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Essential Elements of an Electric Cable Condition Monitoring Program

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ABSTRACT

For more than 20 years the NRC has sponsored research studying the aging degradation, condition monitoring and environmental qualification, and testing practices for electric cables and cable accessories used in nuclear power plants. The essential elements for an effective cable condition monitoring program presented in this report are based upon the results of the NRC's electric cable and equipment research programs, industry guidance and standards, and the experience and observations of others who have studied or conducted electric cable condition monitoring and qualification testing. The program methodology presented herein provides guidance on the selection of cables to be included in the program, characterization and monitoring of cable operating environments and stressors, selection of the most effective and practical condition monitoring techniques, documentation and review of cable condition monitoring testing and inspection results, and the periodic review and assessment of cable condition and operating environments.

FOREWORD

Electric cables are one of the most important components in a nuclear plant because they provide the power needed to operate safety-related equipment and to transmit signals to and from the various controllers used to perform safety operations in the plant. In spite of their importance, cables typically receive little attention because they are considered passive, long-lived components that have proven to be very reliable over the years.

The integrity of electric cables is monitored, to some extent, through periodic testing of the equipment to which they are attached; however, this testing does not specifically focus on the cables and may not be sufficient to detect all of the aging mechanisms to which a particular cable is susceptible. If aging mechanisms remain undetected, they can eventually lead to a deterioration of cable performance and possibly cable failure. In response to Generic Letter 2007-01, licensees provided data showing that the number of cable failures is increasing with plant age and that cable failures are occurring within the plants' 40-year licensing periods. These cable failures have resulted in plant transients and shutdowns, loss of safety redundancy, entries into limiting conditions for operation, and challenges to plant operators. The data also show that as many unanticipated (in-service) cable failures occur as do testing failures. Based on this information and the fact that licensees are now considering license extension to 60 years and more NRC is considering the need to monitor the condition of electric cables throughout their installed life through the implementation of a cable condition monitoring program.

Condition monitoring (CM) is a useful means of determining the condition of installed electric cables, and a great deal of research has been performed to identify effective CM techniques. Plants undergoing license renewal have agreed to a cable-testing program for a limited number of cables that are within the scope of licensee renewal; however, plants not undergoing license renewal have not committed to any cable testing. In addition, most plants do not have a cable diagnostic condition monitoring program in place.

In light of the above issues, the Office of Nuclear Regulatory Research (RES) sponsored the research reported herein to evaluate the various aging mechanisms and failure modes associated with electrical cables along with condition monitoring techniques that may be useful for monitoring degradation of power, control, and instrumentation cables. Based on these evaluations, the essential elements of an effective cable condition monitoring program have been identified. These results will provide the technical basis for the staff to use in developing appropriate regulatory guidance on monitoring of electric cables.

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The polymers 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 environments. Longer cable circuits may pass through several different operating environments over the length of their routing throughout the plant. Portions of a cable circuit may pass through areas experiencing more harsh environmental conditions, such as high temperature, high radiation, high humidity, or flooding of underground cables. There has been concern that such local adverse environmental stressors can cause excessive aging and degradation in the exposed sections of a cable that could significantly shorten its effective service life and cause unexpected early failures.

The integrity and function of power and instrumentation and control (I&C) cables are monitored indirectly through the performance of in-service testing of safety-related systems and components. These tests can demonstrate the function of the cables under test conditions. However, they do not provide assurance that they will continue to perform successfully when they are called upon to operate fully loaded for extended periods as they would under normal service operating conditions or under design basis conditions. In-service testing of a cable does not provide specific information on the status of cable aging degradation processes nor the physical integrity and dielectric strength of its insulation and jacket materials. Consequently, a cable circuit with undetected damaged or degraded insulation could pass an in-service functional test, but still fail unexpectedly when called upon to operate under anticipated environmental conditions or the severe stresses encountered during a design basis event (i.e., fully loaded equipment, more extreme environmental conditions, extended operation in a heavily loaded state).

The 10 CFR Part 50 regulations require licensees to assess the condition of their components, to monitor the performance or condition of structures, systems, and components in a manner sufficient to provide reasonable assurance that they are capable of fulfilling their intended functions, and to establish a test program to ensure that all testing required to demonstrate that components will perform satisfactorily in service is identified and performed. Recent incidents involving early failures of electric cables and cable failures leading to multiple equipment failures, as cited in IN 2002-12, "Submerged Safety-Related Cables," and Generic Letter 2007-01, "Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients," suggest that licensee approaches to cable testing, such as in-service testing, surveillance testing, preventive maintenance, maintenance rule, etc., do not fully characterize the condition of cable insulation nor provide information on the extent of aging and degradation mechanisms that can lead to cable failure. Analysis of the summary of licensee responses to GL 2007-01 inquiries on licensees' experiences regarding cable failures and cable CM activities, revealed wide variations to the approaches and comprehensiveness of cable testing activities. Analysis of the reported cable failures also indicated a trend toward early cable failures occurring prior to the end of the original 40-year license period. These data prompted the NRC to consider whether "...licensees should have a program for using available diagnostic cable testing methods to assess cable condition."

This research study developed recommendations for a comprehensive cable condition monitoring program consisting of nine essential elements. These nine elements consolidate a core program of periodic cable CM inspections and tests, together with the results of in-service testing, cable operating environment monitoring and management activities, and the incorporation of cable-related operating experience. The recommended nine essential elements of the cable CM program are listed in Table ES.1 with a summary of the purpose and expected result for each element of the program.

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. Environmental stressors can include elevated temperatures, high radiation, high humidity, moisture intrusion, accumulation of dirt and dust, and exposure to chemicals or other reactive contaminants. Operational stressors can include external interference, installation and maintenance damage, high voltage stress, materials defects, water treeing, and electrical transients. 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 the example incidents cited in Generic Letter 2007-01. It is therefore important that the cable condition status information that can be provided by periodic condition monitoring inspection and testing of electric cables be considered in the assessment of cable aging and degradation. Severely damaged or degraded cable insulation can then be identified and repaired or replaced to prevent unexpected early failures while in service.

In addition, the benefits of periodic cable condition monitoring inspections and testing can be further complemented by addressing cable operating environments. Environmental stressors, especially temperature, moisture/flooding, and radiation, can be responsible for causing significant aging and degradation of electric cable insulation and jacket materials. Monitoring and management of the environmental conditions in which cables are operated can help licensees to identify adverse stressors so that measures can be taken to control or reduce aging and degradation.

Finally, the review of cable-related operating experience can play an important role in the assessment and management of electric cable aging and degradation. Industry-wide operating experience can alert licensees to cable manufacturing defects, inadequate installation practices, misapplication of cable types, and other environmental and operation factors. Regular review and analysis of in-plant cable failures or cable-related problems can sometimes reveal adverse performance trends or otherwise point to emerging problem areas that can be monitored more closely and/or corrected in a timely fashion before the occurrence of an early cable failure.

Table ES.1 Recommended Nine Essential Elements of a Cable Condition Monitoring Program

Program Element	Purpose	Expected Result
1. Selection of Cables to be Monitored	To identify and select electric cables that are candidates for inclusion in the cable condition monitoring program.	A listing of the most important cables in the plant whose condition should be periodically monitored and evaluated to provide assurance that they are capable of performing their intended function
2. Develop Database of Monitored Cables	To provide a single centralized source of information for all the cables in the program that can be used by the cable engineer as a tool to access, analyze, and evaluate the data and documentation necessary to make cable condition assessments and to guide the direction of program decisions and activities	A database that will provide essential information to support the implementation of the cable CM testing and inspection activities, and the periodic review and assessment of the condition of individual cables
3. Characterize and Monitor Cable Operating Environments	To verify the baseline design operating environment for a cable, to periodically verify actual environmental conditions and identify local adverse environments (e.g., high temperature or radiation, moisture, submergence) that may have developed, and to manage environmental conditions to mitigate the effects on cables	Baseline environmental operating conditions measurements and inspection results, periodic environmental condition monitoring and verification measurements and results, identification and description of local adverse environments, and activities for managing operating environments to mitigate adverse effects on cables
4. Identify Stressors and Aging Mechanism Affecting Cables in the Program	To identify the stressors and determine the aging mechanisms affecting cables in the program	Listing of the stressors and aging mechanisms affecting the condition of each cable in the program to be used in program element 5 to select the most effective CM inspection and testing techniques for each cable
5. Select CM Inspection and Testing Techniques	To determine the most effective CM inspection and testing techniques to detect and monitor the anticipated aging/failure mechanisms for each cable	An initial listing of cable CM inspection and testing techniques and periodic performance frequency for each cable
6. Establish Baseline Condition of Cables in the Program	To measure and document the baseline condition of each cable in the program using the selected cable CM inspection and testing methods identified in program element 5	Baseline cable condition measurements and inspection results for the techniques selected in program element 5
7. Perform periodic CM Inspection and Testing	To periodically measure and document the condition of each cable in the program using the selected cable CM inspection and testing methods identified in program element 5	Periodic record of cable condition measurements and inspection results for the techniques selected in program element 5
8. Review and Incorporate Cable-Related Operating Experience	To review industry-wide and in-plant cable-related operating experience and incorporate changes to the cable CM program as required to address applicable issues and trends	Incorporate changes to the cable CM program based on review of applicable operating experience
9. Periodic Review and Assessment of Cable Condition	To perform a periodic review of the current cable condition CM inspection and testing results, operating environments CM results, trends of cable properties and condition measurements, and applicable operating experience to establish an up-to-date assessment of cable condition, expected service life, and program changes and activities to manage aging degradation of each cable in the program	A formal periodic assessment of cable condition, expected service life, and program changes and activities to manage aging degradation of each cable in the program

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ABBREVIATIONS

AAC . . . . . Alternate ac (power source)
ASTM . . . . . American Society for Testing and Materials
ATWS . . . . . Anticipated Transient Without Scram
AWG . . . . . American Wire Gauge
BNL . . . . . Brookhaven National Laboratory
CM . . . . . Condition Monitoring
CRT . . . . . Cathode Ray Tube (Display)
CSPE . . . . . Chloro-Sulfonated Polyethylene (also known as Hypalon®)
DBE . . . . . Design Basis Event
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
EPIX . . . . . Equipment Performance and Information Exchange System
EQ . . . . . Environmental Qualification
ESF . . . . . Engineered Safety Feature
FMEA . . . . . Failure Modes and Effects Analysis
FTIR . . . . . Fourier Transform Infrared Spectroscopy
I&C . . . . . Instrumentation and Control
IEEE . . . . . Institute of Electrical and Electronics Engineers
INPO . . . . . Institute for Nuclear Power Operations
IR (1) . . . . . Insulation Resistance
IR (2) . . . . . Infrared (imaging thermography)
LCD . . . . . Liquid Crystal Display
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
SBO . . . . . Station Blackout
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

The structures, systems, and components (SSCs) operating in nuclear power plants will routinely be exposed to a variety of environmental and operational stressors that can produce aging and degradation mechanisms. Over time, the aging and degradation mechanisms caused by exposure to these stressors can result in degradation of the SSCs.

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.

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 Generic Letter 2007-01 [Ref. 1]. 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.

In addition, the benefits of periodic cable condition monitoring inspections and testing can be further complemented by addressing cable operating environments. Environmental stressors, especially temperature, moisture/flooding, and radiation, can be responsible for causing significant aging and degradation of electric cable insulation and jacket materials. Monitoring and management of the environmental conditions in which cables are operated can help to control or reduce aging stressors.

