulation system, e.g. insulation resistance, polarization index, dielectric loss measurement, and voltage withstand tests. However, some electrical properties tests, such as time domain reflectometry (TDR), line resonance analysis (LIRA), and partial discharge tests, can provide information not only on the magnitude of degradation, but also the location of the problem.

Mechanical, chemical, physical, and physical appearance properties provide point-of-testing information at the specific location at which a measurement or observation is made, or from which a test specimen is removed. This information is very useful for a general assessment of the status of insulation aging degradation in a given plant area or environment. However, a cable system may pass through several different environments over the length of its routing through the plant and can sometimes be exposed to locally adverse environmental conditions, with locally extreme stressors. Consequently, the mechanical, chemical, or physical property measurements or observations must be made at a locally adverse environment (or on a cable material test specimen removed from a locally adverse environment) in order to properly assess the severity of insulation degradation at a cable's potentially weakest point.

Functional performance tests can demonstrate the overall capability of a cable system to perform its intended safety function as part of a safety system. However, functional testing provides no information on the overall integrity of the cable insulation and the state or rate of degradation of the cable insulation caused by the aging and degradation mechanisms resulting from exposure to nuclear power plant service and environmental stressors.

2.3 Factors to be Considered in Selecting CM Techniques

There are several factors that must be considered in selecting an appropriate CM inspection or testing technique for the cable to be monitored. The following discussion provides guidance that can be used in selecting CM techniques.

2.3.1 Intrusiveness

The intrusiveness of the CM technique is a factor to consider in selecting a CM technique. A sensible approach is to start with the least intrusive technique and increase the intrusiveness only if it is warranted based on the results or past operating experience. As such, screening techniques, such as the visual inspection or illuminated borescope inspection are considered a good first choice to determine whether there is any evidence of cable degradation depending on the accessibility to the full length of the cable and its condition. A decision can then be made to perform more intrusive testing or not based on the results of the screening inspections.

In their responses to US NRC Generic Letter 2007 [Ref. 1 – GL2007-01], nuclear utilities listed several cable condition monitoring, inspection, and preventive maintenance programs that are currently used. The NRC reviewed these activities and concluded that, while they do not provide diagnostic information, they do contribute to delaying cable degradation or providing gross failure indication [Ref. 8 – G.A.Wilson Memo, Nov 12, 2008]. Several of these activities can also be used as indicators for the need for more intrusive condition monitoring. These activities are the following:

- Trending cable issues in the corrective action program
- Testing cables for continuity and/or functionality
- Ground detection systems
- License renewal commitments
- Visual inspections of cables, terminations and tray supports
- Water abatement programs

Any one, or a combination of several of these activities could provide useful information for making a decision to perform more intrusive CM testing.

2.3.2 Cable Characteristics

Once a decision is made to perform more intrusive testing, the characteristics of the cable to be monitored must be considered in selecting an appropriate technique. The following factors should be considered:

- Cable voltage rating
- Cable insulation/jacket material
- Cable shielding
- Cable location
- Cable configuration (single or multiconductor, coaxial, twisted pair)
- Cable application (power, instrumentation, control, communication)

These factors can affect the type of CM technique selected and the procedure that must be followed when conducting the test. The way that functional failure (or success) is defined can also dictate the type of properties that should be measured and trended in order assess the capability of the cable to perform its intended safety function.

2.3.3 Stressors and Degradation Mechanisms

One of the most important factors in the selection cable CM techniques is the knowledge of the operating and service environment to which the cable system will be exposed during its nuclear plant service. The environmental and operational stressors acting on a cable system will cause aging and degradation mechanisms that, over time, will result in degradation, and ultimately, failure of the dielectric integrity of the cable insulation.

The following items must be identified and characterized in order to select the cable CM program inspection and testing activities that can most effectively detect and monitor the aging and degradation mechanism that can lead to cable failure:

- Active environmental stressors
- Operational stressors
- Aging mechanisms to be detected
- Degradation mechanisms to be detected

Using the environmental survey information for a given cable circuit, the cable engineer can establish the anticipated stressors to which the cable will be exposed during normal operation. The aging and degradation mechanisms that these stressors can have on the materials that are used in the construction of that cable and its cable accessories can then be determined in the evaluation process. From this information, a suite of condition monitoring inspection and testing techniques can be selected that can detect, quantify, and monitor the anticipated degradation effects for the cables to be monitored. These inspections and tests would be conducted periodically to provide cable property measurements and performance data that can be compared to baseline measurements and previous CM test results to support a review and assessment of the current condition and status of the cable circuit. [Ref. 40 – NUREG/CR-7000]

Table 2.1 presents a basic matrix summarizing the most common cable aging stressors and aging mechanisms, linked to various potential condition monitoring techniques that can be used to detect them [Ref 40 – NUREG/CR-7000]. Appendix A contains a more detailed matrix summarizing several of the most common in situ and laboratory-type cable condition monitoring techniques along with the applicable cable categories and polymer materials, operating and environmental stressors, and associated cable aging mechanisms that can be detected, characterized, and monitored over time using these CM methods. Single-page summary sheets for each of the CM techniques featured in this report are provided in Appendix B.

Table 2.1 Cable Condition Monitoring Technique Selection Matrix

Stressor	Aging Mechanism	Applicable Condition Monitoring Technique																
		Screening		Pass/Fail					Diagnostic (Shading indicates laboratory test – sample needed)									
		Visual	Borescope	Insulation Resistance	AC Voltage withstand	Hi Potential	IR Thermography	Time Domain Reflectometry	Compressive Modulus	Dielectric Loss	Polarization Index	Partial Discharge	Step Voltage	Line Resonance Analysis	Elongation-at-Break	Oxidation Induction Time/Temp	IR Spectroscopy	Density
Elevated Temperature	Embrittlement	•	•		•	•	•		•			•	•	•	•	•	•	•
	Cracking	•	•		•	•	•	•		•		•	•	•				
Radiation Exposure	Embrittlement	•	•		•	•			•			•	•	•	•	•	•	•
	Cracking	•	•		•	•		•		•		•	•	•				
Mechanical Stress	Mechanical Damage	•	•		•	•		•		•		•	•	•				
	Wear	•	•															
Voltage Stress & Moisture Exposure	Water Treeing				•	•				•		•	•					
Humid Environment	Moisture Intrusion			•	•	•				•	•		•					
Submergence	Moisture Intrusion			•	•	•							•					
Contaminants	Surface Contamination	•	•	•	•	•				•	•		•					

3. COMMONLY USED CABLE CM TECHNIQUES

This Section provides a technical discussion for several of the most commonly used, and currently available, cable condition monitoring techniques. Several of these cable testing techniques are well known to the utility industry and have been used for many years to verify cable integrity prior to energization, to monitor the condition of cable insulation, and for troubleshooting suspected cable problems. Additional new or less well-known techniques are also discussed, to represent promising state-of-the-art condition monitoring techniques. This is not intended to be a comprehensive list, and no attempt has been made to make this list all-inclusive.

The technical merits of the various cable condition monitoring techniques are presented in the framework of the attributes of an ideal cable condition monitoring method as described in the previous section of this report. The techniques discussed are categorized based upon whether they can be performed in situ, or whether they are laboratory techniques. At least two examples of each different type of technique are presented, including screening techniques, pass/fail techniques, and diagnostic techniques. These examples are taken from the currently available population of condition monitoring techniques with the understanding that research is continuing and new, more effective methods of monitoring cable condition are being developed and will be developed in the future. The reader is encouraged to review the literature to identify and implement these new, more effective techniques as they are developed.

It should be noted that the performance of electric cable condition monitoring inspection, measurement, and testing involves work on or in proximity to energized electric cables and equipment. This work should only be performed by certified, experienced personnel with the proper electrical worker safety training and using electrical safety and protection equipment suitable for the type and voltage class of the cables and equipment that will be encountered. In addition to following industry standards and good practices for electrical safety, individual plant procedural requirements for electrical safety, lockout and tagout of equipment and circuits, and electrical maintenance work requirements must also be followed.

3.1 In Situ Condition Monitoring Techniques

There are a number of condition monitoring techniques that can be performed in situ. This is a most desirable feature for a CM technique because it permits measurement of the cable circuit in the location and environment in which it is deployed in the plant. In situ testing minimizes the disturbance to the cable system, and generally, is not harmful or destructive to the cable since the removal of sample cable insulation or jacket material is not required. The following sections provide technical descriptions of several of the most common in situ cable condition monitoring techniques that are presently available.

3.1.1 Visual Inspection

General Description - Visual inspection is one of the most commonly used and effective in situ condition monitoring techniques for electric cables [Ref. 9 – NUREG/CR-6704]. It is performed by visually inspecting a cable using the naked eye to assess its physical condition and to identify the location of damage, degradation, or other significant physical changes in the appearance of a cable system. If direct access is available, the cable can also be touched to obtain tactile information.

Visual inspection is an in situ inspection technique. Since it requires no physical contact with the cable circuit under inspection, the level of intrusiveness is considered minimal and the potential for damage is minimal if cables are touched a little as possible and handled gently if contact is made.

If indications of degradation are identified during visual inspection, additional more intrusive testing may be required. As such, visual inspection is an excellent screening technique. However, it should be noted that visual inspection alone cannot detect and quantify many types of cable degradation and aging mechanisms, and should therefore be supplemented by other CM techniques.

Application – Visual inspection can be applied to any functional type of cable and any type of cable insulation or jacket material. There are no restrictions as to cable configuration or voltage class on which this technique may be used.

Special Equipment Requirements – In its basic form, visual inspection is a naked eye technique so no other special equipment is required. Visual inspection can be improved by the use of a flashlight, magnifying glass, or other magnifying instrument to enhance the inspector's view of the cable. Samples of unaged cable of the same type may be used for direct comparison with the appearance of installed cable. Digital photography may be used to document cable appearance and changes over time.

Special Training Requirements/Ease of Use – This technique is most effective when performed by experienced personnel with knowledge of cable aging mechanisms and effects, as well as familiarity in how cable aging is manifested and detected. Personnel performing the visual inspection should have knowledge of normal and degraded appearance of cable systems and accessories. Maintenance and inspection personnel should be trained to recognize the signs of aging, degradation, and damage to cable systems. For best results, a standardized procedure should be utilized that identifies the various cable attributes to be examined.

Test Results - Cable attributes that can be qualitatively assessed by visually inspection include: 1) color, including changes from the original color and variations along the length of cable, and the degree of sheen; 2) cracks, including crack length, direction, depth, location, and number per unit area; and 3) visible surface contamination, including any foreign material on the surface. In addition, the rigidity of the cable can be qualitatively determined by squeezing and gently flexing it and unusual surface texture and physical damage can be identified by touch.

For best results, a standardized procedure should be utilized that identifies the various cable attributes to be examined and provides a framework within which these attributes can be qualitatively rated and compared. Digital photographs of sections of cables or accessories of special interest can be used for comparison of changes over time.

Acceptance Criteria – If trained personnel, using procedural guidance, determine that the physical condition of a cable system appears normal, with no signs of significant deterioration, then this information can serve as the screening criteria to determine whether or not any additional condition monitoring techniques are needed.

If abnormal degradation is noted and documented, this qualitative visual condition assessment can be used to take immediate action to perform supplemental condition monitoring, repair the damaged sections, or replace the damaged cables or accessories.

Advantages and Limitations - The advantages of this technique are that it is inexpensive and relatively easy to perform, and requires no expensive equipment. A qualitative assessment of the cable's condition is obtained that can provide useful information for determining whether additional, more intrusive testing is required. While no quantitative data are provided, it is possible to trend the results of visual inspections. For example, discoloration or degree of cracking can be noted and trended over time with supplemental photographic records. This technique is most effective when performed by experienced personnel with knowledge of cable aging mechanisms and effects, as well as familiarity in how cable aging is manifested and detected.

Another important advantage of visual inspection is that it can reliably detect sections of cable exhibiting the signs of unexpectedly severe degradation that can be produced by locally adverse environmental conditions.

Disadvantages of this technique are that the cable to be inspected must be accessible and visible. In cases where cables are inaccessible, such as those installed in closed conduits or heavily loaded cable trays, a sample of accessible cables can be used as a surrogate, provided they are representative of the cables of interest. Care must be taken in extrapolating results of the surrogate population to ensure that any conclusions drawn are appropriate for the inaccessible cables. Factors to be considered are cable type, application, and environment.

Another disadvantage is that this technique does not provide quantitative data that can be easily trended. Observations can be recorded and used for comparison with future inspection results; however, the results are subjective and may differ for different inspectors.

Reference -

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

3.1.2 Compressive Modulus (Indenter)

General Description - The compressive modulus of a material is defined as the ratio of compressive stress to compressive strain below the proportional limit. Aging of the polymers used as cable insulation and jacket materials typically causes them to harden, resulting in an increase in compressive modulus. Thus, monitoring the changes in compressive modulus can be used as an indicator of the aging degradation rate of the cable material.

Compressive modulus can be measured using an Indenter Polymer Aging Monitor (Indenter). The indenter presses a pointed metallic probe into the material being tested under controlled conditions and measures the force required for the resulting displacement. These values are then used to calculate the compressive modulus of the material. The probe is computer-controlled, which limits the travel of the probe to prevent damage to the cable. Typically, measurements are taken at various lengths on the cable surface and at various circumferential positions to obtain an accurate representation of the bulk cable compressive modulus.

In testing performed by Brookhaven National Laboratory [Ref. 9 – NUREG/CR-6704] compressive modulus measurement was found to be an effective monitoring technique, which can be used in situ or in the laboratory. The indenter is easy to operate and capable of producing repeatable results that can be correlated to other known measures of cable properties, and can be used as an indicator of cable condition.

The indenter test can be performed by one person in the laboratory, or by two people in situ in a nuclear power plant environment. This is generally a non-destructive test that provides trendable, repeatable measurements of the compressive modulus (hardness) of a polymer that can be correlated to other known measures of cable properties, and can be used as an indicator of cable condition. This test is most appropriate for use on low-voltage cables in situ.

Application - This technique has been shown to be applicable to several common cable insulation and jacket materials, including ethylene propylene rubber (EPR), silicone rubber (SR), Neoprene®, polyvinyl chloride (PVC), cross-linked polyethylene (XLPE) and chlorosulfonated polyethylene (CSPE) [Ref. 9 - NUREG/CR-6704, Ref. 10 – Toman & Gardner, Ref. 11 – NUREG/CR-5772].

The test is minimally intrusive and generally considered non-destructive. Indenter measurements are most suitable for low voltage cables in situ. There is some reluctance among users to perform the test on medium-voltage and higher cables since there is a potential for the probe to damage higher voltage insulation, even though test limits and probe travel can be adjusted to minimize the chance of damaging the jacket or insulation materials.

Special Equipment Requirements – Ogden Indenter Polymer Aging Monitor (Indenter)

Special Training Requirements/Ease of Use – Specialized training and experience on the use of the indenter equipment is required, especially when in situ measurements are being made in a nuclear power plant, where two-person indenter teams are recommended. Personnel performing the test should be knowledgeable on the physical construction of various types of electric cables and experienced in recognizing the signs of aging, polymer degradation, and damage to cable systems.

Test Results – Each indenter measurement generates a compressive modulus value for the material, which is defined as the ratio of compressive stress to compressive strain below the proportional limit. Aging of the polymers used as cable insulation and jacket materials typically causes them to harden, resulting in an increase in compressive modulus. Thus, monitoring the changes in compressive modulus can be used as an indicator of the aging degradation rate of the cable material.

Compressive modulus measurements for some polymers, such as CSPE, neoprene, silicone rubber, and PVC, correspond well to the aging effects of thermal and radiation aging. Other polymer materials, such as EPR and XLPE, exhibit only modest changes in compressive modulus until they have experienced extensive thermal and radiation aging effects. [Ref. 9 - NUREG/CR-6704, Ref. 41 – Draft IEC/IEEE Std. 62582-1, Ref. 42 - Draft IEC/IEEE Std. 62582-2].