Finally, the review of cable-related operating experience can play an important role in the assessment and management of electric cable aging and degradation. Industry-wide operating experience can alert licensees to cable manufacturing defects, inadequate installation practices, misapplication of cable types, and other environmental and operation factors. Regular review and analysis of in-plant cable failures or cable-related problems can sometimes reveal adverse performance trends or otherwise point to emerging problem areas that can be monitored more closely and/or corrected in a timely fashion before the occurrence of an early cable failure.

1.2 Objective

The objective of this research study is to propose a comprehensive electric cable condition monitoring (CM) program that will consolidate a core program of periodic CM inspections and tests, together with the results of in-service testing, environmental monitoring and management activities, and the incorporation of cable-related operating experience. This study develops the background and technical basis for regulatory guidance pertaining to the essential elements of a cable monitoring program.

1.3 Scope

This study includes 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. Most nuclear power plants utilize overhead transmission lines for circuits operating at voltages higher than this, however, it is noted that a few nuclear power plant distribution systems utilize higher voltage power cables that should also be included in a cable condition monitoring program. The boundaries of the cable systems that are to be monitored in the cable CM program will 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. Cables, wiring, splices, and 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 equipment.

Discussions, examples, and guidance regarding condition monitoring inspection and testing techniques, and the essential elements of the cable CM program 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]. With minor variations, the guidance and discussions presented herein are also applicable to the other polymers used in nuclear plant cable insulation and jackets.

Discussions and guidance regarding 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 these cables must be uniquely developed on an application-specific basis.

Another category of cables that should be considered for incorporation into the cable CM program activities is fiber-optic cables used to provide signal transmission interconnections for digital I&C systems that have safety-related or accident mitigation functions. Since optical fibers serve as the conducting medium in these cables, the aging and degradation mechanisms are unique to these cables as compared to electric cables utilizing copper and aluminum conductors. The outer jacket material for a fiber optic cable is usually a polymer so aging and degradation mechanisms would be similar to those experienced by polymer insulated and jacketed electric cables. However, the jacket on a fiber optic cable serves as a protective layer for the internal optical conductors and has no dielectric insulating function. As a result of these significant differences, the failure modes, failure mechanisms, and CM inspection and testing techniques are unique to these cables. Analysis and discussions for the aging, degradation, and CM testing of fiber-optic cables are presented in Appendix A. Discussion and guidance on the selection and incorporation of fiber optic digital I&C cables into the plant cable CM program are presented in the appendix.

1.4 Organization of the Report

Section 2 of the report presents a basic overview of the aging of electric cable systems. A brief general description of the construction of electric cables is followed by a discussion and analysis of the failure modes for power and I&C cables. The most common stressors for medium-voltage power cables and low-voltage power and I&C cables are tabulated. Similarly, discussion and analysis of failure modes for cable splices and connectors are followed by a tabulation of the most common stressors for medium-voltage cable splices and terminations and low-voltage cable splices and terminations. The regulations requiring demonstration of the capability of cable systems to perform their safety function are presented along with a discussion on why a program specifically focused on cable condition monitoring is needed.

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 description for each method is provided along with a table listing the applicability, features, advantages and disadvantages for each technique. A 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 4 presents nine recommended essential elements for an effective cable CM program. The purpose for each element of the program is presented in turn along with discussion and guidance for implementing each element. Finally, the expected results from each program element are presented together with a discussion on how each element supports and interacts with the other cable CM program elements.

Observations on the condition monitoring of electric cables are summarized in Section 5 of the report. A table summarizing the nine essential elements of an effective cable condition monitoring program is presented. Important features of the program methodology are highlighted.

2. OVERVIEW OF CABLE SYSTEM AGING

This section provides a brief description of electric cable construction. Discussion and analysis on the failure modes, stressors, and aging mechanisms for medium-voltage power cables, low-voltage power and I&C cables, medium-voltage splices and terminations, and low-voltage splices and terminations are presented. Finally, applicable regulations requiring demonstration of the capability of cable systems to perform their safety function are listed followed by a discussion on why a program specifically focused on cable condition monitoring is needed.

2.1 Electric Cable Construction

The construction of a typical electric cable consists of a polymer insulating material covering a metallic copper or aluminum electrical conductor. The metallic conductor may be a single strand of solid wire or a bundled group of smaller diameter wires. The insulating material of individual cable conductors is often covered by a layer of polymer jacket material to protect the integrity of the insulating material from physical damage; multiple conductor cables will typically include an overall polymer jacket to protect the individual insulated cables that make up the cable.

Cables are qualified by their manufacturers to provide a specified service life (e.g., 40 years for nuclear power plants) for a specified voltage class (based on the qualified dielectric strength of the polymer insulation) operating continuously at or below a specified maximum ambient temperature (e.g., 90°C). If the insulation and outer jacket material are undamaged, most cables can tolerate occasional wetting, but are not qualified for extended operation in a submerged state.

Electric cables operating in nuclear power plant service can be exposed to a variety of environmental and operational stressors. Environmental stressors can include elevated temperature, high radiation, high humidity, submersion, (note that cables are not qualified for submerged operation unless they have been specifically procured as submarine cables) and exposure to dust, dirt, and corrosive contaminants. Operational stressors can include high voltage, electrical transients, internal ohmic heating, vibration, installation damage, manufacturing defects, and damage inflicted by operating and maintenance activity. Over time, these stressors, and combinations of these stressors, can cause aging and degradation mechanisms that will result in a gradual degradation of the cable insulation and jacket materials.

A nuclear power plant may contain more than 50,000 electric cable circuits, of which about 60% are control circuits, 20% are instrumentation, 13% are ac power, 1% are dc power, and the remainder are miscellaneous communications circuits [Ref. 2]. Most of these electric cable circuits are located in dry, mild operating environments that are well within their qualified operating limits, and therefore perform reliably throughout their qualified service life. Many cable circuits, however, may normally be exposed to one or more of the stressors described above and must be qualified to operate under more harsh operating environments. Electric equipment important to safety, including electric cables, that are required to continue to successfully perform their safety function in the harsh environment throughout the duration of and following design basis events occurring at the end of their qualified life, must be environmentally qualified in accordance with the requirements of 10 CFR 50.49.

2.2 Cable Systems Failure Modes, Stressors, and Aging Mechanisms

The reliability engineer typically uses the failure modes and effects analysis (FMEA) tool to identify the manner or state in which a structure, system, or component (SSC) fails and the resulting effect that the failure mode will have on the function of the SSC. The piece-parts and subcomponents of the SSC are each analyzed in turn to identify the sub-component materials, stressors, potential aging mechanisms, and the potential effect(s) of the stressors and associated degradation/aging mechanisms on the function and operation of the subcomponent, i.e., will the mechanisms result in the subcomponent's failure.

By identifying these stressors, and quantifying their severity, the cable engineer can determine the aging and failure mechanisms that will cause degradation or other damage that, over time, could lead to the ultimate failure of a cable system. This information can then be used to select the most effective CM inspection and testing techniques for detecting and monitoring the anticipated aging/failure mechanisms.

2.2.1 Cable System Failure Modes

For low-voltage and medium-voltage power cables, as well as I&C cables, the basic failure modes are:

- Conductor short circuit to ground
- Conductor-to-conductor short circuit
- Degraded insulation resistance (excessive leakage current)
- Open circuit

For low-voltage and medium-voltage ac power cables, the first two failure modes are electrical faults that would normally cause circuit protection devices to trip and result in loss of electric power transmitted through the affected circuit. For low-voltage dc power cables, depending on the operating configuration of the dc system (grounded versus ungrounded), the electrical fault will result in a trip of the circuit by protective devices or a degraded system alarm. The third failure mode above is an incipient failure for low-voltage power cables, except in the presence of a conductive medium (e.g., water, dirt, high humidity, chemical deposits) that could quickly degrade the condition into one of the other two failure modes. In medium-voltage power cables, the third failure mode can lead to partial discharge, or corona, phenomenon that could cause excessive heating and degradation of the cable insulating materials, and ionization of the air in the vicinity of the current leakage. If not corrected, this failure mode in medium-voltage cables could catastrophically degrade into one or both of the other two failure modes. The fourth power cable failure mode, i.e., open circuit conductor, can result from: a physical event breaking the conductor; vaporization of the conductor by an electrical fault (failure modes 1 & 2) that is not cleared by the circuit protective device; extreme corrosion breaking conductor continuity; electromechanical force from a short circuit transient breaking the conductor; vibration fatigue breaking the conductor; or disconnection of the electrical conducting joint at a splice, termination, or other connection accessory.

In the case of instrumentation and control cables, the first two failure modes will interrupt transmission of analog or digital control signals over the affected circuit, functionally failing the control circuit. Similarly, analog or digital instrumentation signals will be interrupted by either of the first two failure modes resulting in loss of signal throughout the affected instrumentation circuit. I&C circuits may experience degraded function or an increased level or rate of error, or may not be affected at all, by the third failure mode, degraded insulation resistance, depending upon the type of signal that is transmitted and the design of the receiving-end circuits and devices. For I&C cables, the fourth failure mode, open circuit conductor, can occur as a result of a physical event breaking the conductor; extreme corrosion breaking conductor continuity; vibration fatigue breaking the conductor; or disconnection of the electrical conducting joint at a splice, termination, or other connection accessory.

2.2.2 Cable System Aging and Degradation Stressors

Cable systems in nuclear power plant service are subject to a variety of aging and degradation stressors that can produce immediate degradation or aging-related mechanisms and effects causing degradation of the cable components over time. Stressors can generally be categorized as one of two types based upon their origin: 1) environmental stressors originate from conditions in the environment where a cable system is located, or 2) operational stressors that are the result of operational factors such as cable current loading, electrical system transients, or operating and maintenance activities in the vicinity of the cable system.

Using the FMEA analytical approach applied to electric cables, the piece-parts of a cable (e.g., insulation, jacket, conductor) are each analyzed to identify the constituent material(s). The stressors that can affect the material(s) in each piece-part of a particular cable, in a specific application and operating environment, are analyzed to determine whether they can produce a degradation or aging mechanism that could eventually lead to one of the failure modes for the cable. A general summary of stressors and associated potential aging and degradation mechanisms, adapted from References 3 and 4, is provided in Table 2.1 for medium-voltage power, low-voltage power, and I&C cables.

Most of the environmental stressors affecting medium-voltage power cables and low-voltage power and I&C cables are the same for both categories. Operating stressors such as internal ohmic heating of power cables are normally significant only for medium-voltage power cables that are continuously energized and conducting higher current levels. However, some low-voltage power cables, which can include voltages up to 1000V, could also be affected by internal ohmic heating if they continuously conduct higher current levels. Power cables that are fire wrapped or are located in heavily-loaded, random-filled cable raceways may be more susceptible to the long-term effects of internal ohmic heating.

Special consideration should be given by licensees to the problem of monitoring the operating environment for cable circuits routed through inaccessible underground cable ducts and conduits, covered cable distribution trenches, and manhole vaults. These structures can frequently become flooded resulting in power and control cables operating in wetted and completely submerged conditions for extended periods of time. Unless the installed cables have been procured specifically for continuous submerged or submarine operation, the cables installed in duct banks, manholes and bunkers, and direct burial applications are susceptible to moisture- and submergence-related failure mechanisms as listed in Table 2-1.

High voltage potential is normally only a factor in medium-voltage or higher cables because of the effect that this stressor can have on the propagation of water treeing in cable insulation, especially in the presence of moisture, and the occurrence of partial discharge, or corona, in defective or deteriorating insulation. The contribution of voltage is of lesser significance in low-voltage power cables and most I&C circuits. However, water and moisture intrusion can drive insulation degradation mechanisms that can affect the dielectric strength of insulation materials in both low- and medium-voltage cables, even when they are normally deenergized, as was observed in the summary report on licensees' responses to GL 2007-01 [Ref. 8].

It should be noted that there are some specialized I&C cables, such as those used in nuclear instrumentation, which may incorporate low ampacity medium-voltage power conductors bundled together in the same cable with low-voltage instrumentation conductors.

Direct mechanical damage, such as bending, abrasion, cutting, contact, deformation, and perforation resulting from installation and maintenance activities in and around the location of a cable, is a potential stressor that can affect both categories of cables. Electromechanical forces resulting from the passage of high levels of short circuit current through a power cable can potentially cause mechanical damage to cable jacket and insulation material and cable conductors. High voltage stress from lightning strikes or power system transients can also degrade the dielectric strength of cable insulation.A similar FMEA analytical approach can be applied to cable splices and to cable termination connections at terminal blocks, fuse holders, circuit breaker and disconnect switch terminal connectors, electric motor leads, electrical equipment insulating bushings, electrical bus bars, or other electrical equipment termination points. The piece-parts of a cable splice or termination connector are each analyzed to identify the constituent material(s). The stressors that can affect the material(s) in each piece-part of a particular splice or termination connector, in a specific application and operating environment, are analyzed to determine whether they can produce a degradation or aging mechanism that could eventually lead to one of the failure modes for the cable splice or termination connector. A general summary of potential stressors and associated aging and degradation mechanisms, adapted from References 4, 5, and 6, is provided in Table 2.2 for medium-voltage power, for low-voltage power, and I&C cable splices and termination connections.

Cable splices are exposed to the same environmental and operational stressors as the cables on which they are installed. Since cable splices are constructed of many of the same or similar materials as the electric cables on which they are installed, these stressors can also cause aging degradation of the polymer insulating materials used in the cable splice. In addition, the other subcomponents that make up an electric cable splice (insulating tape, fillers, sleeves, insulating compounds, and compression connectors) are also susceptible to aging degradation due to the various stressors to which they are exposed. Connectors, in particular, are susceptible to stressors such as moisture, condensation, vibration, and thermal cycling that can lead to corrosion and loosening of the conductor compression joints or solder joints [Ref. 5]. When cable splices that are not qualified for wetted or continuous submersion are exposed to moisture, or are submerged in water, they can be affected more rapidly and more severely than a cable with intact insulation in the same environment. A poorly installed or designed splice can result in multiple penetration pathways for moisture into the interior of the splice, not only around the splice materials where they abut the surface of the cable insulation, but also through the damaged or cracked outer jacket or insulation [Ref. 5].

Stressors affecting cable termination connections at terminal blocks, fuse holders, circuit breaker and disconnect switch terminal connectors, electric motor leads, electrical equipment insulating bushings, insulating bushings, electrical bus bars, or other electrical equipment termination points are generally the same as those affecting electric cables. The resulting aging and degradation mechanisms acting on the terminations, however, can be very different than for cables and splices because of the variations in the types and designs for these cable system components. These are discussed in the following subsection.

Table 2.1 Summary of Stressors and Potential Aging Mechanisms for MV Power, LV Power, and I&C Cables

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Insulation	• Various polymer materials (e.g., XLPE, EPR)	• Elevated temperature • Elevated radiation fields	• Embrittlement • Cracking	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●	●	●	Elevated temperature due to combination of external environment and internal ohmic heating (MV & LV power cables only)
	• Various polymer materials that are permeable to moisture	• Wetting	• Moisture intrusion	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●	●	●	Long term operation in wet or submerged condition can lead to water treeing
	• Various polymer materials that do not contain a tree retardant additive	• Wetting concurrent with voltage	• Electrochemical reactions • Water treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●			Tree retardant additives can mitigate this aging mechanism.
	• Various polymer materials that have voids or other imperfections	• Voltage • Electrical transient	• Partial discharge (corona) • Electrical treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●			Insulation must contain voids or other imperfections.
	• Various polymer materials (e.g., XLPE, EPR)	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including crushing, bending, tensile deformation	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure		●	●	Only applicable to cables installed in accessible locations
	• Various polymer materials (e.g., XLPE, EPR)	• Installation Damage	• Mechanical damage including crushing, bending, tensile deformation	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure		●	●	

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Jacket	• Various polymer materials (e.g., CSPE, Neoprene)	• Elevated temperature • Elevated radiation fields	• Embrittlement • Cracking	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	●	●	●	The primary function of the cable jacket is to provide mechanical protection to the cable during installation. A secondary function is to mitigate intrusion of contaminants to the interior of the cable
	• Various polymer materials (e.g., CSPE, Neoprene)	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including crushing, bending, cutting, abrasion, gouging, tensile deformation	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	●	●	●	Only applicable to cables installed in accessible locations
	• Various polymer materials (e.g., CSPE, Neoprene)	• Installation damage	• Mechanical damage including crushing, bending, cutting, abrasion, gouging, tensile deformation	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	●	●	●	
	• Various polymer materials (e.g., CSPE, Neoprene)	• Electromechanical forces due to electrical transient	• Mechanical damage	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	●			Can occur if cable has conducted a high-magnitude fault current
Conductor	• Copper • Aluminum	• Wetting due to moisture intrusion • Condensation	• Corrosion • Oxide formation • Loosening of connectors	• Increased electrical resistance • Increased ohmic heating	●	●	●	Internal ohmic heating on MV & LV power cables only
	• Copper • Aluminum	• Vibration	• Metal fatigue • Loosening of connectors	• Loss of structural integrity • Degraded connector contact	●	●	●	Applicable to portion of cables near load terminations

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Conductor (continued)	• Aluminum	• Compressive forces	• Cold flow • Loosening of connectors	• Loss of contact on connectors • Increased electrical resistance • Increased ohmic heating	●	●	●	Applicable to aluminum conductors with static mechanical connectors. Internal ohmic heating on MV & LV power cables only
	• Copper • Aluminum	• Electromechanical forces due to electrical transient	• Mechanical damage including fatigue, bending, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands	●			Can occur if cable has conducted a high-magnitude fault current
	• Copper • Aluminum	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including fatigue, bending, tensile deformation, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands • Open circuit		●	●	
	• Copper • Aluminum	• Installation damage	• Mechanical damage including fatigue, bending, tensile deformation, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands • Open circuit		●	●	
Shield	• Copper tape • Copper wire	• Wetting due to moisture intrusion	• Corrosion • Oxide formation	• Loss of structural integrity • Increased insulation degradation due to partial discharges • Decreased EMI protection	●		●	Partial discharge applicable to MV power cables only Decreased EMI protection applicable to I&C cables only
	• Semi-conducting polymers	• Elevated temperature • Elevated radiation fields	• Embrittlement • Cracking	• Loss of structural integrity • Increased insulation degradation due to partial discharges • Decreased EMI protection	●		●	

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Shield (continued)	• Copper tape • Copper wire	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including fatigue, bending, tensile deformation, cracking	• Loss of structural integrity • Broken conductor strands • Decreased EMI protection		●	●	Decreased EMI protection applicable to I&C cables only
	• Copper tape • Copper wire	• Installation damage	• Mechanical damage including fatigue, bending, tensile deformation, cracking	• Loss of structural integrity • Broken conductor strands • Decreased EMI protection		●	●	Decreased EMI protection applicable to I&C cables only
Sheath	• Lead	• Alkaline environment (e.g., free line from concrete ducts)	• Corrosion	• Loss of structural integrity • Increased intrusion of moisture and contaminants into cable interior	●			Applicable to MV power cables

Table 2.2 Summary of Stressors and Potential Aging Mechanisms for MV Power, LV Power, I&C Cable Splices and Terminal Connections

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Cable Splices								
Insulation; Shield (insulating tapes, potting and sealing compounds, insulating compounds, heat shrink insulation material, stress cones, etc.)	• Various polymer materials (e.g., XLPE, EPR)	• Elevated temperature • Elevated radiation fields • Mechanical & Thermal cycling • Vibration • Overvoltage Stress	• Embrittlement • Cracking • Mechanical Wear • Treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●	●	●	Elevated temperature due to combination of external environment or internal ohmic heating (MV & LV power cable splices only). Overvoltage stress (MV power cable splices only).
	• Various polymer materials that are permeable to moisture	• Wetting • Condensation	• Moisture intrusion	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●	●	●	Long term operation in wet or submerged condition can lead to water treeing. Cracking of splice outer jacket or underlying cable jacket can permit water intrusion into the interior of the splice.
	• Various polymer materials that do not contain a tree retardant additive	• Wetting concurrent with voltage	• Electrochemical reactions • Water treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●			Tree retardant additives can mitigate this aging mechanism.
	• Various polymer materials that have voids or other imperfections	• Voltage • Electrical transient	• Partial discharge (corona) • Electrical treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●			Insulation must contain voids or other imperfections.
	• Various polymer materials (e.g., XLPE, EPR)	• Electromechanical forces due to electrical transient	• Mechanical damage	• Loss of structural integrity • Increased intrusion of contaminants and moisture into the cable splice interior	●			Can occur if cable has conducted a high-magnitude fault current

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Insulation; Shield (continued)	• Various polymer materials (e.g., XLPE, EPR)	• Handling, physical contact, or abuse during maintenance, *operation, or testing* activities	• Mechanical damage including crushing, bending, cutting, *abrasion, gouging,* tensile deformation	• Decrease in dielectric strength • Increase in leakage *currents* • Eventual failure • Decreased EMI protection (Shield, I&C cables)		●	●	Only applicable to cables installed in accessible locations
	• Various polymer materials (e.g., XLPE, EPR)	• Installation Damage	• Mechanical damage including crushing, bending, cutting, abrasion, gouging, tensile deformation	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure • Decreased EMI protection (Shield, I&C *cables)*		●	●	
Connectors (Electrical conductors and shield)	• Copper • Aluminum	• Wetting due to moisture intrusion • Condensation	• Corrosion • Oxide formation • Loosening of connectors	• Increased electrical resistance • Increased ohmic heating	●	●	●	Internal ohmic heating on MV & LV power cable splices only
	• Copper • Aluminum	• Mechanical and Thermal Cycling • Vibration	• Metal fatigue • Loosening of connectors	• Loss of structural integrity • Degraded connector contact • Decreased EMI protection (Shield, I&C cables)	●	●	●	Applicable to cable splices near load terminations or affected by vibrations from operating equipment
	• Aluminum	• Compressive forces	• Cold flow • Loosening of connectors	• Loss of contact on connectors • Increased electrical resistance • Increased ohmic heating	●	●	●	Applicable to aluminum conductors with static mechanical connectors. Internal ohmic heating on MV & LV power *cables only*
	• Copper • Aluminum	• Electromechanical forces due to electrical transient	• Mechanical damage including fatigue, bending, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands	●			Can occur if cable splice has conducted a high-magnitude fault current

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Connectors (continued)	• Copper • Aluminum	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including fatigue, bending, tensile deformation, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands • Open circuit • Decreased EMI protection (Shield, I&C cables)		●	●	Only applicable to cable splices installed in accessible locations. Decreased EMI protection applicable to I&C cables only.
	• Copper • Aluminum	• Installation damage	• Mechanical damage including fatigue, bending, tensile deformation, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands • Open circuit • Decreased EMI protection (Shield, I&C cables)		●	●	Decreased EMI protection applicable to I&C cables only.
Cable Termination Connections								
Insulation; Shield (Insulating tapes, potting and sealing compounds, insulating compounds, heat shrink insulation material, stress cones, insulating boot materials, etc.)	• Various polymer materials (e.g., XLPE, EPR)	• Elevated temperature • Elevated radiation fields • Mechanical & Thermal cycling • Vibration • Overvoltage Stress	• Embrittlement • Cracking • Mechanical Wear • Treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●	●	●	Elevated temperature due to combination of external environment or internal ohmic heating (MV & LV power cables only). Overvoltage stress (MV power cables only)
	• Various polymer materials that are permeable to moisture	• Wetting • Condensation	• Moisture intrusion	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●	●	●	Long term operation in wet or submerged condition can lead to water treeing. Cracking of connector outer jacket or underlying cable jacket can permit water intrusion into the interior of the connector.
	• Various polymer materials that do not contain a tree retardant additive	• Wetting concurrent with voltage	• Electrochemical reactions • Water treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●			Tree retardant additives can mitigate this aging mechanism.