Test results from laboratory measurements, where specimen geometry, temperature and humidity are controlled, can produce reliable and repeatable results that correlate well with other well-established condition monitoring techniques, such as elongation at break (EAB) measurements. Compressive modulus changes do not give a good direct correlation to changes in electrical properties, such as insulation resistance and dielectric strength.

When performed in situ, this test measures the compressive modulus for the outer surface of an electric cable's polymer jacket material. The condition of underlying cable insulation must be inferred from the indenter compressive modulus measurements made on the outer jacket material. In addition, the values obtained are sensitive to cable construction, due to the variations in the rigidity and elasticity of the underlying materials beneath the outer surface being measured. Further, if multiconductor cables are being monitored, measurements will vary at different locations around the outer circumference of the cable, depending on whether an individual conductor or an inter-conductor space is situated directly beneath the indenter probe at the point of measurement. [Ref. 9 – NUREG/CR-6704] Consequently, a mean value for several indenter measurements is required for in situ monitoring because of the influence of cable construction and configuration geometry, particularly in multiple conductor cables.

Compressive modulus measurements can be affected by temperature of the material and by humidity for hygroscopic materials. [Ref. 9 – NUREG/CR-6704]

Acceptance Criteria – Laboratory measurements, in which specimen geometry, temperature, and humidity are controlled, can produce reliable and repeatable results that correlate well with other well-established condition monitoring techniques such as elongation at break (EAB) measurements. These compressive modulus could be linked with other established CM methods to set corrective action levels for cables.

In situ compressive modulus measurements are typically a mean value derived from multiple measurements made in the field in order to compensate for the variations in cable construction and configuration geometry, particularly in the case of multiple conductor cables. Rather than use compressive modulus results as an absolute measure of cable degradation, periodic measurements ought to be compared to baseline compressive modulus measurements from unused or mild environment cables of the same type to establish a rate of degradation for the measured material. These results are best considered along with data from other effective CM test methods to make an overall assessment of the level and rate of cable degradation.

Advantages and Limitations – The advantage of indenter compressive modulus measurements is that they are reliable and repeatable especially under controlled conditions, such as in a laboratory setting. In situ measurements may exhibit more variation but they still provide a good measure of the degradation of the materials in an electric cable.

Another advantage is that the technique is essentially non-destructive and low intrusive for low-voltage cables.

A disadvantage of this technique is that electrical cables are not always easily accessible in nuclear plants. In many cases, cables are installed under other cables in cable trays or run through conduits, which makes them inaccessible for indenter testing. Indenter testing is not always optimal even for accessible cables. For example, cables that may only be accessible for indenter testing on their outer jacket surface, which would provide minimal direct information about concealed inner jackets or insulation. To monitor the modulus of inner jackets or insulation, access might be available at a termination point; however, the termination point may be physically located in a different plant location and exposed to very different service conditions than the cable location of interest.

The compressive modulus gives direct information only on the brittleness of the outer insulation or jacket polymer material but does not tell whether the insulation is weak or significantly degraded. Compressive modulus, measured at a specific point on a cable, is an indicator of the brittleness of the outer surface polymer at that particular point on the cable, and at that particular radial point on the circumferences of the cable. Local variations due to cable internal geometry and local environment are accounted for by obtaining multiple measurements at several linear intervals along the cable section of interest and at several radial points around the cable circumference at each interval. An average of these compressive modulus measurements can then be correlated to other direct measurements of the insulation dielectric strength of a cable, such as leakage current or insulation resistance/polarization index.

Another drawback to this technique is that typical service conditions may not produce significant changes in compressive modulus in every material, which could make correlation of indenter results with thermal or radiation exposure problematic. In cases where cables are exposed to relatively mild service conditions, the resulting small modulus changes might be difficult to correlate with aging without accurate baseline measurements, which may not be available. Modulus response to service conditions may also vary based on cable construction and manufacturers' material formulations. Moreover, the conclusions are precisely applicable only to the area of the cable that was tested. This approach may be desirable to examine a cable section that had exhibited an unusual level of localized degradation due to a locally adverse environment.

References –

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

Draft IEC/IEEE Std. 62582-1 "Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods," Part 1, "General," International Electrotechnical Commission, Geneva, Switzerland. August 2009.

Draft IEC/IEEE Std. 62582-2 "Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods," Part 2, "Indenter modulus," International Electrotechnical Commission, Geneva, Switzerland. August 2009.

Draft EPRI TR-104075, "Evaluation of Cable Polymer Aging Through Indenter Testing of In-Plant and Laboratory-Aged Specimens," Electric Power Research Institute, Palo Alto, CA. January 1996.

3.1.3 Dielectric Loss (Dissipation Factor/Power Factor)

General Description - Dielectric loss measurement is an electrical test that can be performed on cables as an indicator of their condition. It includes two related tests: the dissipation factor test and the power factor test. The principle of operation is based on the fact that when a steady-state ac test voltage (V) is applied across a cable's insulation (i.e., conductor-to-ground), the resulting apparent total current (I) that flows consists of a charging current (I_C) due to the capacitance of the cable insulation and a leakage current (I_R). The relationships among the applied test voltage and the current components are shown in Figure 3.1. The phase angle θ between the applied test voltage (V) and the total current (I) flowing through the insulation is known as the dielectric phase angle. The compliment of the phase angle is called the dielectric loss angle δ.

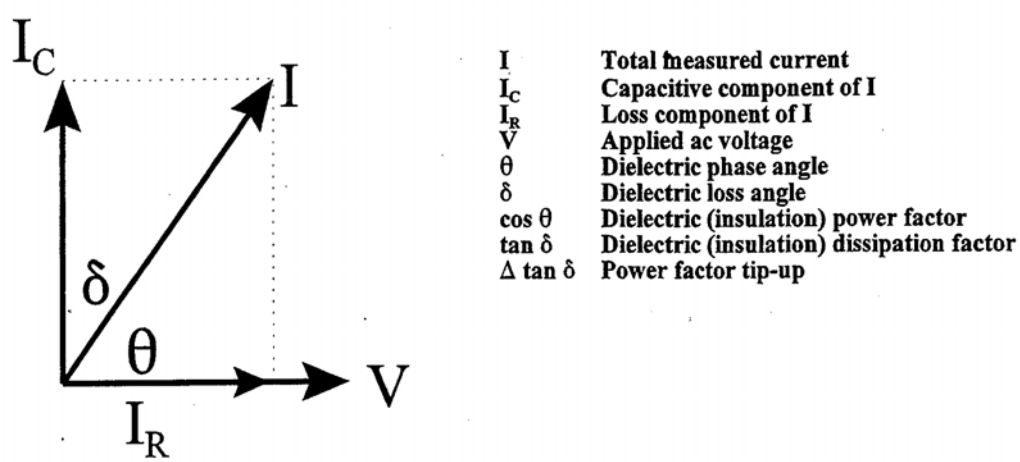

Figure 3.1 Insulation Power Factor Relationship

Typically, leakage current is much smaller than charging current in electric cable insulation, and it is more sensitive to the condition of the insulation. Insulation that is degraded due to aging will allow an increased amount of leakage current, while the capacitive current remains approximately constant. Thus, as cable insulation degrades the ratio of leakage current (I_R) to charging current (I_C) will increase. This ratio (I_R/I_C) is the tangent of the dielectric loss angle (tan δ) and is a measure of dielectric degradation. It is called the dielectric dissipation factor and is commonly used as a measure of insulation condition. Similarly, another means of describing dielectric loss is the dielectric power factor, expressed as the cosine of the dielectric phase angle (cos θ). At very low power factors (<10 percent), the dielectric power factor (cos θ) is approximately equal to the dielectric dissipation factor (tan δ).

Dielectric loss measurements are performed using a waveform generator and a spectrum analyzer. The instrumentation is connected to the conductors of the cable under test, and applies a test voltage signal to the test specimen over a range of frequencies (e.g., 0.1 Hz to 5000 Hz). Measurements are made from conductor-to-conductor, and/or from conductor-to-ground in all the conductor combinations. The resulting current response of the cable is measured and recorded for later analysis. Dissipation factor and power factor are calculated at specific frequencies of the applied test signal. ASTM Standard D150 [Ref. 12 – ASTM D150] and IEEE Standards 400 [Ref. 13 – IEEE Std. 400-2001] and 400.2 [Ref. 14 – IEEE Std. 400.2-2004] provide guidance on the performance of dielectric loss/power factor testing.

Application - This CM method is an in situ, bulk electrical properties test and is considered a non-destructive test. The technique is intrusive because it requires disconnecting the cable terminations in order to connect the test apparatus. Dielectric loss measurement can be made on cables of any application with any type of cable insulation and on low-voltage and medium-voltage cables. It is most suited to low-voltage power and I&C cables in nuclear plants because of the need to disconnect the cable to perform the measurements.

Special Equipment Requirements - Dielectric loss measurements are performed using a waveform generator and a spectrum analyzer. The instrumentation is connected to the conductors of the cable under test, and applies a test voltage signal to the test specimen over a range of frequencies (e.g., 0.1 Hz to 5000 Hz).

Special Training Requirements – Some specialized training and experience on the use of the waveform generator and a spectrum analyzer to obtain dielectric loss measurements is required. Interpretation of the results requires is best performed by an experienced engineer.

Test Results - Dielectric loss measurement is a very simple and straightforward condition monitoring technique that provides quantitative and repeatable results. Many of the factors that can affect the dielectric loss measurement can be controlled or accounted for through analysis. For example, the effect of cable length is very uniform and predictable, resulting in a relative increase in insulation power factor as the length of cable increases. This effect is most easily accounted for by obtaining in situ baseline measurements for each cable to be monitored for comparison with future measurements. Effects due to other operating electrical equipment or energized cables in the same tray as the cable under test are typically concentrated at the 60 Hz frequency of the operating equipment and can be mitigated by using an applied ac test voltage with a frequency below 50 Hz or above 70 Hz. The best results are obtained on cables with shielding, which reduces interference from nearby operating equipment.

As polymer cable insulation ages due to radiation and thermal exposure there will be a small but gradual change in the dielectric properties of the insulation system. For example, in the CM research program reported in NUREG/CR-6704 [Ref. 9. – NUREG/CR-6704], as XLPE- and EPR-insulated cable was subjected to accelerated aging from the unaged state to the equivalent of 60 years of service by exposure to high temperature and service radiation. The dielectric (insulation) power factor (cos θ) was observed to gradually increase as the cable insulation degraded over time. This change was observed over the spectrum of test frequencies from 10Hz up to about 5kHz.

Acceptance Criteria – Generalized acceptable absolute values of dielectric properties are difficult to establish because they can differ as a result of cable construction, configuration geometry, routing, length, and adjacent equipment. The most effective use of dielectric measurements is to establish baseline values for each individual cable system for comparison to periodic measurements over time. No detectable change or very gradual change over time indicates that the insulation is sound. Moisture intrusion or wetting can affect cable capacitance and can therefore be detected by a change in the dielectric measurements for the affected cable.

Advantages and Limitations – The advantages of the dielectric properties measurements method are: it is performed in situ, it is non-destructive, it is applicable to any insulation type and voltage class, only the ends of the cable must be accessible for connection of test equipment, the test is simple to perform, the bulk dielectric condition of the entire insulation system is measured, and results are reliable and repeatable.

A disadvantage of the dielectric loss technique is that the cable under test must be disconnected in order to attach the test instrument. This is undesirable since it can be cause other unforeseen problems or damage to the cable. In situ testing of cables with this technique would require the development of test procedures with independent verification steps, similar to those used for surveillance and maintenance procedures in nuclear power plants. Results can be unreliable on unshielded cables because of irregular ground return path. Because of capacitance issues, long circuits and large conductors cannot be tested with standard test equipment.

References –

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

ASTM D150, "Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation," ASTM International.

IEEE Std. 400-2001, "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems" (Revision of IEEE Std. 400-1991), IEEE, New York, January 29, 2002.

IEEE Std. 400.2-2004, "IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)," IEEE, New York, March 8, 2005.

EPRI TR-103834-P1-2, "Effects of Moisture on the Life of Power Plant Cables," Electric Power Research Institute, Palo Alto, CA. August 1994.

3.1.4 Insulation Resistance and Polarization Index

General Description - Insulation resistance measurement is a standard industry technique that is commonly performed to determine the current condition of cable insulation. It involves the application of a voltage between the cable conductor and a ground to determine the resistance of the insulation separating them. It is based on the principle that when a dc voltage is applied to an insulated conductor, a small but measurable current will flow through the insulation to ground. The total current flowing in the insulation from the conductor to ground is equal to the sum of the capacitive charging current, the leakage current and the dielectric absorption current.

These three component currents change with time. The capacitive charging current and the dielectric absorption current will initially be relatively high when the test voltage is first applied to the test specimen. Since the insulation behaves like a capacitor, after it is energized and charges have aligned across the insulation, these currents will taper off and eventually approach zero. However, leakage current will typically start at zero and then gradually increase. In high integrity insulation, leakage current will reach and maintain a steady value after a certain amount of time. If the insulation is badly deteriorated, wet, or contaminated, the leakage current will be greater than that found in good insulation and it could continue to increase over time. As a result, the total current flowing in a test specimen will start out high when a test voltage is first applied, and vary in different ways over the next several minutes depending on the condition of the insulation. To account for this behavior, insulation resistance is normally measured at one minute and again at ten minutes; then the ratio of the two measurements is calculated. This ratio is called the polarization index. IEEE Standard 400 [Ref. 13 – IEEE Std. 400-2001], IEEE Standard 141 [Ref. 15 – IEEE Std. 141-1993], and ASTM Standard D257 [Ref. 16 – ASTM D257] provide guidance on performing insulation resistance testing.

Application - This CM method is an in situ, bulk electrical properties test and is considered a non-destructive test. The technique is intrusive because it requires disconnecting the cable terminations in order to connect the test apparatus. Insulation resistance/polarization index measurement can be made on cables of any application with any type of cable insulation and on low-voltage and medium-voltage cables. It is most suited to low-voltage power and I&C cables in nuclear plants because of the need to disconnect the cable to perform the measurements.

Special Equipment Requirements – Insulation resistance/polarization index measurements are performed using a megohmmeter. The instrumentation is connected from conductor to ground, conductor to conductor, and conductor to all other conductors for each combination of conductors in the cable-under-test. The applied dc test voltage can be selected by the user, typically in a range from 10 V up to 1000 V. Stopwatch to time the 1-minute and 10-minute readings for determining polarization index.

Special Training Requirements – Some specialized training and experience on the use of the megohmmeter and performance of insulation resistance and polarization index measurements in the field. Interpretation of the results is best performed by an experienced engineer.

Test Results – Insulation resistance and polarization index measurements are very simple and straightforward condition monitoring techniques that provide quantitative and relatively repeatable results. Insulation resistance is very sensitive to temperature and moisture, therefore, in addition to applied voltage, temperature and humidity at the time of the test must be recorded and the results normalized to a base temperature, such as 60ºF (15.6ºC).

IEEE Std. 400 [Ref 13 – IEEE Std. 400-2001] states that the ICEA recommends a minimum insulation resistance of R megohms for 1000 ft. (305 m) per the equation:

$$R = K \log_{10} (D/d)$$

Where: R is insulation resistance in megohms for 1000 ft of cable
K is a constant for the specific type of cable insulation
D is the outside diameter of the insulation
d is the diameter over the conductor shield

Because of the difficulties in correcting for temperature and humidity, insulation resistance testing is very frequently used as a cable condition screening technique. It can quickly be used to determine the pass/fail status of electric cable insulation.

Polarization index, the ratio of the insulation resistance at 10 minutes to the insulation resistance at one minute, can be a more consistent and repeatable indicator of cable insulation integrity since it accounts for the time-dependent behavior of capacitive charging current, leakage current, and dielectric absorption current. Another advantage of polarization index is that the temperature correction factor required to normalize insulation resistance readings drops out of the calculation.

It should be noted that dry air is an excellent insulator, therefore, clean, dry cable insulation can exhibit high insulation resistance values even if the insulation is severely degraded and damaged. It is recommended that insulation resistance results be supplemented with one or more additional condition monitoring techniques in order to assess overall cable condition.