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
Insulation; Shield (continued)	• Various polymer materials that have voids or other imperfections	• Voltage • Electrical transient	• Partial discharge (corona) • Electrical treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	●			Insulation must contain voids or other imperfections.
	• Various polymer materials that have voids or other imperfections	• Electromechanical forces due to electrical transient	• Mechanical Damage	• Loss of structural integrity • Increased intrusion of contaminants and moisture into the cable connector interior	●			Can occur if cable connector has conducted a high-magnitude fault current
	• Various polymer materials (e.g., XLPE, EPR)	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including fatigue, bending, tensile deformation, cracking	• Loss of structural integrity • Broken conductor strands • Decreased EMI protection		●	●	Only applicable to cable connections installed in accessible locations. Decreased EMI protection applicable to I&C cable connections only.
	• Various polymer materials (e.g., XLPE, EPR)	• Installation damage	• Mechanical damage including fatigue, bending, tensile deformation, cracking	• Loss of structural integrity • Broken conductor strands • Decreased EMI protection		●	●	Decreased EMI protection applicable to I&C cable connections only.
Connectors (MV: electrical equipment terminations, terminal bushing, bus bar connector, bolted and compression connectors; LV: equipment & instrument	• Copper • Aluminum	• Wetting due to moisture intrusion • Condensation	• Corrosion • Oxide formation • Loosening of connectors	• Increased electrical resistance • Increased ohmic heating	●	●	●	Internal ohmic heating on MV & LV power cable connections only
	• Copper • Aluminum	• Mechanical and Thermal Cycling • Vibration	• Metal fatigue • Loosening of connectors	• Loss of structural integrity • Degraded connector contact • Decreased EMI protection (Shield, I&C cables)	●	●	●	Applicable to cable connections at load terminations or connectors affected by vibrations from operating equipment

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	MV	LV	I&C	Comments
terminations, screw terminals, compression connectors, terminal blocks, etc.)	• Aluminum	• Compressive forces	• Cold flow • Loosening of connectors	• Loss of contact on connectors • Increased electrical resistance • Increased ohmic heating	●	●	●	Applicable to aluminum conductors with static mechanical connectors. Internal ohmic heating on MV & LV power cable connectors only
	• Copper • Aluminum	• Electromechanical forces due to electrical transient	• Mechanical damage including fatigue, bending, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands	●			Can occur if cable connector has conducted a high-magnitude fault current
	• Copper • Aluminum	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including fatigue, bending, tensile deformation, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands • Open circuit • Decreased EMI protection (Shield, I&C cables)		●	●	Only applicable to cable connectors installed in accessible locations. Decreased EMI protection applicable to I&C cables only.
	• Copper • Aluminum	• Installation damage	• Mechanical damage including fatigue, bending, tensile deformation, cracking • Loosening of connectors	• Loss of structural integrity • Broken conductor strands • Open circuit • Decreased EMI protection (Shield, I&C cables)		●	●	Decreased EMI protection applicable to I&C cables only.

2.2.3 Cable System Aging and Degradation Mechanisms

Table 2.1 indicates that elevated temperature and radiation stressors will cause embrittlement and cracking of the polymer materials used for cable insulation and jacket materials. These mechanisms will lead to a gradual decrease in the dielectric strength of the cable insulation, an increase in leakage current, and eventually will result in one of the failure modes described in subsection 2.2.1. When the stressors of wetting or, wetting combined with higher voltage (generally 480Vac and above), are acting on cables that are not qualified to operate in a wet or submerged state, moisture intrusion, electrochemical reactions, and/or water treeing will occur. These mechanisms will lead to a decrease in the dielectric strength of the cable insulation, an increase in leakage current, and eventually will result in one of the failure modes described in subsection 2.2.1. When continuously energized medium-voltage cables are operating in submerged or wetted conditions for which they are not designed, they can often fail very prematurely [Refs. 1 and 7]. Note that cables are not qualified for extended or continuous operation unless they have been specifically procured as submarine cables. In addition, the higher voltage stressors that exist during normal operation and during electrical system transients in medium-voltage cables can cause partial discharge, or corona, and electrical treeing to occur. These aging mechanisms can decrease dielectric strength over time and eventually can also lead to one of the power cable failure modes. Further details on electrical stressors and associated aging and degradation mechanisms can be found in Section 3.3 of NUREG/CR-6794, "Evaluation of Aging and Environment Qualification Practices for Power Cables Used in Nuclear Power Plants" [Ref. 3], and Section 4 of SAND96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cable and Terminations" [Ref. 2].

The aging mechanisms affecting cable conductors and other cable subcomponents generally develop more slowly and are less likely to occur than insulation failures that account for the majority of cable failures [Refs. 2 and 3]. Conductor failure is very rare in power cables where the wires are large diameter. Low-voltage power and I&C cable conductors are physically smaller-diameter wires and can occasionally break from metal fatigue due to long-term exposure to vibration or excessive handling and termination/determination.

As seen in Table 2.2, the aging and degradation mechanisms affecting the polymer insulating materials used to construct and apply cable splices are similar to those affecting cables, and consequently over time, they can lead to one of the cable splice failure modes. When cable splices that are not qualified for wetted or continuous submersion are exposed to moisture or are submerged in water, they can be affected more rapidly and more severely than a cable with intact insulation in the same environment [Ref. 5]. Depending on the design of a splice, as the constituent materials degrade over time, multiple penetration pathways can develop that can introduce moisture into the interior of the splice. This can occur not only around the splice materials where they abut the surface of the cable insulation, but also through the interior of a cable via a damaged or cracked outer jacket or insulation. If these aging mechanisms progress on an environmentally qualified (EQ) electrical splice, it may shorten the qualified life of the cable splice and, as a consequence, the qualified life of the entire cable that contains the degraded EQ splice.

In addition to the insulation materials, the connector that joins the electrical conductors within a splice can be vulnerable to aging and degradation mechanisms such as vibration, mechanical stress, thermal and mechanical cycling, and electrical transients. These mechanisms can result in metal fatigue of the conductors and/or loosening of the connector. Intrusion of moisture into the interior can cause corrosion and formation of oxides at the connector joint of a splice. This can cause increased electrical resistance and increased ohmic heating. More detailed description of the various stressors and aging mechanisms that can result in the failure of a cable splice can be found in Section 2.2 of NUREG/CR-6788 [Ref. 5].

As described in subsection 2.2.2, the stressors affecting cable termination connections at terminal blocks, fuse holders, circuit breaker and disconnect switch terminal connectors, electric motor leads, electrical equipment insulating bushings, electrical bus bars, or other electrical equipment termination points are generally the same as those affecting electric cables. However, the resulting aging and degradation mechanisms acting on the terminations can be very different than for cables and splices because of the variations in the types and designs for these cable system components. As shown in Table 2.2, the medium-voltage terminations will involve higher voltage connections at electric motors, electrical buses, fuse holders, circuit breaker and disconnect switch terminal connectors, and electrical equipment bushings. Some of these terminations depend on polymer insulation materials to provide the required dielectric strength. These polymers are exposed to the same stressors as cables and splices, and therefore can be affected by the same aging mechanisms, as shown in the tables.

Similar to the cable splices, electrical terminations all involve a physical connector to join the electrical conductor to the termination point. The aging mechanisms of fatigue and loosening of these connections can be caused by the stressors listed in Table 2.2.

2.3 Applicable Regulatory Requirements

NRC regulations require that cables be capable of performing their function when subjected to anticipated environmental conditions, such as moisture or flooding. Further, the design should minimize the probability of power interruption when transferring power between sources. The cable failures that could disable risk-significant equipment are expected to have monitoring programs to demonstrate that the cables can perform their safety function when called on. The applicable regulatory requirements include the following:

NRC regulations in 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 4, state that, "Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation."

NRC regulations in 10 CFR Part 50, Appendix A, GDC 17, state that, "Provisions shall be included to minimize the probability of losing electric power from any of the remaining supplies as a result of, or coincident with, the loss of power generated by the nuclear power unit, the loss of power from the transmission network, or the loss of power from the onsite electric power supplies."

NRC regulations in 10 CFR Part 50, Appendix A, GDC 18, state that, "Electric power systems important to safety shall be designed to permit appropriate periodic inspection and testing of important areas and features, such as wiring, insulation, connections, and switchboards, to assess the continuity of the systems and the condition of their components," "...the operability and functional performance of the components of the systems," "...and... the operability of the systems as a whole."

NRC regulations in 10 CFR 50.65(a)(1) state that, "Each holder of a license to operate a nuclear power plant...shall monitor the performance or condition of structures, systems, or components...in a manner sufficient to provide reasonable assurance that such structures, systems, and components...are capable of fulfilling their intended functions."

NRC regulations in 10 CFR Part 50, Appendix B, Criterion III, state that "...Measures shall also be established for the selection and review for suitability of application of materials, parts, equipment and processes that are essential to the safety-related functions of the structures, systems and components."

NRC regulations in 10 CFR Part 50, Appendix B, Criterion XI, "Test Control," state that, "A test program shall be established to assure that all testing required to demonstrate that structures, systems, and components will perform satisfactorily in service is identified and performed."

NRC regulations in 10 CFR Part 50, Appendix B, Criterion XVI, "Corrective Action," state that, "Measures shall be established to assure that conditions adverse to quality ...are promptly identified and corrected. In the case of significant conditions adverse to quality, the measures shall assure that the cause of the condition is determined and corrective action taken to preclude repetition.

2.4 Increasing Trend of Undetected Early Cable Failures

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 anticipated normal service operating conditions or under design basis conditions. Nor does in-service testing of a cable provide specific information on the status of aging degradation processes, or the physical integrity and dielectric strength of its insulation and jacket materials. Consequently, a cable circuit with undetected damaged or degraded insulation could pass an in-service functional test, but still fail unexpectedly when called upon to operate under anticipated environmental conditions, or the more severe stresses encountered in emergency operation during a design basis event (i.e., fully loaded equipment, more extreme environmental conditions, extended operation in a heavily loaded state).

Longer cable circuits may pass through several different operating environments over the length of their routing throughout the plant. Portions of a cable circuit may pass through areas experiencing more harsh environmental conditions, such as high temperature, high radiation, high humidity, or submersion. There has been concern that such local adverse environmental stressors can cause excessive aging and degradation in the exposed sections of a cable that could significantly shorten its qualified life and cause unexpected early failures.

It should be emphasized that the occurrence of cable system operating environments or locally adverse conditions that are unanticipated or more severe than the original plant design may constitute a design deficiency of the cable system, specifically, a potential violation of GDC 1, 4, 17, and 18. NRC regulations, such as 10 CFR 50, Appendix B, (quality assurance), the maintenance rule (10 CFR 50.65), and environmental qualification regulations (10 CFR 50.49), require that programs and administrative controls be established to monitor and detect degraded conditions on a regular basis and to promptly implement effective corrective actions and design modifications, consistent with its safety significance, so that any further cable degradation is minimized. A cable system must be designed to meet all applicable regulations and to perform its intended function in the plant environment under all anticipated operational occurrences and design basis events.

Several examples of this type have been reported in Information Notice 2002-12, "Submerged Safety-Related Cables" [Ref. 7], and Generic Letter 2007-01, "Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients" [Ref. 1]. In these incidents, medium-voltage power cables in inaccessible or underground cable ducts, cable trenches, or direct buried have been exposed to moisture or submergence for extended periods. Cables exposed to water while energized are susceptible to a phenomenon called 'water treeing' in which tree-like micro-cracks are formed in the insulation due to electrochemical reactions. Growth of water trees will increase with time under continued exposure to moisture and voltage stress eventually leading to complete electrical breakdown of the insulation [Ref. 3].

In GL 2007-01, licensees were requested to provide failure history information for power cables within the scope of 10 CFR 50.65 (the Maintenance Rule) and a description of inspection, testing, and monitoring programs to detect degradation of inaccessible or underground cables supporting systems within the scope of 10 CFR 50.65. The licensee responses to the requested information were analyzed and described by the NRC in a summary report [Ref. 8]. The summary report indicated that 93% of the cable failures analyzed occurred on normally energized power cables. More than 46% of the failures were reported to have occurred while the cable was in service and more than 42% were identified as "testing failures" in which cables failed to meet testing or inspection acceptance criteria. The failure data, as presented in Figure 2.1 reproduced from Reference 8, showed a trend toward early cable failure, the majority occurring in the range of 11-20 years of service and 21-30 years of service; this is shorter than the plants' original 40-year licensing period.

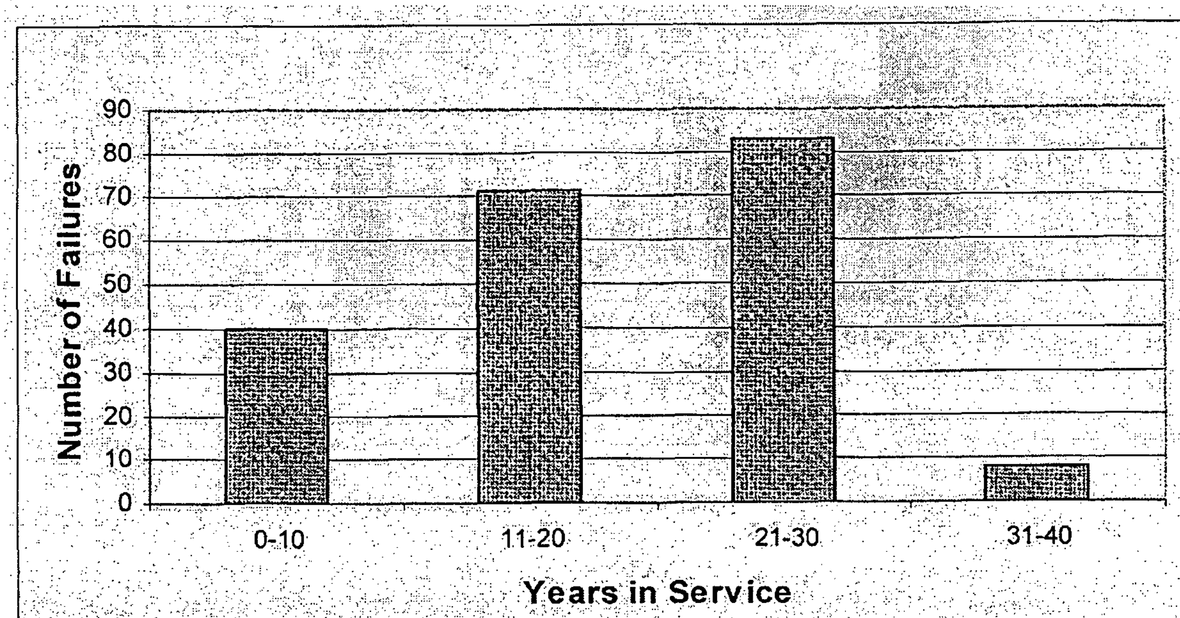


Figure 2.1 Number of failures per ten-year service intervals, GL 2007-01 responses [Ref. 8]

In its recommendations and conclusions for the summary report on licensee responses to GL 2007-01 [Ref. 8], the NRC stated that:

"Plants undergoing license renewal have agreed to a cable testing program for the extended period of plant operation for a limited number of cables that are within the scope of license renewal, but only a few have established a cable testing program for the current operating period. The data obtained from the GL responses show an increasing trend of cable failures. These cables are failing within the plants' 40-year licensing periods. As shown by the January 2008 event at Point Beach Nuclear Plant, cable failures have resulted in plant transients and shutdowns, loss of safety redundancy, entries into limiting conditions for operation, and challenges to plant operators."

"Licensees have identified failed cables and declining insulation resistance properties through current testing practices; however, licensees have also reported that some failures may have occurred before the failed condition was discovered. Although the majority of in-service and testing failures have occurred on cables that are normally energized, the staff is concerned that additional cable failures have not been identified for cables that are not normally energized or tested. The NRC staff recommends that the licensees should also include normally deenergized cables in a cable testing program. It appears that no manufacturer or insulation type is immune from failure. In addition, licensees have identified failures and or declining performance capability for both shielded and unshielded cables."

The NRC further stated in its recommendations and conclusions that:

"The 10 CFR Part 50 regulations require licensees to assess the condition of their components, to monitor the performance or condition of SSCs in a manner sufficient to provide reasonable assurance that they are capable of fulfilling their intended functions, and to establish a test program to ensure that all testing required to demonstrate that components will perform satisfactorily in service is identified and performed. The NRR staff believes that licensees should have a program for using available diagnostic cable testing methods to assess cable condition."

In response to these concerns, this research study develops a comprehensive electric cable condition monitoring (CM) program, consisting of nine recommended essential elements, that will consolidate a core program of periodic CM inspections and tests, together with the results of in-service testing, environmental monitoring and management activities, and the incorporation of cable-related operating experience.

3. COMMONLY USED CABLE CM TECHNIQUES

This Section discusses currently available cable condition monitoring techniques that can be included in a condition monitoring program. The attributes of an effective condition monitoring technique are first presented to provide a framework for evaluating the advantages and limitations of currently available techniques. Following this, an overview of several of the most commonly-used, currently available cable condition monitoring techniques is presented. Several new or less well-known techniques are also discussed for balance. This is not intended to be a comprehensive list, and no attempt has been made to make this list all-inclusive. 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 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.

Finally in this Section, guidance on the selection of a suitable cable condition monitoring technique is presented. This discussion focuses on the factors that should be considered in selecting a technique for a particular application.

3.1 <u>Desired Attributes of an Effective Condition Monitoring Technique</u>

A key element of any electric cable condition monitoring program is the selection of appropriate condition monitoring techniques to achieve the desired result. Condition monitoring involves the observation, measurement and/or trending of one or more condition indicators that can be correlated to the physical condition or functional performance of the cable. An "ideal" condition monitoring technique would have the following desired attributes [Ref. 9] listed below. It should be understood that no single CM Technique will have all of these attributes.

- 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 information obtained from condition monitoring techniques is used to determine the ability of a cable, in its current condition, to perform its intended function within certain acceptance criteria. To obtain useful information, it is important that an appropriate technique be selected for the cable being monitored. An overview of currently available condition monitoring techniques is provided below, including their advantages and disadvantages, as well as insights into the applications for which they are best suited.

3.2 In Situ CM Techniques

There are a number of condition monitoring techniques that can be performed in situ. This is desirable since the removal of sample cable material, which can be destructive, is not required. The following provides a brief description of available in situ condition monitoring techniques.

3.2.1 Visual Inspection

Visual inspection is one of the most commonly used and effective in situ condition monitoring techniques [Ref. 9]. It is performed by visually examining a cable using the naked eye, but can be aided with a flashlight and/or magnifying glass. If direct access is available, the cable can also be touched to obtain tactile information. No other special equipment is required. 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 (See Table 3.2 and Section 4.5).

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. For best results, a standardized procedure should be utilized that identifies the various cable attributes to be examined. Cable attributes that can be visually inspected 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. Also, the rigidity of the cable can be qualitatively determined by squeezing and gently flexing it. 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.

3.2.2 Compressive Modulus (Indenter)

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 degradation rate of the cable material. 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) [Refs. 9, 10, 11].

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. This test is most appropriate for use on low-voltage cables in situ.

In testing performed by Brookhaven National Laboratory [Ref. 9] 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. It can be operated 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 which provides trendable, repeatable results that can be correlated to other known measures of cable properties, and can be used as an indicator of cable condition.

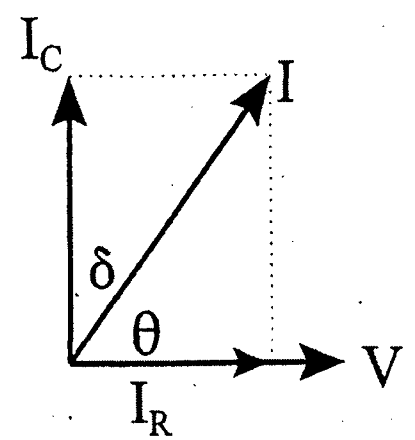
A disadvantage of this technique is that electrical cables are not always easily accessible in nuclear plants. In many cases, cables are installed under other cables in cable trays or run through conduits, which makes them inaccessible for indenter testing. Indenter testing is not always optimal even for accessible cables. For example, cables that may only be accessible for indenter testing on their outer jacket surface, which would provide little 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 desireable to examine a cable section that had undergone a localized degradation."

3.2.3 Dielectric Loss (Dissipation Factor/Power Factor)

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.



I	**Total measured current**
I_C	**Capacitive component of I**
I_R	**Loss component of I**
V	**Applied ac voltage**
θ	**Dielectric phase angle**
δ	**Dielectric loss angle**
cos θ	**Dielectric (insulation) power factor**
tan δ	**Dielectric (insulation) dissipation factor**
Δ tan δ	**Power factor tip-up**

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] and IEEE Standards 400 [Ref. 13] and 400.2 [Ref. 14] provide guidance on the performance of dielectric loss/power factor testing.

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.

Another advantage of the dielectric loss technique is that the cable being tested does not have to be completely accessible. The test equipment can be connected to the ends of the cable, and the test can be performed without physically touching the length of the cable or removing material samples.

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.

3.2.4 Insulation Resistance and Polarization Index

Insulation resistance 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 Standard 141 [Ref. 15], and ASTM Standard D257 [Ref. 16] provide guidance on performing insulation resistance testing.

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 60°F (15.6°C) 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 test performed by BNL [Ref. 9].

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 cables that may be 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.

3.2.5 AC Voltage Withstand Test

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 Hi 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] and IEEE Std. 400.1 [Ref. 17] 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.

A disadvantage of this test is that the high voltage used 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 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.