Acceptance Criteria – Absolute values for minimum acceptable insulation resistance, based on length and insulation type, have been recommended by ICEA as given in the above equation. It should be cautioned that dry air is a very good insulator, and even degraded and damaged cable insulation can exhibit acceptable levels of insulation resistance if it is clean and dry.

Because of the sensitivity of insulation resistance measurements to temperature, moisture and other factors, trending of insulation resistance over time compared to a baseline value can be somewhat unreliable. A better choice for data trending would be the polarization index, which is just as easy to perform, and will give more reliable and repeatable results.

It is recommended that insulation resistance/polarization measurements and data trending be considered along with the results from one or more other cable condition monitoring techniques to assess the condition and rate of degradation for cable insulation.

Advantages and Limitations - Advantages of this test are that it is relatively easy to perform and requires inexpensive equipment. Insulation resistance is often regarded as a simple pass/fail test for the dielectric integrity of electrical equipment and cables since the results are very sensitive to environmental conditions, making them too irregular for trending purposes. The results can be corrected for environmental effects, such as temperature. Measurements are normally corrected to a single temperature, such as 60ºF (15.6ºC) for electric cables. This allows the comparison of measurements taken at different times when the cable might be at different temperatures.

Polarization index provides quantitative results that can be trended over time as a measure of insulation condition. An advantage of using the polarization index is that it is not temperature dependent.

Other factors that can affect insulation resistance include cable length, humidity or moisture within the cable and insulation, dirt, oil, and other surface contaminants, personnel in close proximity to the equipment under test, and electrical equipment operating in the vicinity of the test cable. The effect of length is very uniform and predictable, resulting in a relative decrease in insulation resistance as cable length increases. The effects of length and some of the other factors can be accounted for by obtaining in situ baseline measurements for each cable to be monitored and comparing future measurements to these baseline values. The effect of other operating electrical equipment or energized cables in the same tray was found to be negligible in tests performed by BNL [Ref. 9 – NUREG/CR-6704].

Other advantages of this technique are that resistance measurements made with a megohmmeter are relatively easy to perform and require inexpensive test equipment. The megohmmeter is commonly used by all electrical maintenance personnel in nuclear power plants. To obtain meaningful results for electric cables, a megohmmeter that is capable of accurately measuring insulation resistance in the Teraohm range is required.

A disadvantage of the insulation resistance and polarization index techniques is that the cable under test must be disconnected in order to attach the test instrument. This is undesirable since it requires handling of the cable, which could result in unintentional damage, particularly for aged cable insulation that may have become embrittled. In nuclear power plants, the performance of this test would have to be controlled by procedures containing independent verification steps, as are commonly used for surveillance and maintenance activities.

Another disadvantage is that this test is not as sensitive to insulation degradation as other techniques. In some cases, such as in dry air, severe damage to the insulation may result in little change in insulation resistance. In addition, leakage currents are very small, and can be very difficult to measure accurately. They are very sensitive to surrounding environmental conditions and will vary considerably from the slightest change, such as someone walking by the cable under test.

References –

IEEE Std. 141-1993 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Chapter 12, IEEE, New York, 1993.

ASTM Standard D257, "Test Methods for DC Resistance or Conductance of Insulating Materials," ASTM International.

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

3.1.5 AC Voltage Withstand Test

General Description - The ac voltage withstand test is similar to the dc high potential test in which a cable's insulation is exposed to a high test voltage to demonstrate that the insulation can withstand a voltage potential higher than it is expected to see during service. The principle behind the test is that if defects are present in the cable, the high test voltage will force them to fail. Absent any failures, the cable is considered to be in good condition and able to continue in service. However, in the ac voltage withstand test, the test voltage is applied at very low frequencies (<1Hz) to minimize potentially adverse charging effects in the insulation that are inherent to the dc high potential test.

The test is performed with a high potential test set that applies a relatively high test voltage (e.g., 2 times rated voltage) for a set period of time (e.g., 15 minutes) between each conductor and ground. If the cable is able to withstand the voltage for the specified period, it is deemed to have passed the test and is fit for continued service; therefore, this is considered a pass/fail type test. This test is applicable to installed cables that contain a shield that can be used as a ground plane. IEEE Std. 400 [Ref. 13 – IEEE Std. 400-2001] and IEEE Std. 400.2 [Ref. 14 – IEEE Std. 400.2-2004] provide guidance on performing low frequency withstand tests.

This is a relatively simple test to perform that can provide insights into the overall condition of a cable's insulation. If defects are found and result in failure during the test, it might be possible to repair or replace the degraded or defective section(s) of the cable and return it to service.

Application - This CM method is an in situ, bulk electrical properties test, and it is considered a potentially destructive test. The technique is intrusive because it requires disconnecting the cable terminations in order to connect the test apparatus. The ac withstand voltage test can be applied to cables of any application and with any type of cable insulation. However, because of the high voltages being applied and the potentially destructive nature of the test, it is normally performed on shielded, medium- and high-voltage class cables.

Special Equipment Requirements - The test is performed with a high potential test set that applies a relatively high test voltage (e.g., 2 times rated voltage) for a set period of time (e.g., 15 minutes) between each conductor and ground.

Very long cable circuits requiring large charging currents will necessitate the use of an high potential test set with sufficient capacity to supply the power requirements of the test.

Special Training Requirements – Specialized training and experience on the use of the high potential test equipment and connectors and the performance of in situ high voltage testing under field conditions. Interpretation of the results requires is best performed by an experienced engineer.

Test Results – In the ac high potential test the ac voltage is applied in a gradually increasing ramp to minimize the buildup of high voltage stresses that could damage the cable. The method can be performed as a pass/fail test to identify insulation that has been weakened by degradation processes over time. The test can also be used to measure the magnitude of leakage current and the resulting insulation power factor, when the high potential ac voltage is applied.

Acceptance Criteria – When the ac voltage withstand test is intended to be a pass/fail test, an insulation breakdown or an excessively high magnitude of leakage current constitutes failure. Absolute limits on leakage current can be established by the user.

If the insulation of the cable-under-test does not fail during the application of the ac potential ramp, measurements of leakage current and insulation power factor can be obtained for the specified test frequency. These values may be compared with baseline values for the same cable to assess the current state and rate of insulation degradation.

Advantages and Limitations - A disadvantage of this test is that the high voltage applied to the cable-under-test has the potential to cause a voltage breakdown that could permanently damage the cable insulation. Each time the test is performed on a cable, the application of high voltage may cause an incremental increase in the amount of degradation to the dielectric integrity of the insulation. If this test is repeated excessively, the dielectric strength of the insulation could weaken to the point that the cable will fail due to the testing.

Another disadvantage is that the cable-under-test must be disconnected to attach the test equipment. This is undesirable for the reasons stated previously for the IR test.

References –

IEEE Std. 141-1993 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Chapter 12, IEEE, New York, 1993.

IEEE Std. 400-2001, "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems" (Revision of IEEE Std. 400-1991), IEEE, New York, January 29, 2002.

IEEE Std. 400.2-2004, "IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)," IEEE, New York, March 8, 2005.

ASTM D149, "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies," ASTM International.

3.1.6 Partial Discharge Test

General Description - Partial discharge testing is an ac electrical technique that can be used for condition monitoring on medium-voltage cables. It is performed by applying a sufficiently high voltage stress (the inception voltage) across a cable's insulation to induce an electrical discharge (also known as partial discharge or corona) in the small voids present within the insulation, or in air gaps between insulation and a ground plane, such as a shield in the cable. The occurrence of partial discharges indicates the presence of degradation sites in the insulation. This test can be performed at power frequency (i.e., 60Hz) or at very low frequencies (< 1Hz). Very low frequencies are sometimes used since they result in different partial discharge characteristics that may detect degradation sites that are not evident at power frequency. This test is potentially damaging since the discharges induced can cause degradation of the insulation over a period of time due to localized overheating. IEEE Std. 400-2001, "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems" [Ref. 13 – IEEE Std. 400-2001], IEEE Std. 400.3-2006, "IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment" [Ref.18 – IEEE Std. 400.3-2006], ASTM Standard D470, "Standard Test Methods for Crosslinked Insulations and Jackets for Wire and Cable" [Ref. 19 – ASTM D470] and ASTM D2633, "Standard Test

Methods for Thermoplastic Insulations and Jackets for Wire and Cable" [Ref. 20 – ASTM D2633], provide guidance on performing partial discharge testing. Additional information on partial discharge testing of low-voltage cables is provided in Reference 21 [Ref. 21 – Steiner & Martzloff, 1990].

Partial discharges typically carry electrical charges in the range of picocoulombs (pC), and can be measured using an oscilloscope connected to the cable under test. Also, their location can be determined by measuring the time lag between direct and reflected pulses from the discharge site. Alternatively, the discharges can be detected using acoustic emission monitoring techniques [Ref. 22 – Y. Tian, et. al., 2007].

Application - This CM method is an in situ, bulk electrical properties test, and it is considered a potentially destructive test because of the high ac voltage that is applied to the cable-under-test. The technique is intrusive because it requires disconnecting the cable terminations in order to connect the test apparatus. The partial discharge test is generally applied to medium-voltage and higher power cables and with any type of polymer cable insulation. Because of the high voltages being applied and the potentially destructive nature of the test, it is normally performed on shielded, medium- and high-voltage class power cables.

Special Equipment Requirements - The test is performed using highly specialized partial discharge testing equipment capable of providing an high voltage ac source of specified frequency that is capable of inducing the onset of partial discharges at voids, imperfections, gaps, or other anomalous locations within the cable insulation system. The testing apparatus also includes detection instrumentation capable of electrically identifying the magnitude and location of partial discharges in the insulation system. Acoustic detection techniques may also be used to supplement electrical detection methods as described in Reference 22 [Ref. 22 - Y. Tian, et. al.-2007]. The requirements and capabilities of this equipment are described in IEEE Std. 400.3, "IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment." [Ref 18 – IEEE Std. 400.3-2006]

Special Training Requirements – Specialized training and experience on the setup, application, and safe operation of the partial discharge testing apparatus is essential if good results are to be obtained. Because of the complex nature of this test and the number of variables that must be considered, it is recommended that this testing be conducted by specialized consultants or a dedicated partial discharge testing group familiar with the equipment being utilized and thoroughly experienced in the partial discharge testing method.

Interpretation of the results is best performed by experienced engineers because of the complex nature of the measurements, the number of variables involved, and the wide variety of approaches to the interpretation of the data. Guidance and information on the collecting and interpretation of partial discharge test data are provided in IEEE Std. 400.3-2006. [Ref. 18 – IEEE Std.400.3-2006]

Test Results – The partial discharge test provides the following information: the quantity of significant partial discharge sites above a specified detection level, magnitude or severity of the defect at each of the identified partial discharge sites, and the location of each of the significant partial discharge sites within the insulation system of the cable-under-test. Guidance and information on the interpretation and use of partial discharge test results is presented in IEEE Std. 400.3 [Ref. 18– IEEE Std. 400.3-2006].

The difficulty in interpretation of partial discharge results is described in IEEE Std. 400.3 [Ref 18 – IEEE Std 400.3-2006] as follows:

> "Data interpretation for both extruded and laminated cable systems is difficult… The PD characteristics produced by most defects usually exhibit significant variations over both the short and the long term. The magnitudes of the variations depend on the type and location of the defects, the type of cable system, and the operating conditions. Low magnitude discharges may not be measured if there is high background noise during the PD measurement.
>
> "In general the accuracy in interpretation of PD data is good when testing "very good" (low levels of PD activity) or "very bad" cable systems with, for example, low PDIV with well-defined PD characteristics. The accuracy in interpretation is less when testing able systems between "very good" and "very bad" conditions. Cable attenuation and background noise affect the PD detection and measurement sensitivity of every circuit. Thus, there is a risk of not being able to detect PD pulses or wrongly identifying pulses as PD pulses, according to the test conditions. This could lead to the risk of an incorrect assessment of the cable circuit. This risk must be recognized by everyone involved in the cable testing, the cable owner, and the test provider."

Acceptance Criteria – The threshold of "significant" partial discharges can be selected and the partial discharge test will identify the location and severity of the partial discharge sites. Based on the interpretation of the partial discharge test data, the cable user must then decide on corrective action: re-test, repair, replace, refurbish, continue to monitor on a periodic basis, or perform other testing to verify indications of the partial discharge test.

Advantages and Limitations – The advantages of partial discharge testing are that it identifies the significant partial discharge sites in a cable insulation system, the severity of the defects is provided, and the location of each of the significant partial discharge sites (and insulation defects) is given.

Limitations of the test technique are that it requires disconnecting the cable terminations for attachment of the testing apparatus, performance of the test is complex and requires high skill level, and interpretation of the test results requires an extremely high skill level to provide the greatest accuracy.

Other limitations are that the method requires relatively high voltages to be applied to the cable, which would be a concern due to the potential to damage the cable or surrounding equipment. Also, nearby operating electrical equipment in a nuclear power plant environment could interfere with the test due to noise interference, so this test is most successful on shielded cables.

References -

IEEE Std. 400.3-2006, "IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment," IEEE, New York, February 5, 2007.

ICEA T-24-380-1994, "Guide for Partial-Discharge Test Procedure."

IEC 60270, "High-voltage test techniques—Partial discharge measurements," International Electrotechnical Commission, Geneva, Switzerland.

IEC 60885-2, 1987, Electrical test methods for electric cables—Part 2: Partial discharge tests," International Electrotechnical Commission, Geneva, Switzerland.

IEC 60885-3, 1987, Electrical test methods for electric cables—Part 3: Test methods for partial discharge measurements on lengths of extruded power cables," International Electrotechnical Commission, Geneva, Switzerland.

Tian, Y. et al., "Acoustic Emission Detection of Partial Discharges in Polymeric Insulation," paper presented at Eleventh International Symposium on High Voltage Engineering, August 23-27, 1999.

3.1.7 DC High Potential Test

General Description - The dc high potential test is similar to the ac voltage withstand test in which a cable's insulation is subjected to a high voltage potential to determine if the insulation can withstand a potential higher than expected in service for a specific period of time. Since most cable insulating materials can sustain application of high dc potential without damage for very long periods, dc test voltages are sometimes preferred for repetitive field testing of cable insulation. Guidance for performing this test is provided in IEEE Std. 400.1 [Ref. 17 – IEEE Std. 400.1-2007] and IEEE Standard 141-1993 [Ref. 15 – IEEE Std. 141-1993].

Advantages and Limitations - Advantages and disadvantages of this test are similar to the ac voltage withstand test, with the exception that the dc test voltage is less likely to adversely affect the cable insulation. Another advantage to this test is that the test equipment is much smaller and more portable.

Recent research by EPRI on medium voltage XLPE- and EPR-insulated cables has shown that dc high potential testing of field-aged cables could potentially damage or cause extruded cables, especially field-aged XLPE-insulated cable, to fail prematurely [Refs. 47 & 48 – TR-101245, V1&V2]. Among the conclusions reached in this study are: dc high potential testing of field-aged cables can reduce cable life, dc high potential testing of field-aged cables generally increase water tree growth, and pre-energization dc high potential testing of new medium-voltage cable does not cause significant reduction in cable life.

References –

IEEE Std. 141-1993 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Chapter 12, IEEE, New York, 1993.

IEEE Std. 400-2001, “IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems” (Revision of IEEE Std. 400-1991), IEEE, New York, January 29, 2002.

IEEE Std. 400.1-2007 (Active), “IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage” (Revision of IEEE Std. 400-1991), IEEE, New York, September 21, 2007.

ASTM D3755, “Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials Under Direct Voltage Stress,” ASTM International.

EPRI TR-101245, V1&V2, “Effect of DC Testing on Extruded Cross-Linked Polyethylene Insulated Cables,” Electric Power Research Institute, Palo Alto, CA. 1993 (V1) and 1995 (V2).