3.2.6 Partial Discharge Test

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. 400.3-2006, "IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment" [Ref.18], ASTM Standard D470, "Standard Test Methods for Crosslinked Insulations and Jackets for Wire and Cable" [Ref. 19] and ASTM D2633, "Standard Test

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

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].

This test has limitations for use in the field since it 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 plant environment could interfere with the test due to noise interference, so this test is most successful on shielded cables.

3.2.7 DC High Potential Test

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] and IEEE Standard 141-1993 [Ref. 15].

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.

3.2.8 Step Voltage Test

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] and IEEE Standard 141-1993 [Ref. 15].

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.

3.2.9 Time Domain Reflectometry

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].

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.

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 represent a 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.

3.2.10 Infrared (IR) Thermography

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]. 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.

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.

3.2.11 Illuminated Borescope

The use of an illuminated borescope to inspect inaccessible cables has proven to be a useful screening technique for identifying stressors that can lead to cable degradation. It can also detect visible cable damage. The borescope can be inserted into conduits or other locations containing cables that would ordinarily be inaccessible to inspection for mechanical damage that may have been caused during installation or service, 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.

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 if additional testing is needed.

3.2.12 Line Resonance Analysis (LIRA)

The Line Resonance Analysis (LIRA) test 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 aging of the cable insulation. In addition, it is claimed that this technique can detect and localize meaningful property changes for various different insulation types and geometries for both aging and non-aging related effects [Ref. 24]. Additional research is ongoing on this technique.
An advantage of this technique is that it can be performed in situ without de-terminating the cable. 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. Training and experience are needed to obtain meaningful results.

3.3 <u>Laboratory CM Techniques</u>

If samples of the cables to be inspected are available, there are condition monitoring techniques available that can be performed in a laboratory. An overview of some of the most common laboratory techniques is provided below.

3.3.1 Elongation-at-Break

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]. 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] and D412 [Ref. 26]. 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. This is a destructive test for the extracted specimen from the cable.

EAB measurements provide a useful quantitative assessment of the condition of cable materials and are widely used 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. 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, testing has shown that there is usually some useful service life remaining at levels well below this [Ref. 9].

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.

3.3.2 Oxidation Induction Time/Temperature

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] provides guidance on performing OIT testing. Use of this technique for cable condition monitoring is discussed in References 9 and 28.

OITM 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). 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.

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., 18°F/min (10°C/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.

This test has similar advantages and disadvantages to the OITM test.

3.3.3 Fourier Transform Infrared Spectroscopy

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].

In studying the oxidation of cable materials an important wave number 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.

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.

3.3.4 Density

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].

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] and D1505 [Ref. 31] provide guidance on performing density measurements.

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 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 technique will only provide information for the localized area from which the sample is taken.

"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."

Table 3.1 Summary of Cable Condition Monitoring Techniques

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

3.4 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. Section 4.5 provids additional guidance and information on the selection of CM inspection and testing techniques for electric cables in a cable CM program (element 5 of the cable CM program). It also provides a detailed description of the selection process and how it integrates with the other essential elements of the monitoring program.

3.4.1 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 response to Generic Letter 2007, 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]. 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 combination of these activities could provide useful information for making a decision to perform more intrusive CM testing.

3.4.2 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
- Active stressors
- Aging mechanisms to be detected

The overview of condition monitoring techniques presented previously discussed the applicability of each technique and can be used as guidance for selecting an appropriate technique for a specific application. Table 3.2 presents a 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.

Table 3.2 Cable Condition Monitoring Technique Selection Matrix

		Applicable Condition Monitoring Technique																
		Screening		Pass/Fail					Diagnostic (Shading indicates laboratory test – sample needed)									
Stressor	Aging Mechanism	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	•	•	•	•	•				•	•		•					

Multiple CM techniques should be utilized to effectively monitor the condition of a cable since no single technique can completely characterize the condition of a cable and its insulation. [Ref.9] For cables that are exposed to several different stressors, a combination of different CM techniques may be warranted to ensure that all aging mechanisms are addressed. Section 4.5 provides additional guidance and information on the selection of CM inspection and testing techniques for electric cables in a cable CM program (element 5 of the cable CM program).

4. ESSENTIAL ELEMENTS OF A CABLE CONDITION MONITORING PROGRAM

In this section of the report, nine essential elements that constitute an effective cable condition monitoring (CM) program are presented.

These elements are as follows:

1. Selection of cables to be monitored
2. Development of database for monitored cables
3. Characterize and monitor service environments
4. Identify stressors and expected aging mechanisms
5. Select CM techniques suitable to monitored cables
6. Establish baseline condition of monitored cables
7. Perform test & inspection activities for periodic CM of cables
8. Periodic review & incorporation of plant & industry experience
9. Periodic review & assessment of monitored cables condition

Each element will be described in detail in the following subsections. The purpose for each of the individual elements of the cable CM program will be presented along with how the element fits into the overall cable CM program. Guidance will be provided for implementation of the important features or activities associated with the program element. Finally, the expected results or outcomes of each program element will be described. The guidance will also provide information needed to integrate each element into the overall cable CM program. Figure 4.1 presents a block diagram showing the elements of the cable CM program and their principle interactions.

4.1 Selection of Cables to be Monitored

The purpose of the first element of the program is to identify and select electric cables that are candidates for inclusion in the cable condition monitoring program. Power, instrumentation, and control cables that have high safety significance, high plant risk significance, or are important to continued safe operation of the plant would form the core group of cables to be included in the program. Generally, these cables have either a direct safety-related function, are required to achieve and maintain safe shutdown, or are required to mitigate the consequences of design basis accidents. These would also include, computer and digital I&C cables that have a safety-related function or are required for mitigation of the consequences of an accident.

Much of the cable selection process for implementing a cable CM program is already guided by Title 10 to the Code of Federal Regulations, Part 50 (10 CFR 50), requirements applying to the licensing and operation of commercial nuclear power plants. The design criteria for nuclear plant systems, structures, and components, which include electric power cables and instrumentation and controls (I&C) cables, are given in Appendix A to 10 CFR 50.

More specifically, as related to the safety function of electric cables, 10 CFR 50, Appendix A, General Design Criterion 4 (GDC 4), "Environmental and Dynamic Effects Design Bases," states that "structures, systems and components important to safety shall be designated to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation." GDC 17, "Electric Power Systems, "requires that onsite and offsite electrical power systems "be provided to facilitate the functioning of structures, systems and

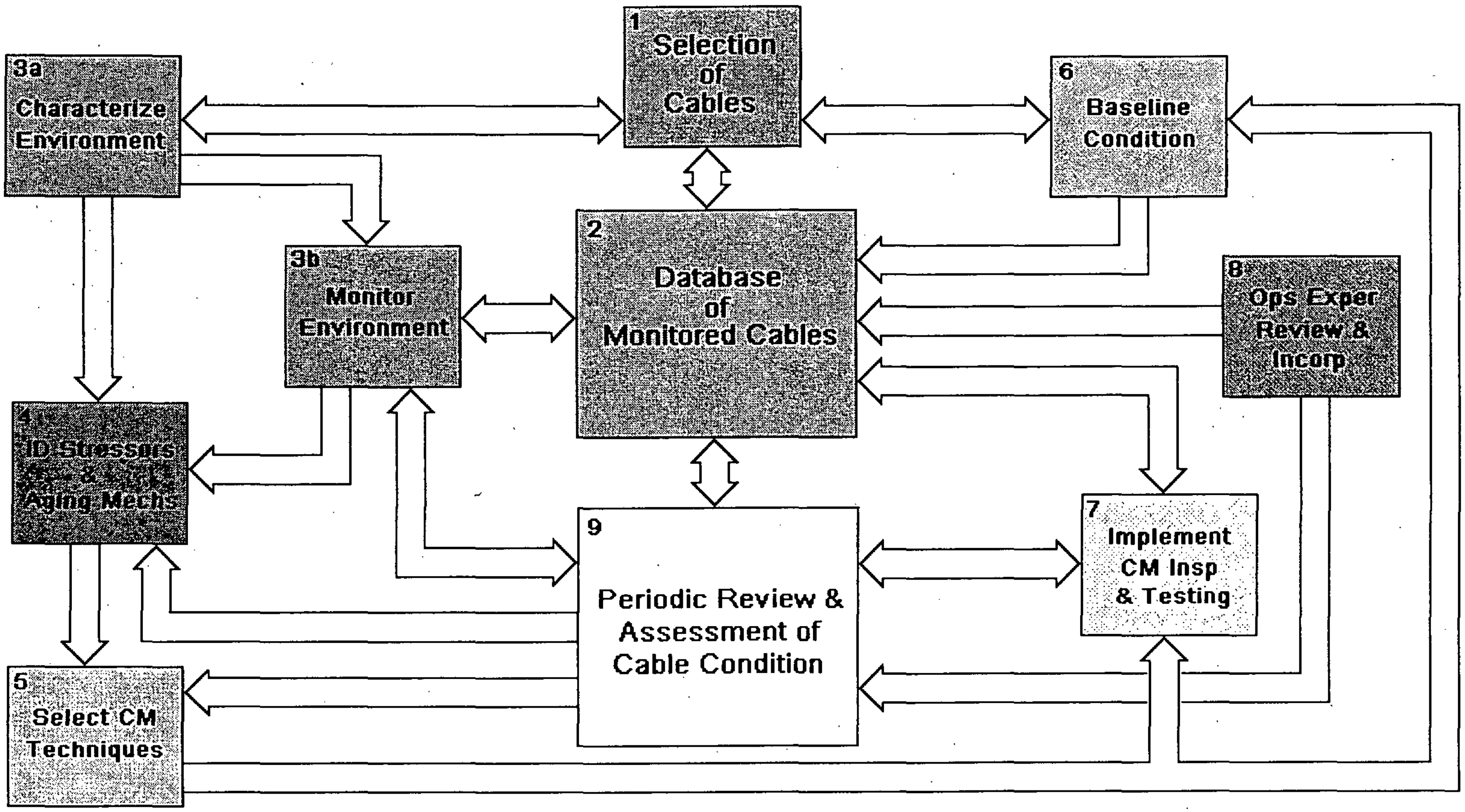


Figure 4.1 - Block diagram of the elements of a cable CM program and their interactions

components important to safety," and that "provisions must be included to minimize the probability of losing electric power from any of the remaining [electric power] supplies as a result of, or coincident with, the loss of power generated by the nuclear power unit, the loss of power from the transmission network, or the loss of power from the onsite electric power supplies." Finally, GDC 18, "Inspection and Testing of Electric Power Systems," requires that "electric power systems important to safety shall be designed to permit appropriate periodic inspection and testing of important areas and features, such as wiring, insulation, connections and switchboards, to assess the continuity of the systems and the condition of their components," and that "... systems shall be designed with a capability to test periodically (1) the operability and functional performance of the components of the systems..., and (2) the operability of the systems as a whole..., including operation of applicable portions of the protection system, and the transfer of power among the nuclear power unit, the offsite power system, and the onsite power system.

Other NRC regulations that would guide the selection of cables for the cable CM program are: fire protection (Appendix R to 10 CFR 50 and 10 CFR 50.48), environmental qualification of electric equipment important to safety (10 CFR 50.49), the station blackout rule (10 CFR 50.63), the maintenance rule (10 CFR 50.65), plant license renewal requirements (10 CFR 54), anticipated transients without scram (ATWS) (10 CFR 50.62), and protection against pressurized thermal events (10 CFR 50.61). Each of these regulations is discussed below as it relates to the selection of cables for a condition monitoring program.

All licensees are required to maintain plant design control documentation, installation and construction records, cable systems installation, maintenance, and operating procedures, testing and inspection documentation, cable procurement documentation, and other quality control records in accordance with the requirements of Appendix B to 10 CFR 50, *quality assurance criteria for nuclear power plants*. As a result, the existing plant listing of safety-related electric power cables and I&C cables can serve as the core listing of cables to be included in the cable CM program. The licensee's listing of environmentally qualified (EQ) Class 1E electric cables, as defined in 10 CFR 50.49 and IEEE Std. 323-1974 [Ref. 32], will be a subset of the entire listing of safety-related cables in the plant. However, since there may be some non-safety-related cables that are specified with environmental qualification requirements as a result of potential exposure to other-than-mild, or locally adverse, service environments, the listing of EQ cables should be reviewed to determine whether there are any cables in this category that should be added to the list of cables for the CM program.

Electric power cables, circuit systems, and I&C cables that are designed to satisfy the requirements for loss of all alternating current power in a light-water cooled nuclear power plant as defined in 10 CFR 50.63 (the station blackout rule) should be identified and included in the cable CM program. Because of the importance of the alternate ac (AAC) power source in the plant's capability to withstand station blackout, the function of all the power circuits and I&C circuits associated with connection, control, and monitoring of the AAC power supply to the plant must be ensured. This may be even more critical in a multiple unit plant with shared AAC power sources or shared onsite emergency power sources. Consequently, it is recommended that all of the power and I&C cables associated with satisfying the requirements of 10 CFR 50.63 be included in the listing of cables to be monitored in the cable CM program.

In compliance with the requirements of 10 CFR 50.65 (maintenance rule), licensees are required to implement a program for monitoring the performance or condition of all structures, systems, and components within the scope of the maintenance rule, against licensee–established goals, in a manner sufficient to provide reasonable assurance that these structures, systems, and components are capable of fulfilling their intended functions. The scope of the maintenance rule monitoring program, as defined for safety-related and non-safety-related structures, systems, and components in 10 CFR 50.65, paragraph (b), will encompass a group of electric power and I&C cables of high importance. It is recommended that cables in the scope of the maintenance rule be included in the cable CM program.

Each licensee is required to develop and implement a plant fire protection plan and program in accordance with the requirements of 10 CFR 50.48 and Appendix R to 10 CFR 50. The fire protection program will designate the structures, systems, and components that are to be protected against fire damage in each fire area of the plant so that the capability to achieve and maintain safe shutdown is ensured in accordance with the fire protection regulations. It is recommended that the list of protected electric cable circuits in the station fire protection program necessary to satisfy the requirements of the fire protection regulations be added to the list of monitored electric power and I&C cables for the cable CM program.

The scope of safety-related and non-safety-related systems, structures, and components within the license renewal regulation is defined in 10 CFR 54.4. These can include electric cables, conductor insulation material, and cable accessories. Table 6 of NUREG-1801, the GALL Report, Volume 1, Revision 1, and Section XI of Volume 2, Revision 1 [Ref. 33], identify several license renewal aging management programs (AMPs) for electrical equipment that affect electric cables, connections, and fuse holders. These are:

XI.E.1	Electrical Cables and Connections Not Subject to 10 CFR 50.49 Environmental Qualification Requirements
XI.E2	Electrical Cables and Connections Not Subject to 10 CFR 50.49 Environmental Qualification Requirements Used in Instrumentation Circuits
XI.E3	Inaccessible Medium-Voltage Cables Not Subject to 10 CFR 50.49 Environmental Qualification Requirements
XI.E5	Fuse Holders
XI.E6	Electrical Cable Connections Not Subject to 10 CFR 50.49 Environmental Qualification Requirements

The electric cables, connectors, and accessories that are identified as being within the scope of the above license renewal aging management programs are candidates for inclusion in the cable CM monitoring program. Cable monitoring activities under these license renewal AMPs may be no more than an evaluation of periodic surveillance testing results to identify the existence of cable aging degradation. Consequently, the cable systems and accessories within the scope of the license renewal evaluation could be included in the cable CM program, where they would be given more detailed and extensive inspections, monitoring tests, and condition evaluation to ensure their proper function.

Another important source of guidance for the selection of cables to be included in the CM program is operating experience. This ties in with program element 8, review and incorporation of operating experience, discussed in subsection 4.8, and program element 9, periodic review and assessment of cable condition, discussed in subsection 4.9 of this report. The operating and failure experience with electric cable systems and accessories gathered throughout the nuclear industry is a valuable source of information that can alert licensees to generic problems that can affect the electric cables installed in nuclear power plants. These problems include manufacturing defects, deficient installation practices, unusual susceptibilities to service conditions, frequently-encountered adverse local conditions, and generic application problems. Adverse conditions in service environments, incompatible cable configurations, incompatible combinations of insulating or jacket materials, improperly applied cable accessories, and other cable system vulnerabilities may appear over time within a single plant or throughout the nuclear industry. Manufacturers' bulletins and information letters, NRC correspondence and information notices, NRC and industry cable aging evaluation studies, and industry databases, such as the Institute for Nuclear Plant Operations' (INPO) Nuclear Plant Reliability Data System (NPRDS), the INPO Equipment Performance and Information Exchange (EPIX) reporting system, and the NRC's Licensee Event Report (LER) database, are good sources for identifying generic problems in cable systems and informing licensees of problems so that corrective actions, such as increased cable CM, can be implemented. Operating and failure experience within one's own plant, if properly identified, documented, and periodically evaluated, can also provide guidance on the selection of groups of cables that have common characteristics, materials, or applications that make them candidates for increased scrutiny within the cable CM program. Groups of electric cables that are exposed to and affected by similar adverse service environments, such as flooding of underground cable duct banks and manholes, should be included, along with their service environments, in the cable CM program so that the adverse service conditions, and the potentially increased rate of degradation of cable insulating materials, may be monitored more thoroughly and more frequently.

A final category of cables that is recommended for inclusion in the cable monitoring program would be those cables that could cause a plant trip or transient . These are circuits that may not be directly credited with a nuclear safety function or support functions that are important to nuclear safety, however, their availability has been identified for avoiding plant transients. This improves overall plant stability, thereby reducing challenges to electric power safety systems

The end result of the licensee's cable selection process will be a listing of all the most important cables in the plant whose condition should be periodically monitored and evaluated to assure that they are capable of performing their intended function. The characteristics, application, operating environment, CM inspection and test data, and condition of the selected cables will be incorporated into the cable CM program database discussed in the following subsection.

4.2 <u>Database of Monitored Cables</u>

The second element of the cable CM program is the database for the electric cables that are to be monitored under the program. The purpose of the cable CM program database is to provide a single centralized source of information for the cables in the program so that the cable monitoring program engineer can access, analyze, and evaluate the documentation and data necessary to make cable condition assessments and to guide the direction of program decisions and activities. The database will document: physical characteristics of cable systems in the program, details of installation and service environments (described in subsections 4.3 and 4.6), baseline CM test and inspection results (described in subsections 4.3 and 4.6), periodic CM test and inspection results (described in subsection 4.7), and periodic condition assessments and corrective actions (described in subsections 4.8 and 4.9).

Referring to Figure 4.1, it can be seen that the monitored cables database serves as a key element in the CM program in that it assimilates information and data from every other element in the program to provide a source of documentation that can be accessed, analyzed, and evaluated. By bringing together information on the physical characteristics of cables in the program with periodic inspection and condition monitoring results, the cable engineer has a ready resource of relevant information for assessing the present condition of each cable in the program. Quantitative test measurements can be analyzed and trended against baseline measurements to assess changes in cable parameters and track degradation of insulating materials. These can be combined with baseline inspection data and periodic inspection results to make an informed assessment of cable condition. Installation information and periodic environmental monitoring measurements can be reviewed to verify that operating conditions have remained within the environmental parameters specified in the original plant design. The engineer can also verify that the service conditions under which environmentally qualified cables and accessories are operating remain within the parameters of their qualified life. Using the database, the cable engineer can evaluate the cable condition, operating environment, and changes in condition and environment over time to determine whether corrective actions should be initiated to manage cable aging as well as any environmental stressors that can affect cable aging and performance.

In order to achieve the aforementioned objectives for supporting the cable CM program, the database must contain essential information and data in a user-friendly, sortable, flexible, expandable, and accessible form. Sufficient storage capacity must be available to handle the various types of data that will be gathered and processed. Commercial database software programs, such as Microsoft Access, have been used successfully by the authors in cable condition monitoring testing programs and have proven to be versatile enough to accommodate CM inspection and test data storage, retrieval, and analysis. The database can be completely computer-based. However, a combination of computer-based information and hard-copy information keyed and linked to a computer-based list of cables and cable data may be preferred by some users.

It is recommended that the cable systems database include the following essential categories of data in order to adequately support a cable CM program: 1) unique cable/circuit identifier, 2) cable construction and manufacturing information, 3) application information, 4) cable installation and environments information, 5) cable inspections and condition monitoring test results, 6) applicable operating experience, and 7) periodic cable evaluation and assessment results. Table 4.1 summarizes the recommended major categories of information to be included in the CM program database, including the specific items recommended within each category. Each item represents cable characteristics that have been shown to have an effect on the degradation or damage of electric cable insulation and jacket materials and the overall performance of a cable over time. This is summarized in the "purpose" column of Table 4.1.

Realistically, all of the information listed in Table 4.1 may not be available for every cable in the cable CM program. For low-voltage power and I&C cables operating in mild, dry, indoor, above-grade environments, it is not as critical to have all these data available in the database. However, for cable systems operating in harsh environments and with potential exposure to locally adverse stressors, these data will allow the cable engineer to access and analyze periodic testing and inspection data, identify problem environments or unusual performance degradation, and make the link to common factors that may affect other cables with similar characteristics, installation locations, or aging stressors. The ability to access, sort, link, trend, and analyze up-to-date manufacturing, application, inspection and test data, and operating experience is an essential element of the cable CM program. It gives the cable engineer a powerful tool enabling him to make informed decisions on modifying periodic testing frequency, adding CM tests, or implementing other corrective actions to manage cable degradation and/or adverse environmental factors.

The resulting database will provide essential information to support the implementation of the cable CM testing and inspection activities and the periodic review and assessment of the condition of individual cables. The cable CM program database should be maintained and administratively controlled to obtain the maximum utility from the database and to optimize the effectiveness of the cable CM program.

4.3 Characterize and Monitor Environments

The third element of the cable CM program is the characterization and monitoring of the service environments in which the cables in the CM program will be operating. By characterizing the conditions in a cable's normal operating environment and identifying any sections of a cable run that could be exposed to potentially more severe adverse conditions, the cable engineer can determine the global and local stressors that could cause a significant increase in the rate of aging degradation or other damage to a cable (see cable CM program element 4, discussed in subsection 4.4). The cable engineer will also use the environmental information to determine, and document in the database, the frequency for the performance of periodic cable inspections and condition monitoring testing, the frequency for periodic monitoring and verification of global environmental conditions, and the frequency for monitoring the status of any adverse local environmental "hot spots" (local adverse stressors) that have previously been identified. Identifying the locations of environmental "hot spots" will also help the cable engineer to specify more frequent or more detailed CM inspection and testing for those cable circuits, or sections of the cable circuits, that are exposed to the identified local adverse stressors (see subsections 4.6, 4.7, and 4.9).