3.1.8 Step Voltage Test

General Description - The step voltage test is similar to the high potential test in that dc test voltage is applied to a cable; however, in this test, the voltage starts low and is increased in steps until the desired maximum test voltage is achieved. Each step increase in voltage potential is followed by a hold period during which the leakage current through the insulation is measured. This is considered a diagnostic test since the leakage currents can be recorded and trended to provide insights into the condition of the insulation as a function of age and voltage potential. Guidance for performing this test is provided in IEEE Std. 400.1 [Ref. 17 – IEEE Std. 400.1-2007] and IEEE Standard 141-1993 [Ref. 15 – IEEE Std. 141-1993].

Advantages and Limitations - Advantages and disadvantages of this test are similar to those of the high potential test, with the exception that damage to the cable can be mitigated since leakage current can be monitored and the test terminated upon indications of excessively high leakage currents. Nevertheless, this test can be destructive.

References – Same as above for dc high potential test.

3.1.9 Time Domain Reflectometry

General Description - Time Domain Reflectometry (TDR) is a commonly used technique for assessing the condition of instrumentation, control, and power cables in inaccessible locations. The TDR works on the same principle as radar. A non-destructive pulse of energy is transmitted down a cable from one end, and is reflected back when it encounters (1) the far end of the cable, (2) a fault along the cable, or (3) some other problem that causes a change in the electrical impedance of the cable. The time for the signal to travel to where the impedance change is located and return back is measured by the TDR and converted into a distance. This distance is used to locate the impedance change [Ref. 9 – NUREG/CR-6704].

Application - This CM method is an in situ, electrical properties test, and it is considered a non-destructive test because of the low voltage of the test pulses. The technique is intrusive because it requires disconnecting the cable terminations in order to connect the test apparatus. The TDR test can be applied to cables of any application, with any type of cable insulation, and any voltage class.

Specialized Equipment Requirements – Time domain reflectometer (TDR) testing apparatus which consists of: a test pulse generator, an oscilloscope to measure, time, and display the return pulse, and a chart recorder or digital storage device to capture the test data for future reference and comparison.

Specialized Training Requirements – Specialized training and experience on the use of the TDR testing apparatus. High skill level is required to gather significant TDR data and to identify and characterize problem areas.

Test Results - The simplest form of TDR will display the distance to an impedance change, which could be a fault. More sophisticated TDRs can display the actual waveform or "signature" of the cable on a CRT or LCD, which will show the pulse transmitted down the cable from the instrument and any reflections that come back to the TDR from discontinuities or impedance variations along the length of the cable. Impedance variations can be caused by degradation due to aging.

TDR testing can be used to monitor cable condition by first obtaining an initial in situ baseline cable signature for a specific cable, and then comparing future TDR signatures to the baseline to identify and trend in-service degradation over time. Once the characteristic velocity of propagation for specific insulating materials and cable configurations has been determined, an experienced operator can use the TDR to detect and physically locate any cable damage that may have occurred since the last cable inspection.

Acceptance Criteria – Absolute acceptance criteria for TDR test data are not practical. This technique is best used by comparison of periodic TDR measurements against a baseline test result to identify the presence and physical location of any significant changes; these changes could indicate sites of greater degradation or other significant cable damage.

The TDR is useful in detecting the presence of moisture or submersion of the cable-under-test in standing water.

Advantages and Limitations - An advantage of TDR testing is that it is a non-destructive test that can be performed in situ to monitor the condition of low-voltage or medium-voltage cables. It provides information that can be used to determine the severity and location of a discontinuity, which could be indicative of severe insulation degradation or an impending cable fault. In addition, the test equipment needed is only moderately expensive, and the data can be trended against historic baseline reflectograms.

Disadvantages of the TDR are that the cable under test must be disconnected in order to perform the test. Also, training and experience are required of the testing personnel in order to obtain useful results, and transient conditions, such as immersion, are only detected if they are present during the TDR test.

References –

IEEE Std. 141-1993 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Chapter 12, IEEE, New York, 1993.

Technical Bulletin 070-6267-02, "1502B Metallic Time Domain Reflectometer-Service Manual," Tektronix, Inc., Beaverton, Oregon. February 1989.

3.1.10 Infrared (IR) Thermography

General Description - Infrared thermography is a non-destructive, non-contact inspection of electrical equipment that is simple to perform and is valuable in identifying potentially damaging service conditions where elevated temperatures are present [Ref. 23 – Seffrin, June 1996]. It is performed using a thermal detection or imaging system to detect, measure, and/or display the infrared, or heat radiation emitted by an object. Depending on the sensitivity and sophistication of the infrared detector, extremely accurate temperature measurements, as fine as one tenth of a degree F, may be obtained.

IR thermography can be performed with spot meters or imagers, both of which are capable of accurately measuring infrared radiation emitted from thermally hot electric equipment. The spot meter converts infrared radiation into a numeric temperature value. It is used by aiming the spot meter at the spot to be monitored, typically aided by a laser guided pointing device, and activating the device. While infrared spot meters are inexpensive and easy to operate, they require some skill, knowledge, and experience to obtain accurate, repeatable, and usable data.

Imagers convert infrared radiation into a visual image or thermogram. These devices can identify hotspots when temperature differences are as small as one tenth of a degree F. Computer software packages are available that provide trending options in which several thermal images can be analyzed over a period of time and the associated temperature data graphed.

Application – The IR thermography CM method is an in situ, physical properties test. It is non-destructive and non-intrusive since it only requires line-of-sight visual access to the cable-under-test in order to produce a thermogram. The IR thermography test method can be applied to cables and accessories of any application, with any type of cable insulation, and any voltage class.

Special Equipment Requirements - IR thermography can be performed with spot meters or IR imagers, that produce a photograph-like thermogram false-color image. Computer software packages can be used to store, analyze, and trend IR thermograms and data.

Special Training Requirements – Specialized training and experience are required for operation of IR spot meters and IR imagers. Experience is very important in the setting of the measurement parameters in order to obtain accurate and useful data and in the selection of equipment and locations to be surveyed for condition monitoring.

Test Results – IR thermography can be performed with spot meters or imagers, both of which are capable of accurately measuring infrared radiation emitted from thermally hot electric equipment. The spot meter converts infrared radiation into a numeric temperature value. IR imaging will convert infrared radiation into a visual image or thermogram. These devices can identify hotspots when temperature differences are as small as one tenth of a degree F. Computer software packages are available that provide trending options in which several thermal images can be analyzed over a period of time and the associated temperature data graphed.

Acceptance Criteria – IR thermography can be used to identify cables, splices, or terminations that are generating an unusual amount of heat which is indicative of a faulty, high resistance connection due dirt, corrosion, or other contamination. Cracked or damaged insulating or jacket materials can sometimes be identified by these techniques.

Infrared imaging provides a useful tool for identifying temperature hot-spots, which could lead to accelerated degradation of electric cable systems. The high resolution temperature detection capabilities of the instruments combined with image storage and analysis software make it possible to trend the thermal data obtained.

Advantages and Limitations – Advantages of the IR thermography CM method are that it is in situ, non-instrusive (does not require any contact with the cable-under-test), and non-destructive. With the proper setting of IR imaging parameters, very accurate surface temperature information can be gathered and differential temperature as small as 0.1 degree F. are achievable.

Another advantage is that the IR thermograms and data obtained using the high-resolution temperature detection capability of these instruments can be analyzed and stored for comparison with baseline data, and trended for changes over time. This enables close monitoring of thermal hot-spots that could lead to accelerated degradation of electric cable systems.

Disadvantages of the IR thermography CM method are that it requires line-of-sight accessibility to the cables and accessories that are to be monitored and a high level of skill and experience is needed to set up and operate the equipment, select equipment and locations for IR thermography survey, obtain the IR measurements, and to analyze the results.

References –

EPRI TR-107142, "Infrared Thermography Field Application Guide," Electric Power Research Institute, Palo Alto, CA. January 1999.

EPRI NP-6973s, Rev. 2, "Infrared Thermography Guide, Revision2," Electric Power Research Institute, Palo Alto, CA. December 1994.

3.1.11 Illuminated Borescope

General Description – The use of an illuminated borescope as an enhanced visual inspection tool to examine otherwise inaccessible cables has proven to be a useful screening technique for identifying stressors that can lead to cable degradation. It can also be used to detect visible cable damage. The borescope can be inserted into conduits, or other locations containing cables that would ordinarily be inaccessible, to visually inspect for mechanical damage that may have been caused during installation or service, the location and extent of electrical fault damage, or for indications that water has been present indicating submergence of the cables during service. The borescope can also detect the presence of other contaminants, such as dirt, sharp metal debris, or chemicals that can cause accelerated degradation of the cables. Based upon the results of a borescope inspection, a decision can be made as to whether additional, more intrusive testing is needed.

Application - The borescope inspection CM method is an in situ, physical properties/visual appearance survey method. It is non-destructive and minimally intrusive; cables do not need to be disconnected, however, it is recommended that all electrical cable systems be de-energized during the test for safety reasons. The borescope inspection technique can be used to examine the interior of underground or inaccessible duct banks, conduit runs, or other inaccessible confined equipment enclosures. The borescope inspection is an enhanced visual inspection method, therefore it can be used to inspect to cables and accessories of any application, with any type of cable insulation, and any voltage class.

Special Equipment Requirements – Illuminated focusing borescope equipment is required with sufficient length to reach into ducts, conduits, or other enclosed spaces where inspection is required. A digital camcorder or other image storage devices to maintain a video record of the inspection.

Special Training Requirements – A mild level of training is needed to achieve proficiency in operating the specific equipment, camcorders, or other accessories associated with the borescope equipment.

Test Results – Illuminated focusing borescope inspection produces an enhanced visual record of the physical appearance and condition of the cable, conduit, duct, splices or other cable accessories along the length of the cable circuit. It can provide immediate visual indication of: the presence and location of standing water; evidence of previous flooding or water intrusion, cable or duct contamination by sand, silt, animal debris, or other detritus; cable outer jacket damage or degradation; or cable fault damage.

Acceptance Criteria – The absence of standing water or evidence of flooding and submersion during a borescope inspection of underground or inaccessible cable ducts or conduits are indicative of an acceptable cable environment. No evidence of cable surface contamination, damage, degradation or other objects in the duct or conduit is also an indicator of an acceptable cable operating environment.

Borescope inspection video records do not provide qualitative data that is trendable over time. Subjective comparison of the appearance of a cable or splice over time is possible but it would be a qualitative assessment.

Borescope inspection results can best be used as a screening technique to determine whether an acceptable operating environment exists in the normally inaccessible cable runs. If a degraded condition is detected during inspection, the borescope inspection technique provides location and severity information (through evaluation of the physical appearance of the cable at the damage site) on which to base the decision to initiate corrective action or whether additional CM testing is needed to support an evaluation of cable insulation condition and rate of degradation.

Advantages and Limitations - Advantages of this technique are that it is non-destructive, simple to perform and requires little training to be successful. A disadvantage is that it does not provide quantitative data that can be trended; therefore, its main benefit is as a screening technique to determine whether immediate corrective action is required or if additional or more frequent cable CM testing is needed.

Reference – User manual(s) for the specific illuminated focusing borescope equipment and accessories.

3.1.12 Line Resonance Analysis (LIRA)

General Description -The Line Resonance Analysis (LIRA) test method is a relatively new electrical condition monitoring technique that is based on the analysis of electrical test signals input to the cable-under-test using a waveform generator. The technique models a wire system using transmission line theory and uses narrow-band frequency domain analysis of high frequency resonance effects of unmatched transmission lines to detect changes in the cable insulation's properties. The cumulative phase shift of the input impedance due to the permittivity change in the insulation is used as a condition indicator for aging and small defects. Amplitude change is used to account for larger effects.

This technique is claimed to be sensitive to small changes in wire system electric parameters, such as the insulation permittivity, that are a significant condition indicator for the aging of electric cable insulation. In addition, it is claimed that this technique can detect and localize meaningful property changes for various different electric cable insulation types and geometries for both aging and non-aging related effects [Ref. 24 – Fantoni Presentation, April 5, 2005]. Additional research is ongoing on this technique.

Application - It is claimed that this technique can detect and localize meaningful property changes for various different electric cable insulation types and geometries for both aging and non-aging related effects.

Special Equipment Requirements – LIRA testing apparatus and accessories: LIRA Generator; LIRA Modulator; digital storage oscilloscope (DSO); LIRA Analyzer; LIRA Simulator.

Special Training Requirements – The LIRA CM technique is not a simple test to perform or interpret. Training and experience are needed to setup the test apparatus and obtain meaningful results. There is also a high level of skill and experience required to interpret the results of the LIRA testing.

Test Results – The LIRA measurement consists of two condition monitoring indicators: 1) the line impedance phase shift and 2) the HotSpot Detector signature. The line impedance phase shift compares a baseline condition reading of the complex line impedance as a function of the applied signal frequency to current readings to assess a change in global electrical properties of the cable. The HotSpot Detector quantifies and locates a cable fault or defect along the length of the cable to within 0.5% of its total length.

Comparison of periodic cable impedance readings with baseline readings can be used to monitor aging and degradation of electric cables.

Acceptance Criteria – Absolute acceptance criteria are difficult to establish due to the complexity of the measurement and interpretation of the results, and the sensitivity of the test results to various cable parameters such as length, insulation type, environmental factors, and cable construction. The technique is best used to monitor the changes in cable electrical properties over time in comparison to baseline readings. Threshold levels for change, or rate of change, of the complex impedance of the monitored cable can be established by the user. These data can be used by the owner to assess current condition of a cable and support decisions to initiate corrective actions or supplement monitoring with additional or more frequent CM testing.

Advantages and Limitations – A major advantage of this technique is that it can be performed in situ without disconnecting the cable and only a single access point is needed. The effects of loads attached to the cable can be accounted for in the analysis of results. Also, degradation is claimed to be detectable prior to a failure occurring.

A disadvantage of this technique is that it is not a simple test to perform or interpret. A very high level of training and experience are needed to obtain meaningful results; the use of LIRA specialist consultants is recommended.

Reference –

> Presentation to NRC, "Wire System Aging Condition Monitoring and Fault Detection using Line Resonance Analysis," April 5, 2005, Paolo F. Fantoni, OECD Halden Reactor Project, Institutt for Energiteknikk, Halden, Norway.

3.2 Laboratory CM Techniques

In contrast to the in situ cable condition monitoring techniques, most of the laboratory cable condition monitoring techniques will destroy the polymer specimen that is being tested. The laboratory tests can be very accurate since they are conducted under the controlled conditions of the testing laboratory. For polymer research work, laboratory tests, such as the elongation at break, can be a very accurate and repeatable measure of the status of cable insulation aging degradation and there is no concern about the effect of removal of polymer jacket or insulation specimens from a cable being used for materials research.

If destructive laboratory techniques are to be used to monitor the condition of cables in the field, obtaining materials specimens can be a problem. If only tiny specimens are needed, they can be taken from the ends of very low-voltage power and I&C cable runs where they are connected to terminal blocks; but this location is also the mildest environment along a cable run so they are not representative of the harshest conditions to which a cable is exposed. Therefore, it is preferable to anticipate the quantities of material test specimens that will be required, prepare these from the same lot of cables that are to be monitored, and place the materials specimens in the field where they will be exposed to the same operating environments as the monitored cables. The specimens can then be retrieved periodically for laboratory CM testing to track the progress of aging degradation in operating cables [Ref. 40 – NUREG/CR-7000].

Given that the necessary materials samples for the cables to be monitored are available, there are a number of condition monitoring techniques available that can be performed in a laboratory. An overview of some of the most common laboratory techniques is provided below.

3.2.1 Elongation at Break

General Description - An industry standard technique for measuring a polymer's condition is elongation at break (EAB). EAB is a measure of a material's resistance to fracture under an applied tensile stress and is often termed the "ductility" of a material. When exposed to stressors such as elevated temperature and radiation levels, polymers tend to lose their ductility. As such, ductility can be used as a measure of polymer condition. The rate of ductility loss is determined by the material composition, as well as the severity of the stressors; however, in general, ductility will decrease with age. EAB has been shown to be a very accurate and repeatable method of monitoring polymer condition.

Since many cable insulation and jacket materials are polymers, EAB has proven to be an excellent condition monitoring technique for electric cables [Ref. 9 – NUREG/CR-6704]. This is particularly true for cables in a nuclear power plant environment, in which cables are exposed to a combination of thermal oxidation and gamma radiation effects.

EAB tests are typically performed using a calibrated tensile tester in accordance with ASTM Standard D638 [Ref. 25 – ASTM D638] and D412 [Ref. 26 – ASTM D412]. Test specimens are prepared from cable samples that are typically several inches long. The test specimens are commonly formed in the shape of a "dog bone" by stamping the cable material with an ASTM-approved die. The samples are then installed in the tensile tester and pulled under very specific loading conditions until they break [Ref. 43 – Draft IEC/IEEE Std. 62582-3]. This is a destructive test for the extracted specimen from the cable.

Application – The elongation at break technique can be applied to any type of polymer cable insulation or jacket material. EAB results track well with aging degradation for many polymers, such as EPDM, EPR, CSPE, SR, and PVC. The method is less useful for XLPE which tends to exhibit only gradual changes with age until approaching end-of-life when the EAB change rapidly [Ref. 41 – Draft IEC/IEEE Std. 62582-1].

Special Equipment Requirements – Polymer tensile testing machine, extensometer, software, and accessories. Standard ASTM or ISO cutting dies to prepare the standard sized and shaped tensile testing specimens for the polymer material being tested.

Special Training Requirements – Specialized training and experience is required to operate the polymer tensile testing machine, properly position and hold test specimens in the crosshead grips, and apply the software to analyze and display test results. A medium level of skill and knowledge of polymer degradation processes is recommended for the preparation of tensile test specimens since the results are heavily dependent on their uniformity and dimensions.

Test Results - EAB measurements provide a useful quantitative assessment of the condition of cable materials and are widely used by polymer cable insulation researchers as a benchmark for characterizing such materials. It is a reliable technique for determining the condition of polymers and provides trendable data that can be directly correlated with material condition. In general, as EAB decreases, crack initiation and propagation become possible from in-service stresses. This could lead to moisture intrusion and current leakage.

Acceptance Criteria - Currently, there is no standardized acceptance criterion for the minimum EAB for a cable material that will define the end of its useful service life for normal, mild or harsh environments. A conservative value of ≥50 percent has sometimes been used as an acceptance criterion; however, research testing has shown that there is usually some useful service life remaining at levels well below this [Ref. 9 – NUREG/CR-6704].

Advantages and Limitations – The advantage of the EAB test is that it has been demonstrated, through extensive research testing, that the EAB results correlate well with the progress of aging degradation in many polymers. EAB results are reliable and repeatable if the specimens are prepared carefully and consistently and the tensile testing is conducted under precisely controlled conditions by experienced personnel.

Tensile properties may vary with specimen preparation, with the speed of the moveable crosshead member, and the environmental conditions at testing. To achieve precise comparative results, all these factors must be closely controlled.

Tensile strength and elongation at break values obtained for unreinforced propylene plastics can be highly variable as a result of inconsistencies in drawing or necking that occurs in the center section of a test specimen under an applied tensile stress. The effect of necking is to reduce the cross-sectional area of the test specimen, thereby affecting the true stress, i.e., the load on the specimen divided by the instantaneous cross-sectional area through which it acts. Consequently, ASTM D 638 recommends testing at least five specimens in the case of isotropic materials and at least ten specimens, five normal to, and five parallel with, the principal axis of anisotropy, for each sample point in the case of anisotropic materials. It is also recommended that specimens that break as a result of a fortuitous flaw, improperly prepared test specimen, or at a location outside of the predetermined gage marks be discarded and retested with another specimen [Ref. 25 – ASTM D638 and Ref. 43 – Draft IEC/IEEE Std. 62582-3].

The primary disadvantage of the EAB test is that it is a destructive test, and relatively large amounts of cable are required. The necessary samples can only be obtained if a cable is removed from service, or if surveillance-type cables are installed specifically for periodic EAB testing.

References –

ASTM D638, “Standard Test Method for Tensile Properties of Plastics,” ASTM International.

Draft IEC/IEEE Std. 62582-1 “Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods,” Part 1, “General,” International Electrotechnical Commission, Geneva, Switzerland. August 2009.

Draft IEC/IEEE Std. 62582-3 “Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods,” Part 3, "Elongation at break," International Electrotechnical Commission, Geneva, Switzerland. August 2009.

ISO D 527-1, "Plastics -- Determination of tensile properties -- Part 1: General principles," International Organization for Standardization, Geneva, Switzerland.

ISO D 527-2, "Plastics -- Determination of tensile properties -- Part 2: Test conditions for moulding and extrusion plastics," International Organization for Standardization, Geneva, Switzerland.

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

3.2.2 Oxidation Induction Time/Temperature

General Description - In formulating materials that must perform for long periods of time in an environment that exposes them to oxidation, such as electric cable insulation and jacket materials, antioxidants are commonly added as one of the ingredients. The antioxidants retard the onset of oxidation, which can degrade the cable materials. Over time, these antioxidants leach to the surface and are dissipated to the environment, thus increasing the susceptibility of the material to oxidation. Consequently, as the cable insulation ages, the time to oxidation decreases. By measuring the amount of time required for oxidation of a material sample to occur under controlled conditions, the level of antioxidant remaining in the material can be estimated and correlated to the remaining life of the material.

Oxidation induction time (OITM) is a measure of the time at which rapid oxidation of a test material occurs when exposed to a predetermined constant test temperature in a flowing oxygen environment. It is measured with a differential scanning calorimeter (DSC), which is essentially an oven with the capabilities for very precise control and measurement of the heat energy supplied to a test sample. In the OITM test, the DSC supplies heat to a small (approximately 10 mg) sample of material that is placed in a small aluminum pan. The sample is cut into small pieces, each less than about 1 mg in mass. An empty pan is placed in the heating chamber of the DSC adjacent to the pan containing the test specimen to act as a control. The difference in heat supplied to the two pans is measured and represents the heat supplied to the sample.

At the beginning of the test, the temperature of the pans is raised to the predetermined test temperature in flowing nitrogen, which takes about 20 minutes. A nitrogen purge is used initially to prevent oxidation from occurring until the clock is started. When the temperature approaches the test temperature, the nitrogen is replaced by oxygen flowing at a specified rate (e.g., 50 ml/min) and the clock is started. The OITM is the time from the start of oxygen flow to the time that rapid oxidation of the sample occurs. The onset of oxidation is manifested by the appearance of a large exothermic peak in the oxidation curve (the thermogram), which is monitored as the test progresses. Typically, the OITM is measured using software supplied with the DSC. Usually, at least two replicate samples are tested to assure reproducibility. ASTM Standard D3895 [Ref. 27 – ASTM D3895] provides guidance on performing OIT testing. Use of this technique for cable condition monitoring is discussed in References 9 [Ref. 9 - NUREG/CR-6704] and 27 [Ref. 27 - ASTM D3895].

A variation of the OITM test is the oxidation induction temperature (OITP) test, which is also measured using a DSC. In this test, the test specimen is prepared in an identical way to those for OITM. However, instead of maintaining a constant test temperature and measuring the time at which oxidation initiates, the temperature of the sample is increased at a constant specified rate (e.g., 18ºF/min (10ºC/min)) in flowing oxygen and the temperature at which oxidation initiates is noted, which is the OITP. The onset of oxidation is usually considered to occur when the sample has become depleted of antioxidants, which allows the main polymer backbone to suffer rapid attack.

Application - The OITM/OITP technique can be applied to any type of polymer cable insulation or jacket material.

Special Equipment Requirements – Differential scanning calorimeter, precision balance, oxygen gas supply, nitrogen purge gas supply.

Special Training Requirements – A moderate amount of training in the operation of the differential scanning calorimeter is required to perform the measurements. A high level of skill and experience is required to interpret the results of the OIT/OITM testing.

Test Results – The Oxidation Induction Time (OITM) technique provides a measurement of the amount of time required for oxidation of a material sample to occur under controlled conditions so that the level of antioxidant remaining in the material can be estimated and correlated to the remaining life of the material.

In the Oxidation Induction Temperature (OITP) technique, instead of maintaining a constant test temperature and measuring the time at which oxidation initiates, the temperature of the sample is increased at a constant specified rate (e.g., 18ºF/min (10ºC/min)) in flowing oxygen and the temperature at which oxidation initiates is noted, which is the OITP. The onset of oxidation is usually considered to occur when the sample has become depleted of antioxidants, which allows the main polymer backbone to suffer rapid attack.

Very good results have been obtained for XLPE, PE, EPR, and EPDM materials [Ref. 9 – NUREG/CR-6704 and Refs. 41 and 44 Draft IEC/IEEE Stds. 62582-1 and –4]. The method is not suitable for chlorinated polymers, such as CSPE and PVC, because the highly corrosive products released during the thermal measurements can damage the DSC [Ref. 44 - Draft IEC/IEEE Std. 62582-4]. Use of the OITM/OITM technique for cable condition monitoring is discussed in References 9 [Ref. 9 - NUREG/CR-6704] and 27 [Ref. 27 - ASTM D3895].

Acceptance Criteria – Because of the variations in the polymer formulations for each manufacturer, the effects of additives and colorizers, and the distribution of antioxidants throughout the material, an absolute acceptance criterion is not practical. The best approach is to establish a baseline of OITM and OITP for each material and to compare subsequent periodic measurements against those baseline values to assess the progress and rate of aging degradation in the insulating material for the cables being monitored.

Advantages and Limitations - OITM / OITP is a destructive test from the standpoint of the test sample used; however, many consider this test to be non-destructive from the standpoint of the cable being tested since only a very small sample is required (i.e., 10 mg or less). It is possible that a sample this small can be obtained without damaging the cable, although the cable would have to be handled at some level. There are concerns that disturbing the cable at all to obtain such a material sample could cause problems and is undesirable. For inaccessible cables, the sample would have to be obtained from a remote location, which may not be representative of the location of interest.

Removal of insulation or jacket samples from any operating power cable would typically not be allowed by the plant operator and is not recommended from the standpoint of the potential damage that could be inflicted on the dielectric integrity of the insulation system. The preferable approach in all cases would be to place sacrificial specimens of identical materials in locations of interest along the routing of cables circuits to be monitored. Samples can then be taken from the materials specimens periodically for laboratory testing to monitor the degradation process.

References –

ASTM D 3895, "Test Method for Oxidative Induction Time of Polyolefins by Thermal Analysis," ASTM International.

Draft IEC/IEEE Std. 62582-1 "Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods," Part 1, "General," International Electrotechnical Commission, Geneva, Switzerland. August 2009.

Draft IEC/IEEE Std. 62582-4 "Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods," Part 4, "Oxidation induction techniques," International Electrotechnical Commission, Geneva, Switzerland. August 2009.

ISO Std. 11357-6, "Plastics – Differential scanning calorimetry (DSC) – Part 6: Determination of oxidation induction time (isothermal OIT) and oxidation induction temperature (dynamic OIT)," International Organization for Standardization, Geneva, Switzerland.

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

3.2.3 Fourier Transform Infrared Spectroscopy

General Description - Fourier Transform Infrared (FTIR) Spectroscopy is a well-known laboratory technique for studying the molecular structure of materials. It is performed using a spectroscope, in which a small material sample is exposed to infrared radiation. The absorbance or transmittance of this radiation by the material at various wavelengths is then measured. The principle behind this test is that, as radiation passes through a polymer, atoms absorb radiation and begin to vibrate. For a particular chemical bond, maximum vibration occurs for a specific wavelength of radiation. By irradiating a specimen with a continuous spectrum of infrared radiation and identifying the wavelengths at which maximum absorbance or transmittance occurs, the chemical bonds that are vibrating can be identified by comparison with known characteristics for chemical bonds available from the open literature [Ref. 9 – NUREG/CR-6704].

In studying the oxidation of cable materials an important wavenumber in the FTIR spectrum occurs at 1730 cm^{-1}, which indicates the presence of the carbonyl (C=O) peak. This peak is a direct indication that the polymer is undergoing oxidation and carbonyl bonds are being generated. A second important wavenumber occurs at 2915 cm^{-1} representing the $–CH_2$ bond that is part of the polymer's backbone structure. These bonds may also be present in the other constituents that are additives in the polymer material formulation [Ref. 9 – NUREG/CR-6704].

Application – The FTIR spectroscopy technique has been used successfully to characterize aging degradation for XLPE and EPR cable insulation and CSPE jacket material. It is not conclusively known how well the method will work with other types of materials used for cable insulation and jacket materials.

Special Equipment Requirements – Fourier transform infrared spectrometer equipment, refracting crystals, spectrum analysis software, and accessories.

Special Training Requirements - A high level of skill, experience, and knowledge in the operation of the FTIR spectrometer, FTIR spectroscopy, and polymer chemistry is required to properly use this technique. An engineering materials specialist knowledgeable and experienced in FTIR spectroscopy and polymer chemistry is required to interpret the polymer spectra generated by the FTIR spectroscope.

Test Results – Transmittance spectra of polymer materials are produced by the analytical software from the spectral analysis by the FTIR spectrograph. Oxidation of the materials results in peaks in the FTIR spectrum at wavenumber 1730 cm^{-1}, representing the presence of the carbonyl (C=O) bonds, and at wavenumber 2916 cm^{-1}, representing the presence of the $–CH_2$ bonds. The magnitudes of the peaks in the spectra reflected the changes in the polymer molecular structure as it oxidized over time increasing the presence of carbonyl bonds and decreasing the number of $–CH_2$ bonds. The transmittance percent at the selected wavenumber peaks also changed as the polymer materials aged due to thermal and radiation aging of the specimens.

Acceptance Criteria – Because of the variations in the polymer formulations for each manufacturer, the effects of additives and colorizers, and the distribution of antioxidants throughout the material, an absolute acceptance criterion is not practical. Variations in the testing technique, the type of refracting crystal used, and difficulties in maintain good optical contact with the specimens as they age and become more rigid also complicate the use of absolute acceptance criteria.

The best approach is to establish baseline transmittance spectra and transmittance percent values at the selected significant peak wavenumbers for each material. As the materials age, subsequent periodic measurements can then be compared to those baseline spectra and transmittance percent values for the selected peak wavenumbers to assess the progress and rate of aging degradation in the insulating material for the cables being monitored.

Advantages and Limitations - An advantage of this technique is that samples can be obtained from very small areas of cable; therefore, it can be considered a non-destructive technique. In addition, quantitative results are provided that can be trended over time for use in tracking the condition of the cable.

A disadvantage of the FTIR spectroscopy technique is that it is a surface examination procedure in which the infrared radiation passes into the surface of the specimen and is refracted back into the spectroscope crystal. The material's transmittance is determined through analysis of the intensity of the incident and reflected rays. Under harsh environment condition (i.e., elevated temperatures) an oxidation gradient could develop at the specimen surface, resulting in the spectroscope detecting a higher amount of oxidation than the average bulk value. Correlation of FTIR results for such cables with results from other techniques that accurately reflect average bulk properties, such as EAB, could be problematic. This deviation from average bulk conditions would be exacerbated as aging temperatures increase. More accurate estimates of bulk aging would be expected for cable specimens naturally-aged at service temperatures low enough to mitigate the establishment of an oxidation gradient within the cable material.

FTIR testing also has the disadvantage that, for inaccessible cables, the sample would have to be obtained from a remote location, which may not be representative of the location of interest.

Another disadvantage of the technique is the complexity of conducting the test and in the interpretation of the test results, both requiring a very high level of skill, training, and experience in the technique to extract meaningful results.

Reference –

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

3.2.4 Density

General Description - Measuring and trending the density of a cable's insulation is another technique that has been used to monitor the condition of electric cables. As polymers age, oxidation typically occurs resulting in changes to the material structure, including cross-linking and chain scission, along with the generation of oxidation products. These processes can cause shrinkage of the material, along with an increase in density. Measuring and trending the density of a cable's insulating material can, therefore, be used as a measure of cable aging [Ref. 29 – K.T.Gillen, et. al., 1999 and Ref. 51 – SAND2005-7331].

Density measurements can be made using a small piece of material (<1mg); therefore, this technique can be considered non-destructive. One method of measuring a polymer's density is to place a material sample into a calibrated liquid column, which is composed of salt solutions of various densities, or mixtures of ethanol and water, containing a gradient in density. After equilibrium is reached, the density is determined using a calibration curve for the column. Another approach involves the use of micro-balances to measure the weight of a sample both in air and then in a liquid of lower density than the sample. From these weights the density of the sample can be calculated. ASTM Standard D792 [Ref. 30 – ASTM D792] and D1505 [Ref. 31 – ASTM D1505] provide guidance on performing density measurements.

Application – The density measurement technique has been used successfully to characterize aging degradation for most polymers used for cable insulation and jacket materials.

Special Equipment Requirements – Standard physical chemistry laboratory equipment, e.g. gradient columns, solutions with different densities, precision balance.

Special Training Requirements – No special training required; standard laboratory technician skills, standard laboratory procedures.

Test Results – Density values for tested specimens.

Acceptance Criteria – There are no specific acceptance criteria for polymer material density measurements. The best approach is to establish baseline density measurements and as the materials age, subsequent periodic measurements can then be compared to those baseline density measurement values to assess the progress and rate of aging degradation in the insulating material for the cables being monitored.

Advantages and Limitations - Density measurements for typical cable insulating materials have shown good correlation with the aging of polymers as determined by other proven techniques, such as EAB. Thus, this technique could be useful as a potential monitoring technique for some cable insulating materials.

A disadvantage of this technique is that a sample of the cable insulation material must be obtained to perform this test. This presents the same problems discussed earlier in regard to accessibility and disturbance of the cable while in service. In addition, this a localized CM technique in that it will only provide information for the localized area from which the sample is taken.

References –

ASTM Standard D792, “Test Method for Specific Gravity (Relative Density) and Density of Plastics by Displacement,” ASTM International.

ASTM Standard D1505, “Test Method for Density of Plastics by the Density Gradient Method,” ASTM International.

Gillen, K.T., et al., “Density Measurements as a Condition Monitoring Approach for Following the Aging of Nuclear Power Plant Cable Materials,” Radiation Physics and Chemistry, v56, pp 429-447, 1999 Elsevier Science Ltd, Exeter England.

SAND2005-7331, “Nuclear Energy Plant Optimization (NEPO) Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials,” Sandia National Laboratories, Albuquerque, NM. November 2005.

Caution: (1) The acceptance values for various tests discussed above need special considerations for the safety significance of the cable and the environment in which it is located. For example, an underground cable that brings power to a safety bus could potentially disable a train of equipment, therefore, a conservative acceptance value is desirable. (2) The acceptance value for cables that are located in a harsh environment and expected to function during and after the impact of LOCA, need to account for the potential degradation from the accident.

4. SUMMARY

The electric cable condition monitoring techniques described in this report represent the most commonly used methods employed in the electric utility industry to detect cable insulation degradation and damage, characterize the condition of electric cable systems, monitor the status and rate of aging degradation processes, and assess the dielectric integrity of cable insulation systems. Many of the methods described represent mature technologies that have been utilized successfully in the industry for many decades; some of the techniques are newer technologies that, over time, may be developed to become as reliable and successful as the traditional test methods.

The techniques described in this report are not intended to be a comprehensive list of accepted CM methods, but rather are representative of the techniques available for characterizing and monitoring the condition of electric cables. As even newer cable CM technologies are introduced to the industry, their capabilities and merits can be evaluated against the desired attributes of the "ideal" cable CM techniques. If the newer methods show promise and gain acceptance, they can be added to the toolbox of testing methods available to the cable engineer to evaluate electric cable condition and insulation integrity.

As discussed in Section 1.1, recent electric cable operating experience has shown that there is a definite need for nuclear power plant licensees to take a more proactive approach in verifying the status of electric cable insulation integrity and demonstrating that safety-related and important-to-safety cable circuits are capable of performing their intended safety function. The more frequent occurrence of premature cable failures, often before the end of the original 40-year qualified life, have shown that functional testing alone does not fully demonstrate the capability of a cable circuit to perform its function under all normal and abnormal operating conditions, because it does not fully characterize the condition and dielectric integrity of the cable's insulation system [Ref.8 – G.A. Wilson Memo, Nov. 12, 2008].

To successfully achieve this goal, a programmatic approach to cable condition monitoring should be implemented based on the proven electric cable condition monitoring techniques described in this technical report. Such a measured approach would include cable functional testing, supplemented by periodic cable CM testing, using one or more CM techniques selected to detect and monitor the anticipated types of cable aging degradation mechanisms, and characterization and periodic monitoring of the cable operating environments.

Suggested approaches to comprehensive cable condition monitoring programs for nuclear power plants are presented in NUREG/CR-7000, "Essential Elements of an Electric Cable Condition Monitoring Program" [Ref. 40 – NUREG/CR-7000], SAND96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cable and Terminations" [Ref. 2 – SAND96-0344], IEEE Std. P1205-2000, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations"]Ref. 34 - IEEE Std. P1205], and EPRI TR-109619, "Guideline for the Management of Adverse Localized Equipment Environments" [Ref. 35 – EPRI TR-109619].

5. REFERENCES

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APPENDIX A:

MATRIX OF CABLE CM TECHNIQUES

Table A.1 Matrix of Cable Condition Monitoring Techniques [Ref. 40 – NUREG/CR-7000]

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Aging Mechanisms Detected	Advantages	Limitations
In Situ CM techniques						
Visual Inspection	Screening	All accessible cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress Voltage stress & Moisture exposure Submergence Exposure to chemicals and other surface contaminants	Thermally induced embrittlement and cracking Radiation induced embrittlement and cracking Mechanical damage and wear Potential for water treeing Potential for moisture intrusion Surface Contamination	Simple to perform Inexpensive equipment Provides useful qualitative information on cable condition- Can detect localized degradation	Requires access to cable under test Does not provide quantitative data on cable condition Knowledge and experience produce best results
Compressive Modulus (Indenter)	Diagnostic	Low-voltage cables Most effective for Ethylene-Propylene Rubber, Polyvinyl Chloride, Chlorosulfonated Polyethylene, Silicon Rubber, Cross-linked Polyethylene, and Neoprene® materials	Elevated Temperature Radiation exposure	Thermally induced embrittlement Radiation induced embrittlement	Relatively easy to perform Provides trendable data on commonly used cable insulation materials Results can be correlated to known measures of cable condition	Requires access to cable under test Location of test specimen may not be in area of concern Difficult to obtain direct access to insulation in problem areas
Dielectric Loss - Dissipation Factor/ Power Factor (AC Voltage @ varying frequencies))	Diagnostic	Low- and Medium-voltage cables Best results on shielded cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress Voltage stress & Moisture exposure Submergence Exposure to chemicals and other surface contaminants	Thermally induced cracking Radiation induced cracking Mechanical damage Water treeing Moisture intrusion Surface Contamination	Relatively easy to perform Provides trendable data on commonly used cable insulation materials Access to entire cable not required Can be correlated to known measures of cable condition	Cable must be determinated to perform test Best results obtained on shielded cables
Insulation	Pass/Fail	Low- and Medium-voltage cables	Elevated Temperature	Thermally induced cracking in the presence	Relatively easy to perform Access to entire cable not	Cable must be determinated to perform

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Aging Mechanisms Detected	Advantages	Limitations
Resistance (DC Low Voltage)		All insulation and jacket materials	Radiation exposure Moisture exposure Submergence	of moisture Radiation induced cracking in the presence of moisture Moisture intrusion	required Can be corrected for environmental effects	test Typically considered a go/no-go test with little trendable data May not detect severe insulation degradation under certain conditions Insulation resistance can be difficult to measure accurately under certain conditions
Polarization Index (DC High Voltage)	Diagnostic	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure Moisture exposure Submergence Exposure to contaminants	Thermally induced cracking in the presence of moisture Radiation induced cracking in the presence of moisture Moisture intrusion Surface contamination	Relatively easy to perform Access to entire cable not required Does not need to be corrected for temperature effects Can provide trendable data	Cable must be determinated to perform test May not detect severe insulation degradation under certain conditions Insulation resistance can be difficult to measure accurately under certain conditions
AC Voltage Withstand Test (AC High Voltage @ very low frequency)	Pass/Fail	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress Voltage stress & Moisture exposure Submergence Exposure to chemicals and other surface contaminants	Thermally induced embrittlement and cracking Radiation induced embrittlement and cracking Mechanical damage Water treeing Moisture intrusion Surface Contamination	Access to entire cable not required Can detect cable defects prior to failure in service	Cable must be determinated to perform test Testing may damage the cable insulation
Partial Discharge Test (AC High Voltage @ 60 Hz or very low frequency)	Diagnostic	Low- and Medium-voltage shielded cables All insulation and jacket materials; however, interpretation of results for extruded insulation and paper	Elevated Temperature Radiation exposure Mechanical stress Voltage stress & Moisture exposure	Thermally induced embrittlement and cracking Radiation induced embrittlement and cracking Mechanical damage	Relatively easy to perform Access to entire cable not required Can detect degradation sites prior to failure in service	Cable must be determinated to perform test Testing may damage the cable insulation

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Aging Mechanisms Detected	Advantages	Limitations
		insulated/lead covered cables may be problematic		Water treeing		
High Potential Test (DC High Voltage)	Pass/Fail	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress Voltage stress & Moisture exposure Submergence Exposure to chemicals and other surface contaminants	Thermally induced embrittlement and cracking Radiation induced embrittlement and cracking Mechanical damage Water treeing Moisture intrusion Surface Contamination	Relatively easy to perform Access to entire cable not required Can detect degradation sites prior to failure in service	Cable must be determinated to perform test Testing may damage the cable insulation
Step Voltage Test (DC High Voltage)	Diagnostic	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress Voltage stress & Moisture exposure Submergence Exposure to chemicals and other surface contaminants	Thermally induced embrittlement and cracking Radiation induced embrittlement and cracking Mechanical damage Water treeing Moisture intrusion Surface Contamination	Relatively easy to perform Provides trendable data on commonly used cable insulation materials Access to entire cable not required	Cable must be determinated to perform test Testing may damage the cable insulation
Time Domain Reflectometry	Pass/Fail or Diagnostic	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress	Thermally induced cracking Radiation induced cracking Severe mechanical damage	Provides useful information for identifying and locating potential defects in cable Nondestructive	Cable must be determinated to perform test Training and experience required for best results Transient conditions only detectable when present
Infrared Thermography	Pass/Fail	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Ohmic heating	Thermally induced embrittlement and cracking	Relatively easy to perform Properly corrected data identifies temperature and location of hot spots Measurements can be made when circuit is	Requires training and experience for best results Measurements made when circuit is operating at full load can be a

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Aging Mechanisms Detected	Advantages	Limitations
					operating at full load Data may be stored and trended with appropriate software Non-destructive, non-intrusive, does not require cable to be determinated	safety concern High end imagers and analysis software are expensive Area to be monitored must be visually accessible
Illuminated Borescope	Screening	Inaccessible Low- and Medium-voltage cables All insulation and jacket materials	Mechanical stress Submergence Exposure to chemicals and other surface contaminants	Mechanical damage Potential for moisture intrusion Surface Contamination	Relatively easy to perform Can be performed on inaccessible cables to detect the presence of stressors	Does not provide quantitative data that can be trended
Line Resonance Analysis	Diagnostic	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure Mechanical stress	Thermally induced embrittlement and cracking Radiation induced embrittlement and cracking Severe mechanical damage	Can be performed in situ without determinating the cable The effects of loads attached to the cable can be accounted for in the analysis of results. Can locate localized degradation.	It is not a simple test to perform or interpret Training and experience are needed to obtain meaningful results
Laboratory CM Techniques						
Elongation-at-Break	Diagnostic	Low- and Medium-voltage cables All insulation and jacket materials	Elevated Temperature Radiation exposure	Thermally induced embrittlement Radiation induced embrittlement	Provides information on insulation condition that can be correlated with electrical performance Proven technique for monitoring material condition Data is trendable	Destructive test Requires relatively expensive equipment and training to perform
Oxidation Induction Time Oxidation Induction	Diagnostic	Low- and Medium-voltage cables Most effective for Ethylene Propylene Rubber, Polyethylene,	Elevated Temperature Radiation exposure	Thermally induced embrittlement Radiation induced embrittlement	Provides information on insulation condition that can be correlated with electrical performance Considered non-	Requires access to cable to obtain a small sample of insulation or jacket material Requires formal training to

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Aging Mechanisms Detected	Advantages	Limitations
Temperature		and Cross-Linked Polyethylene materials			destructive since only a small sample of insulation material is required	perform and interpret results Location of test specimen may not be in area of concern
Fourier Transform Infrared Spectroscopy	Diagnostic	Low- and Medium-voltage cables Most effective for Ethylene Propylene Rubber, Polyethylene, and Cross-Linked Polyethylene materials	Elevated Temperature Radiation exposure	Thermally induced embrittlement Radiation induced embrittlement	Provides information on insulation condition that can be correlated with electrical performance Considered non-destructive since only a small sample of insulation material is required	Requires access to cable to obtain a small sample of insulation or jacket material Requires formal training to perform and interpret results Location of test specimen may not be in area of concern
Density	Diagnostic	Low- and Medium voltage cables Most effective for Ethylene-Propylene Rubber, Polyethylene, Polyvinyl Chloride, Chlorosulfonated Polyethylene, and Neoprene® materials	Elevated Temperature Radiation exposure	Thermally induced embrittlement Radiation induced embrittlement	Provides information on insulation condition that can be correlated with electrical performance Considered non-destructive since only a small sample of insulation material is required	Requires access to cable to obtain a small sample of insulation or jacket material Requires formal training to perform and interpret results Location of test specimen may not be in area of concern

APPENDIX B:

CABLE CM TECHNIQUE SUMMARY SHEETS

Cable Condition Monitoring Technique Summary Sheet

Name of Test: **Visual Inspection**		
Type of Test	**Property Measured**	**Intrusiveness**
In Situ	Physical-Visual Appearance; surface texture and damage	Low intrusiveness; non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
All	All	LV & MV	All

Special Equipment Requirements

Flashlight, magnifying lens, tape measure. Digital camera (optional)

Special Training Requirements / Ease of Use

Knowledge of normal and degraded appearance of cable systems and accessories; training to recognize the signs of aging, degradation, and damage to cable systems.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Qualitative assessment of cable color, surface cracks, and surface contamination. Tactile info on surface texture/degradation and rigidity. Digital photos of degraded or damaged cable surfaces.	Normal appearance indicates little or no degradation is occurring. Abnormal appearance or damage indicates other more-intrusive CM techniques should be conducted to assess level and rate of cable degradation.

Advantages

Easy to perform and inexpensive; can detect degradation due to locally adverse conditions;

Limitations

Cable to be inspected must be accessible and visible.
Results are not quantitative; trending of qualitative results is difficult.
Appearance data are subjective and may vary from inspector to inspector.

References & Applicable Standards

NUREG/CR-6704, “Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables,” Brookhaven National Laboratory.

Name of Test:

Compressive Modulus (Indenter)

Type of Test	Property Measured	Intrusiveness
In Situ/Laboratory	Compressive Modulus (Hardness)	Low intrusiveness; non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
Power, I&C, Comm.	EPR, SR, Neoprene, CSPE, PVC, XLPE	LV MV w/ caution	1/C & Coax (best) Multi/C (avg)

Special Equipment Requirements

Ogden Indenter Polymer Aging Monitor (Indenter tester)

Special Training Requirements / Ease of Use

Training on use of indenter test equipment and software.
Knowledge of cable construction and signs of aging, degradation and damage to cable systems.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Compressive modulus measurements. Good results and repeatability for SR, CSPE, PVC, Neoprene; very gradual change for XLPE and EPR until end of service life. Mean value of multiple measurements required for multi-conductor cables to counter variations due to cable geometry and underlying materials.	Lab measurements are reliable and repeatable; correlate well with other mechanical CM methods such as EAB. In situ results are best used to periodically monitor compressive modulus changes in comparison to unaged baseline values. Compressive modulus measurements could be linked with other established CM methods to set corrective action levels for cables.

Advantages

In situ CM technique; non-destructive; good repeatability of results; compressive modulus results correlate well with other established CM methods.

Limitations

Cables must be accessible for in situ measurement.
Measurements are made on outer surface; condition of underlying insulation must be inferred.
Results affected by underlying cable construction, cable geometry, temperature, humidity.
Aging-related changes in compressive modulus very small for some polymers until end-of-life.

References & Applicable Standards

NUREG/CR-6704, “Assessment of EQ Practices & CM Techniques for LV Electric Cables,” BNL
Draft IEC/IEEE Std. 62582-1, electrical equipment CM methods, Part1, “General”
Draft IEC/IEEE Std. 62582-2, electrical equipment CM methods, Part2, “Indenter modulus”
Draft EPRI TR-104075, “Evaluation of Cable Polymer Aging Through Indenter Testing of In-Plant and Laboratory-Aged Specimens”

Name of Test:

Dielectric Loss (Dissipation Factor/Power Factor)

Type of Test	Property Measured	Intrusiveness
In Situ	Insulation dielectric properties	High intrusiveness; Non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
Power, I&C, Comm.	All	LV and MV	1/C/ w/ gnd or shield; Multi/C

Special Equipment Requirements

Waveform generator and spectrum analyzer; specialized commercial dielectric test equipment

Special Training Requirements / Ease of Use

Experience and training on the use of the specialized test equipment is required.
Experienced engineer required to analyze results.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Dielectric loss measurement for the entire insulation system at one or more specified frequencies. As polymer cable insulation ages due to radiation and thermal exposure there will be a small but gradual change in the dielectric properties of the insulation system, e.g., dielectric (insulation) power factor (cos θ) will gradually increase over time as the insulation ages.	Absolute acceptance criteria not practical. No change or minimal change indicates sound insulation. Most effective use of dielectric measurements is to establish baseline values for each individual cable system for comparison to periodic measurements over time.

Advantages

In situ CM technique; non-destructive; easy to perform; good repeatability of results; dielectric properties of insulation correlate well with other established CM methods. Measures integrity of entire insulation system. Only require access to ends of cable circuit to attach test equipment.

Limitations

End terminations of the cable-under-test must be disconnected to permit attachment of the test equipment. Results can be unreliable on unshielded cables because of irregular ground return path. Because of capacitance issues, long circuits and large conductors cannot be tested with standard test equipment.

References & Applicable Standards

ASTM D150, “Standard Test Methods for AC Loss Characteristics & Permittivity (Dielectric Constant) of Solid Electrical Insulation.
NUREG/CR-6704, “Assessment of EQ Practices & CM Techniques for LV Electric Cables,” BNL
EPRI TR-103834-P1-2, “Effects of Moisture on the Life of Power Plant Cables.”

Cable Condition Monitoring Technique Summary Sheet

Name of Test: **Insulation Resistance / Polarization Index**		
Type of Test	**Property Measured**	**Intrusiveness**
In Situ	Insulation dielectric properties; leakage current	High intrusiveness; Non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
Power, I&C, Comm.	All	LV, MV, & higher	1/C/ w/ gnd or shield; Multi/C

Special Equipment Requirements

Megohmmeter

Special Training Requirements / Ease of Use

Some specialized training and experience on the use of the megohmmeter and performance of insulation resistance and polarization index measurements in the field. Interpretation of the results is best performed by an experienced engineer.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
IR and PI measurements are very simple and straightforward CM techniques that provide quantitative and relatively repeatable results. IR is very sensitive to temperature and moisture, therefore, in addition to applied voltage, temperature and humidity at the time of the test must be recorded and the results normalized to a base temperature, such as 60ºF (15.6ºC).	Absolute values for min acceptable IR, based on length and insulation type, have been recommended by ICEA. PI will give more reliable and repeatable results for trending. IR/PI results and data trending should be considered along with the results from one or more other cable CM methods to assess the condition and rate of degradation for cable insulation.

Advantages

Easy to perform and IR often regarded as a simple pass/fail test for insulation dielectric integrity. PI provides quantitative results that can be trended over time.

Limitations

Cable-under-test must be disconnected in order to attach the test instrument. Not as sensitive to insulation degradation as other techniques. Leakage currents are very small, and can be very difficult to measure accurately; they are very sensitive to surrounding environmental conditions.

References & Applicable Standards

IEEE Std. 141-1993 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Chapter 12, IEEE, New York, 1993.
ASTM Standard D257, "Test Methods for DC Resistance or Conductance of Insulating Materials," ASTM International.
NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

Name of Test:

AC Voltage Withstand Test

Type of Test	Property Measured	Intrusiveness
In Situ	Insulation dielectric properties; leakage current	High intrusiveness; Potentially destructive

Application

Cable Type	Materials	Voltage Class	Configuration
Power	All	MV & higher	1/C/ w/ gnd or shield; Multi/C

Special Equipment Requirements

The test is performed with a high potential test set that applies a relatively high test voltage (e.g., 2 times rated voltage) for a set period of time between each conductor and ground.

Special Training Requirements / Ease of Use

Specialized training and experience on use of the high potential test equipment and connectors and the performance of in situ high voltage testing under field conditions. Interpretation of the results requires is best performed by an experienced engineer.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
ac voltage is applied in a ramp to minimized the buildup of high voltage stresses that could damage the cable. Can be performed as a pass/fail test to identify insulation that has been weakened by degradation processes over time. Test can also be used to measure magnitude of leakage current, when the high potential ac voltage is applied, and the resulting insulation power factor.	As pass/fail test, insulation breakdown or an excessively high magnitude of leakage current constitutes failure. Absolute limits on leakage current can be established by the user. Leakage current and insulation power factor can be obtained for specified test frequency and values may be compared with baseline values for the same cable to assess the status and rate of insulation degradation over time.

Advantages

Easy to perform and regarded as a simple pass/fail test for insulation dielectric integrity.

Limitations

High voltage applied to the cable-under-test has the potential to cause a voltage breakdown that could permanently damage the cable insulation. Each time the test is performed on a cable, the application of high voltage may cause an incremental increase in the amount of degradation to the dielectric integrity of the insulation.

Cable-under-test must be disconnected to attach the test equipment.

References & Applicable Standards

ASTM D149, “Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies,” ASTM International.

IEEE Std. 400-2001, “IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems” (Revision of IEEE Std. 400-1991), IEEE, New York, January 29, 2002.

IEEE Std. 400.2-2004, “IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF),” IEEE, New York, March 8, 2005.

IEEE Std. 141-1993 (Red Book), “IEEE Recommended Practice for Electric Power Distribution for Industrial Plants,” Chapter 12, IEEE, New York, 1993

Cable Condition Monitoring Technique Summary Sheet

<table>
<tr><td colspan="4">Name of Test:
Partial Discharge Test</td></tr>
<tr><td colspan="2">Type of Test</td><td>Property Measured</td><td>Intrusiveness</td></tr>
<tr><td colspan="2">In Situ</td><td>Magnitude and location of partial discharges</td><td>High intrusiveness; medium potential destructiveness</td></tr>
<tr><td colspan="4">Application</td></tr>
<tr><td>Cable Type</td><td>Materials</td><td>Voltage Class</td><td>Configuration</td></tr>
<tr><td>Power</td><td>All</td><td>MV & higher</td><td>1/C/ w/ gnd or shield; Multi/C</td></tr>
<tr><td colspan="4">Special Equipment Requirements</td></tr>
<tr><td colspan="4">Specialized partial discharge testing & detection equipment and software. Acoustic detection equipment.</td></tr>
<tr><td colspan="4">Special Training Requirements / Ease of Use</td></tr>
<tr><td colspan="4">Specialized training and experience on the setup, application, and safe operation of the partial discharge testing apparatus. Testing and Interpretation of the results is best performed by experienced engineers because of the complex nature of the technique.</td></tr>
<tr><td colspan="4">Test Results</td></tr>
<tr><td colspan="2">Format/Interpretation of Test Results</td><td colspan="2">Acceptance Criteria</td></tr>
<tr><td colspan="2">Quantity of significant partial discharge sites above a specified detection level, magnitude or severity of the defect at each partial discharge sites, and the location of each of the significant partial discharge sites within the insulation system. Interpretation of the results is best performed by experienced engineers. because complexity of testing and interpretation of data.</td><td colspan="2">Threshold of “significant” partial discharges can be selected; partial discharge test will identify the location and severity of partial discharge sites. Based on the interpretation of the partial discharge test data, the cable user must then decide on corrective action: re-test, repair, replace, refurbish, continue to monitor on a periodic basis, or perform other testing to verify indications of the partial discharge test.</td></tr>
<tr><td colspan="4">Advantages</td></tr>
<tr><td colspan="4">Identifies the significant pd sites in insulation system, severity of the defects is provided, and the location of each of the significant pd sites (and insulation defects) is given.</td></tr>
<tr><td colspan="4">Limitations</td></tr>
<tr><td colspan="4">Requires disconnecting the cable terminations for attachment of the testing apparatus, test performance is complex and requires high skill level; interpretation of results requires very high skill level. High testing voltage has potential to weaken and permanently damage insulation.</td></tr>
<tr><td colspan="4">References & Applicable Standards</td></tr>
<tr><td colspan="4">IEEE Std. 400.3-2006, “IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment,” IEEE, New York, February 5, 2007.
ICEA T-24-380-1994, “Guide for Partial-Discharge Test Procedure.”
IEC 60270, “High-voltage test techniques—Partial discharge measurements,” International Electrotechnical Commission, Geneva, Switzerland.
IEC 60885-2, 1987, Electrical test methods for electric cables—Part 2: Partial discharge tests,” International Electrotechnical Commission, Geneva, Switzerland.
IEC 60885-3, 1987, Electrical test methods for electric cables—Part 3: Test methods for partial discharge measurements on lengths of extruded power cables,” International Electrotechnical Commission, Geneva, Switzerland.</td></tr>
</table>

Cable Condition Monitoring Technique Summary Sheet

Name of Test: DC High Potential Test		
Type of Test	**Property Measured**	**Intrusiveness**
In Situ	Insulation dielectric properties; leakage current	High intrusiveness; medium to high potential destructiveness

Application

Cable Type	Materials	Voltage Class	Configuration
Power	All	MV & higher	1/C/ w/ gnd or shield; Multi/C

Special Equipment Requirements

The test is performed with a high potential test set that applies a relatively high test voltage for a set period of time between each conductor and ground.

Special Training Requirements / Ease of Use

Specialized training and experience on use of the high potential test equipment and connectors and the performance of in situ high voltage testing under field conditions. Interpretation of the results requires is best performed by an experienced engineer.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Can be performed as a pass/fail test to identify insulation that has been weakened by degradation processes over time. Test can also be used to measure magnitude of leakage current.	When intended as a pass/fail test, an insulation breakdown or an excessively high magnitude of leakage current constitutes failure. Absolute limits on leakage current can be established by the user. Leakage current can be trended and/or compared with baseline values.

Advantages

Easy to perform and regarded as a simple pass/fail test for insulation dielectric integrity.

Limitations

Recent research by EPRI on MV XLPE- and EPR- insulated cables has shown that dc high potential testing of field-aged cables could potentially damage or cause extruded cables, esp. field-aged XLPE-insulated cable, to fail prematurely [EPRI TR-101245, V1&V2]. Among the conclusions reached: dc hi-pot testing of field-aged cables can reduce cable life and generally increased water tree growth; dc hi-pot testing of new MV cable didn't reduce cable life.

References & Applicable Standards

IEEE Std. 400-2001, "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems," IEEE, New York, January 29, 2002.
IEEE Std. 400.1-2007 (Active), "IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage," IEEE, NY.
ASTM D3755, "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials Under Direct Voltage Stress," ASTM International.
EPRI TR-101245, V1&V2, "Effect of DC Testing on Extruded Cross-Linked Polyethylene Insulated Cables," Electric Power Research Institute, Palo Alto, CA. 1993 (V1) and 1995 (V2).

Name of Test:

Step Voltage Test

Type of Test	Property Measured	Intrusiveness
In Situ	Electrical/Mechanical/Physical/ Physical-Visual Appearance	High intrusiveness; medium to high potential destructiveness

Application

Cable Type	Materials	Voltage Class	Configuration
Power	All	MV & higher	1/C/ w/ gnd or shield; Multi/C

Special Equipment Requirements

The test is performed with a high potential test set that applies a relatively high test voltage for a set period of time between each conductor and ground.

Special Training Requirements / Ease of Use

Specialized training and experience on use of the high potential test equipment and connectors and the performance of in situ high voltage testing under field conditions. Interpretation of the results requires is best performed by an experienced engineer.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Can be performed as a pass/fail test to identify insulation that has been weakened by degradation processes over time. Test voltages applied in increasing steps up to max test voltage, measuring leakage current at each increment. Test can be aborted if excess leakage current exceeds preset limit to avoid damage or insulation breakdown.	When intended as a pass/fail test, an insulation breakdown or an excessively high magnitude of leakage current constitutes failure. Absolute limits on leakage current can be established by the user. Leakage current can be trended and/or compared with baseline values.

Advantages

Easy to perform and regarded as a simple pass/fail test for insulation dielectric integrity. Test can be aborted if preset leakage current limit exceeded to avoid insulation damage/breakdown.

Limitations

Cable-under-test must be disconnected from terminations to attach test equipment.
Recent research by EPRI on MV XLPE- and EPR- insulated cables has shown that dc high potential testing of field-aged cables could potentially damage or cause extruded cables, esp. field-aged XLPE-insulated cable, to fail prematurely [EPRI TR-101245, V1&V2].

References & Applicable Standards

IEEE Std. 400-2001, "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems," IEEE, New York, January 29, 2002.
IEEE Std. 400.1-2007 (Active), "IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage," IEEE, NY.
ASTM D3755, "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials Under Direct Voltage Stress," ASTM International.
EPRI TR-101245, V1&V2, "Effect of DC Testing on Extruded Cross-Linked Polyethylene Insulated Cables," Electric Power Research Institute, Palo Alto, CA. 1993 (V1) and 1995 (V2).

Name of Test:

Time Domain Reflectometry (TDR)

Type of Test	Property Measured	Intrusiveness
In situ	Magnitude & location of changes in cable impedance	High intrusiveness; Non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
All	All	LV & MV	1/C/ w/ gnd or shield; Multi/C

Special Equipment Requirements

Time domain reflectometer (TDR) testing apparatus, accessories, and analytical software.

Special Training Requirements / Ease of Use

Specialized training and experience on the use of the TDR testing apparatus. High skill level is required to gather significant TDR data and to identify and characterize problem areas.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Basic TDR displays location of impedance change, which could be a fault or water. Adv. DRs can display the actual waveform or "signature" of the cable on a CRT or LCD, which will show the pulse transmitted down the cable from the instrument and any reflections that come back to the TDR from discontinuities or impedance variations along the length of the cable.	No absolute acceptance criteria. Once characteristic velocity of propagation for specific insulating materials and cable configurations has been determined, an experienced TDR operator can detect and physically locate any cable damage or degradation that may have occurred since the baseline TDR survey or any subsequent cable inspections.

Advantages

In situ, non-destructive test; Identifies severity/location of a discontinuity, which may indicate severe insulation degradation or impending cable fault. Data can be trended against baseline.

Limitations

Cable-under-test must be disconnected from terminations to attach test equipment. High level of training and experience required to obtain useful results. Transient conditions, such as immersion, are only detected if they are present during the TDR test.

References & Applicable Standards

IEEE Std. 141-1993 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Chapter 12, IEEE, New York, 1993.

Technical Bulletin 070-6267-02, "1502B Metallic Time Domain Reflectometer-Service Manual," Tektronix, Inc., Beaverton, Oregon. February 1989.

Name of Test:

Infrared (IR) Thermography

Type of Test	Property Measured	Intrusiveness
In Situ	High resistance/degraded splices, connections, tap-offs	Non-intrusive, non-contact; No potential for damage

Application

Cable Type	Materials	Voltage Class	Configuration
All	All	LV, MV, & higher	All

Special Equipment Requirements

IR thermography czn be performed with spot meters, but IR imagers, that produce a photograph-like thermogram false-color image are best. Computer software packages can be used to store, analyze, and trend IR thermograms and data.

Special Training Requirements / Ease of Use

Specialized training and experience are required for operation of IR spot meters and IR imagers. Experience is very important in the setting of the measurement parameters in order to obtain accurate and useful data and in the selection of equipment and locations to be surveyed for condition monitoring.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
IR thermography can be performed with spot meters or imagers, both of which are capable of accurately measuring infrared radiation emitted from thermally hot electric equipment. The spot meter converts infrared radiation into a numeric temperature value. IR imaging will convert infrared radiation into a visual image or thermogram. These devices can identify hotspots when temperature differences are as small as one tenth of a degree F. Computer software packages are available that provide trending options in which several thermal images can be analyzed over a period of time and the associated temperature data graphed.	IR thermography can identify faulty cables, connectors, splices, or terminations that are generating an excessive heat indicative of a degraded high resistance connection due dirt, corrosion, of other contamination. Cracked or damaged insulating or jacket materials can also be identified by these techniques. IR imaging provides a useful tool for identifying temperature hot-spots, which could lead to accelerated degradation of electric cable systems. The high resolution temperature detection and image storage capabilities of analysis software make it possible to trend the thermal data obtained.

Advantages

Non-intrusive; non-contact; no potential to damage cable systems; accurate; trendable

Limitations

Requires line-of-sight accessibility. High level of skill and experience to set up and operate the equipment, identify survey locations for IR thermography, and analyze the results.

References & Applicable Standards

EPRI TR-107142, "Infrared Thermography Field Application Guide," Electric Power Research Institute, Palo Alto, CA. January 1999.

EPRI NP-6973s, Rev. 2, "Infrared Thermography Guide, Revision2," Electric Power Research Institute, Palo Alto, CA. December 1994.

Name of Test:

Illuminated Borescope Inspection

Type of Test	Property Measured	Intrusiveness
In Situ	Physical-Visual Appearance	Low intrusiveness; Non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
All	All	LV; MV & higher w/ caution	All

Special Equipment Requirements

Illuminated focusing borescope equipment. Digital camcorder or other storage devices to maintain a video record of the inspection.

Special Training Requirements / Ease of Use

A mild level of training is needed to achieve proficiency in operating the specific equipment, camcorders, or other accessories associated with the borescope equipment.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Illuminated focusing borescope inspection produces an enhanced visual record of the physical appearance and condition of the cable, conduit, duct, splices or other cable accessories along the length of the cable circuit. It can provide immediate visual indication of: the presence and location of standing water; evidence of previous flooding or water intrusion, cable or duct contamination by sand, silt, animal debris, or other detritus; cable outer jacket damage or degradation; or cable fault damage.	The absence of standing water or evidence of flooding and submersion during a borescope inspection of underground or inaccessible cable ducts or conduits are indicative of an acceptable cable environment. No evidence of cable surface contamination, damage, degradation or other objects in the duct or conduit are also indicators of an acceptable cable operating environment.

Advantages

Non-destructive, simple to perform, and requires little training to be successful. Provides visual survey of underground or otherwise inaccessible cable runs.

Limitations

A disadvantage is that it does not provide quantitative data that can be trended; therefore, its main benefit is as a screening technique to determine whether immediate corrective action is required or if additional or more frequent cable CM testing is needed.

References & Applicable Standards

User manual(s) for the specific illuminated focusing borescope equipment and accessories.

Name of Test:

Line Resonance Analysis (LIRA)

Type of Test	Property Measured	Intrusiveness
In Situ	Insulation dielectric properties	Low intrusiveness; Non-destructive

Application

Cable Type	Materials	Voltage Class	Configuration
Power, I&C, Comm.	All	LV; MV & higher with caution	All

Special Equipment Requirements

LIRA testing apparatus and accessories: LIRA Generator; LIRA Modulator; digital storage oscilloscope (DSO); LIRA Analyzer; LIRA Simulator.

Special Training Requirements / Ease of Use

The LIRA CM technique is not a simple test to perform or interpret. Training and experience are needed to setup the test apparatus and obtain meaningful results. There is also a high level of skill and experience required to interpret the results of the LIRA testing.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
LIRA measurement consists of two CM indicators: 1) the line impedance phase shift and 2) the HotSpot Detector signature. The line impedance phase shift compares a baseline condition reading of the complex line impedance as a function of the applied signal frequency to current readings to assess a change in global electrical properties of the cable. The HotSpot Detector quantifies and locates a cable fault or defect along the length of the cable to within 0.5% of its total length.	Absolute acceptance criteria are difficult to establish due to complexity of the measurement and interpretation of the results, and the sensitivity of the test results to various cable parameters such as length, insulation type, environmental factors, and cable construction. LIRA is best used to monitor the changes in cable electrical properties over time compared to baseline readings. Threshold levels for change, or rate of change, of the complex impedance of the monitored cable can be established by the user.

Advantages

Performed in situ without disconnecting the cable; only a single access point is needed; non-destructive. Effects of attached loads can be accounted for in the analysis of results. Also, degradation is claimed to be detectable prior to a failure occurring.

Limitations

A very high level of training and experience are needed to obtain meaningful results; the use of LIRA specialist consultants is recommended.

References & Applicable Standards

Presentation to NRC, “Wire System Aging Condition Monitoring and Fault Detection using Line Resonance Analysis,” April 5, 2005, Paolo F. Fantoni, OECD Halden Reactor Project, Institutt for Energiteknikk, Halden, Norway.

<table>
<tr><td colspan="12">Name of Test:
Elongation at Break</td></tr>
<tr><td colspan="4">Type of Test</td><td colspan="4">Property Measured</td><td colspan="4">Intrusiveness</td></tr>
<tr><td colspan="4">Laboratory</td><td colspan="4">Polymer tensile strength;
Ultimate elongation</td><td colspan="4">Surrogate Specimens Req'd;
Destructive to Specimen</td></tr>
<tr><td colspan="12">Application</td></tr>
<tr><td colspan="3">Cable Type</td><td colspan="3">Materials</td><td colspan="3">Voltage Class</td><td colspan="3">Configuration</td></tr>
<tr><td colspan="3">All</td><td colspan="3">EPDM, EPR, CSPE, SR, PVC. Also XLPE</td><td colspan="3">All</td><td colspan="3">All</td></tr>
<tr><td colspan="12">Special Equipment Requirements</td></tr>
<tr><td colspan="12">Polymer tensile testing machine, extensometer, software, and accessories. Standard ASTM or ISO cutting dies to prepare the standard sized and shaped tensile testing specimens.</td></tr>
<tr><td colspan="12">Special Training Requirements / Ease of Use</td></tr>
<tr><td colspan="12">Specialized training and experience for testing and specimen preparation.</td></tr>
<tr><td colspan="12">Test Results</td></tr>
<tr><td colspan="6">Format/Interpretation of Test Results</td><td colspan="6">Acceptance Criteria</td></tr>
<tr><td colspan="6">EAB measurements provide a useful quantitative assessment of the condition of cable materials and are widely used by polymer cable insulation researchers as a benchmark for characterizing such materials. It is a reliable technique for determining the condition of polymers and provides trendable data that can be directly correlated with material condition.</td><td colspan="6">Currently, there is no standardized acceptance criterion for the minimum EAB for a cable material that will define the end of its useful service life for normal, mild or harsh environments. A conservative value of ≥50 percent has sometimes been used as an acceptance criterion; however, research testing has shown that there is usually some useful service life remaining at levels well below this [NUREG/CR-6704].</td></tr>
<tr><td colspan="12">Advantages</td></tr>
<tr><td colspan="12">EAB results correlate well with the progress of aging degradation in many polymers. EAB results are reliable and repeatable if the specimens are prepared carefully and consistently and the tensile testing is conducted under precisely controlled conditions by experienced personnel.</td></tr>
<tr><td colspan="12">Limitations</td></tr>
<tr><td colspan="12">Tensile properties may vary with specimen preparation, with the speed of the moveable crosshead member, and the environmental conditions at testing.
Destructive test to specimen, and relatively large amounts of cable are required.</td></tr>
<tr><td colspan="12">References & Applicable Standards</td></tr>
<tr><td colspan="12">ASTM D638, "Standard Test Method for Tensile Properties of Plastics," ASTM International.
Draft IEC/IEEE Std. 62582-3 "Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods," Part 3, "Elongation at break," International Electrotechnical Commission, Geneva, Switzerland. August 2009.
ISO D 527-2, "Plastics -- Determination of tensile properties -- Part 2: Test conditions for moulding and extrusion plastics," International Organization for Standardization, Geneva, Switzerland.
NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.</td></tr>
</table>

Cable Condition Monitoring Technique Summary Sheet

Name of Test:

Oxidation Induction Time (OIT) / Temperature (OITM)

Type of Test	Property Measured	Intrusiveness
Laboratory	Chemical Properties – oxidation of polymer	Surrogate Specimens Req'd; Destructive to Specimen

Application

Cable Type	Materials	Voltage Class	Configuration
All	XLPE, EPDM, EPR, CSPE, SR, PVC, EVA	All	All

Special Equipment Requirements

Differential scanning calorimeter, precision balance, O_2 gas supply, N_2 purge gas supply.

Special Training Requirements / Ease of Use

Moderate amount of training in the operation of the differential scanning calorimeter is required to perform the measurements. High level of skill and experience to interpret testing results.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
OITM measures time req'd for oxidation of a material sample to occur under controlled conditions; estimates antioxidant remaining correlating to remaining life. In OITP, an increasing temp. ramp is applied to sample in O_2 and the temperature at which oxidation initiates is recorded, indicating depletion of antioxidants has occurred. Very good results for XLPE, PE, EPR, and EPDM; method not well suited to chlorinated polymers, such as CSPE and PVC, because the highly corrosive products released can damage the DSC.	Absolute acceptance criterion is not practical. Best approach is to establish a baseline of OITM and OITP for each material and to compare subsequent periodic measurements against those baseline values to assess the progress and rate of aging degradation in the insulating material for the specific cables being monitored.

Advantages

Reliable & repeatable results for common polymer materials; correlates with aging degradation.

Limitations

Surrogate specimens req'd since method is destructive to test specimen; results applicable only for the exact polymer formulation and environmental exposure history at the specific plant location from which the specimen was removed. High skill level req'd to interpret testing results.

References & Applicable Standards

ASTM D 3895, "Test Method for Oxidative Induction Time of Polyolefins by Thermal Analysis," ASTM International.

Draft IEC/IEEE Std. 62582-4 "Nuclear power plants-Instrumentation and control important to safety – electrical equipment condition monitoring methods," Part 4, "Oxidation induction techniques," International Electrotechnical Commission, Geneva, Switzerland. August 2009.

ISO Std. 11357-6, "Plastics – Differential scanning calorimetry (DSC) – Part 6: Determination of oxidation induction time (isothermal OIT) and oxidation induction temperature (dynamic OIT)," International Organization for Standardization, Geneva, Switzerland.

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," BNL, Volume 2, February 2001.

Name of Test:

Fourier Transform Infrared (FTIR) Spectroscopy

Type of Test	Property Measured	Intrusiveness
Laboratory	Chem. Properties: Qty of carbonyl & $-CH_4$ bonds	Surrogate Specimens Req'd; Destructive to Specimen

Application

Cable Type	Materials	Voltage Class	Configuration
All	XLPE, EPR, CSPE; Other polymers unkwn	All	All

Special Equipment Requirements

Fourier transform infrared spectrometer equipment, refracting crystals, spectrum analysis software, and accessories.

Special Training Requirements / Ease of Use

High skill, experience, and knowledge in FTIR spectroscopy & polymer chemistry req'd to successfully use this technique. Materials specialist knowledgeable and experienced in FTIR spectroscopy and polymer chemistry req'd to interpret the polymer spectra generated by tests.

Test Results

Format/Interpretation of Test Results	Acceptance Criteria
Transmittance spectra are produced by the analytical software from the spectral analysis by the FTIR spectrograph. Oxidation of the materials results in peaks in the FTIR spectrum at wavenumber 1730 cm-1, representing the presence of the carbonyl (C=O) bonds, and at wavenumber 2916 cm-1, representing the presence of the –CH2 bonds. Magnitudes of the peaks in the spectra reflect the changes in the polymer molecular structure as it oxidizes over time.	Absolute acceptance criterion is not practical. Best approach is to establish baseline transmittance spectra and transmittance percent values at the selected significant peak wavenumbers for each material. As the materials age, subsequent periodic measurements can then be compared to those baseline spectra and transmittance percent values for the selected peak wavenumbers to assess the progress and rate of aging degradation in the insulating material for the cables being monitored.

Advantages

Reliable & repeatable results for common polymer materials; correlates with aging degradation; test results are trendable.

Limitations

Surrogate specimens req'd since method is destructive to test specimen; results applicable only for the exact polymer formulation and environmental exposure history at the specific plant location from which the specimen was removed. FTIR is a surface condition measurement; may be an oxidation gradient from surface to interior of the polymer material. High skill level req'd to interpret testing results.

References & Applicable Standards

NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables," Brookhaven National Laboratory, Volume 2, February 2001.

<table>
<tr><td colspan="4">Name of Test:
Density</td></tr>
<tr><td colspan="2">Type of Test</td><td>Property Measured</td><td>Intrusiveness</td></tr>
<tr><td colspan="2">Insitu/Lab</td><td>Chemical/Physical Property: material density</td><td>Low/Medium/High</td></tr>
<tr><td colspan="4">Application</td></tr>
<tr><td>Cable Type</td><td>Materials</td><td>Voltage Class</td><td>Configuration</td></tr>
<tr><td>All</td><td>All</td><td>All</td><td>All</td></tr>
<tr><td colspan="4">Special Equipment Requirements</td></tr>
<tr><td colspan="4">Standard physical chemistry laboratory equipment, e.g. gradient columns, solutions with different densities, precision balance.</td></tr>
<tr><td colspan="4">Special Training Requirements / Ease of Use</td></tr>
<tr><td colspan="4">No special training required; standard laboratory technician skills, standard laboratory procedures.</td></tr>
<tr><td colspan="4">Test Results</td></tr>
<tr><td colspan="2">Format/Interpretation of Test Results</td><td colspan="2">Acceptance Criteria</td></tr>
<tr><td colspan="2">Density values for tested specimens.</td><td colspan="2">No specific acceptance criterion for polymer material density measurements. Best approach is to establish baseline density measurements and as the materials age, subsequent periodic measurements can then be compared to those baseline density measurement values to assess progress and rate of aging degradation in the insulating material for the cables being monitored.</td></tr>
<tr><td colspan="4">Advantages</td></tr>
<tr><td colspan="4">Density measurements for typical cable insulating materials have shown good correlation with the aging of polymers as determined by other proven techniques, such as EAB. Thus, this technique could be useful as a potential monitoring technique for some cable insulating materials.</td></tr>
<tr><td colspan="4">Limitations</td></tr>
<tr><td colspan="4">Surrogate specimens req'd since method is destructive to test specimen; results applicable only for the exact polymer formulation and environmental exposure history at the specific plant location from which the specimen was removed. A disadvantage of this technique is that a sample of the cable insulation material must be obtained to perform this test.</td></tr>
<tr><td colspan="4">References & Applicable Standards</td></tr>
<tr><td colspan="4">ASTM Standard D792, “Test Method for Specific Gravity (Relative Density) and Density of Plastics by Displacement,” ASTM International.
ASTM Standard D1505, “Test Method for Density of Plastics by the Density Gradient Method,” ASTM International.
SAND2005-7331, NEPO Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials,” Sandia National Laboratories, Albuquerque, NM. November 2005.
Gillen, K.T., et al., “Density Measurements as a Condition Monitoring Approach for Following the Aging of Nuclear Power Plant Cable Materials,” Radiation Physics and Chemistry, v56, pp 429-447, 1999 Elsevier Science Ltd, Exeter England.</td></tr>
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