It should be emphasized that the occurrence of cable system operating environments or locally adverse conditions that are unanticipated or more severe than the original plant design may constitute a design deficiency of the cable system, specifically, a potential violation of GDC 1, 4, 17, and 18. NRC regulations, such as 10 CFR 50, Appendix B, (quality assurance), the maintenance rule (10 CFR 50.65), and environmental qualification regulations (10 CFR 50.49), require that programs and administrative controls be established to monitor and detect degraded conditions on a regular basis and to promptly implement effective corrective actions and design modifications, consistent with its safety significance, so that any further cable degradation is minimized. A cable system must be designed to meet all applicable regulations and to perform its intended function in the plant environment under all anticipated operational occurrences and design basis events.

This element consists of three groups of activities: 1) characterization of the cable system's operating environment, 2) periodic monitoring and verification of operating environments and identified local adverse environmental "hot spots," and 3) managing environmental conditions to mitigate the effects on cable systems. Guidance for implementing the activities in this element will be discussed in the following subsections.

4.3.1 Characterizing Cable Operating Environments

Characterization of the cable system's operating environments is necessary to establish and document the actual baseline environmental conditions that the cable system will be exposed to during normal operations. It is accomplished by:

- review of the design, specification, and installation documentation for the cable circuit, in order to locate the routing of the cable circuit throughout the plant;

Table 4.1 Recommended Categories of Information to be Included in a Cable CM Program Database

Database Item	Expected data or format	Purpose
Unique Electric Cable/Circuit Identifier		
Cable/Circuit ID Number	alpha/numeric ID	uniquely identifies a monitored cable
Cable Construction and Manufacturing Information		
Manufacturer	manufacturer name	uniquely identifies cables from a certain manufacturer
Manufacture Date	date	used for age calculation and identifying polymer formula by date
Purchase Order/Date	PO number and date	used to match cable to purchase specifications and age calculation
Insulation Material	polymer (XLPE, EPR, SR, CSPE)	characteristic that can affect aging/degradation/performance
Conductor Insulation Color	color	characteristic that can affect aging/degradation/performance
Activation Energy	value (eV) at reference temp	used in Arrhenius equation time-temperature calculation
Jacket Material/Bonded	polymer/bonding (if applicable)	characteristic that can affect aging/degradation/performance
Overall Jacket Color	color	characteristic that can affect aging/degradation/performance
Conductor Jacket Color	color	characteristic that can affect aging/degradation/performance
Activation Energy	value (eV) at reference temp	used in Arrhenius time-temperature calculation
Filler Materials	polymer	characteristic that can affect aging/degradation/performance
Cable Configuration		characteristic that can affect aging/degradation/performance
Number of Conductors	number of conductors	
Conductor Size	AWG conductor size	
Conductor Stranding	number of strands	
Conductor Material	Cu, Al, other	
Ground Conductor/Material	Cu, Al, other (if applicable)	
Shielding/Material/Type	Cu, Al, other (if applicable) & type	
Temperature Rating	value	characteristic that can affect aging/degradation/performance & application
Special Qualification/Documentation	EQ, seismic, hi-rad, hi-temp, FR	characteristics that can affect aging/degradation/performance & application

Application Information

Function	power, instrumentation, control	characteristic that can affect aging/degradation/performance
Type	ac, dc, digital	characteristic that can affect aging/degradation/performance
Voltage	value and/or level	characteristic that can affect aging/degradation/performance
Safety Class	Class 1E or non-Class 1E	affects safety significance & application
EQ Required	EQ or non-EQ	affects safety significance & application
Additional Regulatory Requirements	SBO, FP, Maint. Rule, Lic. Renewal	affects safety significance, importance, & application
Energization Status	continuous, emergency only, control signals only, intermittent, etc.	characteristic that can affect aging/degradation/performance

Cable Installation and Environments

Routing Information		used to characterize operating environment & adverse localized stressors
Location(s)	bldg & plant locations	
Drawing Reference(s)	drawing numbers	
Raceway Type/ID	conduit, tray, UG duct & ID numbers	
Length in Each Type	length	
Orientation(s)	horizontal, vertical	
Installation Date	date	used determine service age and to calculate thermal equivalent life
Terminations		used to characterize cable termination
Type(s)	pigtails, terminal block, bushing, lug	
Location(s)	equipment/termination ID	
Splices/Accessories ID Number(s)		used to characterize cable splices
Type(s)	accessory type	
Location(s)	eqpt./raceway/cable ID number	
Installation Date(s)	date	
EQ Req'd	yes/no	
Environment(s)/Stressors		characterize normal and adverse localized service conditions
Normal Operating Temp(s)	temperature value	
Normal Radiation Dose Rate	radiation dose value	
Adverse Local Environments		
Type(s)	temp,rad,steam,water,vibration,etc.	
Location(s)	eqpt./raceway/cable ID number	
CAP Number(s)	corrective action program ref no	
Date(s)	date condition observed	
Adverse Local Stressors		
Type(s)	heat,rad,chems,water,vibration,etc.	
Location(s)	eqpt./raceway/cable ID number	
CAP Number(s)	corrective action program ref no	
Date(s)	date condition observed	

Cable Inspections & CM Testing Results		
Cable Baseline Visual Inspection		characterize cable baseline condition & local adverse environments/stressors
Procedure	inspection procedure number	
Results	baseline inspection results	
Date	date	
Cable Baseline CM testing		characterize cable baseline condition & local adverse environments/stressors
Procedure	test procedure number	
Results	condition measurement data	
Date	date	
Periodic Visual Condition Inspection		periodic characterization of cable condition and service environment
Procedure	test procedure number	
Frequency	performance frequency	
Results	periodic inspection results	
Date	date	
Periodic CM Baseline CM testing		periodic characterization of cable condition and service environment
Procedure	test procedure number	
Frequency	performance frequency	
Results	condition measurement data	
Date	date	
Applicable Surveillance Tests		calibration/functional surveillance test results
Procedure/Surv. Number	test procedure/surveillance number	
Frequency	performance frequency	
Results	calibration/functional test data	
Date	date	

Applicable Operating Experience		
Manufacturer's Notifications		document applicable manufacturer's notifications & plant corrective action
Type	SIL, TIL, mfg's literature	
Reference	document number	
Date	document date	
CAP Number(s)	corrective action program ref. no.	
Corr. Action(s) Implemented	yes/no/in review/in progress	
Date(s)	date(s)	
Industry Notifications		document applicable industry notifications & plant corrective action
Type	INPO Rpt, EPRI Rpt, EEI Rpt	
Reference	document number	
Date	document date	
CAP Number(s)	corrective action program ref. no.	
Corr. Action(s) Implemented	yes/no/in review/in progress	
Date(s)	date(s)	
NRC Notifications		document applicable NRC notifications & plant corrective action
Type	IN, GL, GSI, NUREG Rpts	
Reference	document number	
Date	document date	
CAP Number(s)	corrective action program ref. no.	
Corr. Action(s) Implemented	yes/no/in review/in progress	
Date(s)	date(s)	
Internal Operating/Failure Experience		document applicable in-plant cable-related failures & plant corrective action
Type	Failure, test, maint, inspection	
Date	date of event	
CAP Number(s)	corrective action program ref. no.	
Corr. Action(s) Implemented	yes/no/in review/in progress	
Date(s)	date(s)	

Periodic Cable Evaluation and Assessment Results		
Review Baseline Cable Condition	document baseline condition	establish baseline condition for comparison of future inspection/test results
Date	document service environment	verify environment within design specs; baseline for future data comparison
Review Baseline Service Environment	periodic review of cable condition	assess cable condition, remaining life, CM insp. frequency, required actions
Date	frequency of review/assessment	
Review CM Inspection Results	review cable/environment condition	assess cable/environment condition, remaining life, CM insp frequency, required actions
Review Frequency	frequency of review/assessment	
Review Date	date of review/assessment	
Actions Recommended	corrective action(s)	
CAP Number(s)	corrective action program ref. no.	
Corr. Action(s) Implemented	yes/no/in review/in progress	
Date(s)	date(s)	
Review CM Test Results	periodic review of cable CM test(s)	assess/trend cable CM data, remaining life, CM test freq., required actions
Review Frequency	frequency of review/assessment	
Review Date	date of review/assessment	
Actions Recommended	corrective action(s)	
CAP Number(s)	corrective action program ref. no.	
Corr. Action(s) Implemented	yes/no/in review/in progress	
Date(s)	date(s)	

- review of existing environmental survey information from programs such as radiation protection and environmental qualification in order to quantify the environmental conditions to which a cable circuit is exposed;

- in situ measurements of environmental conditions; and

- initial walkdown visual inspection of the accessible portions of the cable circuit to verify the actual in-plant environmental conditions and identify any localized adverse environmental conditions that could potentially affect the performance of the cable, splices, terminations, or other cable accessories.

The initial environmental characterization walkdown inspection could be performed in conjunction with the baseline visual inspection conducted to establish baseline cable condition in support of CM program element 6, described in subsection 4.6. Both activities will make use of cable design, specification and installation documentation, require the review of cable circuit routing information, and require a physical walkdown of the same accessible sections of each cable circuit. Results of the walkdown inspections should be documented in the cable CM database. Based upon the results of the environmental walkdown inspection and the baseline measurements of the cable operating environment(s), the cable engineer can make a determination on the frequency for periodic walkdown inspection and monitoring of a cable circuits operating conditions and the frequency for monitoring and inspection of any localized adverse environments that had been identified in the initial walkdown. The initial inspection and CM testing frequencies for environments thus determined by the cable engineer should be documented in the cable CM database.

The following environmental conditions are the most important factors to be considered when characterizing the operating environment of a cable system since they have been shown to have an effect on the aging degradation and performance of electric cables:

- Temperature (high and low)
- Radiation (type and dose rate)
- High humidity
- Moisture (wetting of cable surfaces)
- Standing water or flooding of cables (submersion of cables)
- Vibration
- Dirt and dust
- Exposure to chemicals or other reactive contaminants
- Exposure to sunlight (ultraviolet radiation)

In addition to identifying and documenting the aforementioned conditions during the cable system walkdown, the cable engineer should inspect for proximity to heat sources such as high temperature steam lines, large uninsulated valve bodies, unit area heaters, and high powered lighting fixtures. Storage tanks and piping carrying steam, borated water, hydraulic fluid, or other chemicals above, or in proximity to, cable circuits are potential sources of high temperature/pressure steam leakage, high temperature exposure, wetting or flooding, and exposure to reactive chemicals. Physical contact between polymer-insulated cables and structures, plant equipment, piping, thermal insulation, worker stepping, and other objects can deform, abrade, or degrade the performance of the cable insulating materials. Vibration of electrical cables can occur at the cable terminations to electric drive motors or at the terminations to instruments mounted on or near operating machinery or large pipelines.

Longer cable circuits may pass through several different operating environments over the length of their routing throughout the plant. Each of these variations should be documented in the cable CM database. Sections of the cable circuits passing through mild operating environments may only require periodic environmental monitoring at extended intervals to verify that operating conditions have remained within the expected range of the original design. Portions of the cable circuit that pass through areas experiencing more harsh environmental conditions, such as high temperature, high radiation, or high humidity, or that are exposed to any localized adverse environments identified in the baseline environmental walkdown inspection would be subject to more frequent inspection or cable CM testing to monitor and assess the effect on cable condition and performance.

It may be determined during the review of the results of the environmental walkdown that the environmental measurements obtained from existing programs, such as radiation protection or environmental qualification, are not sufficient to properly quantify environmental conditions in an area. The cable engineer may then decide to install supplemental instrumentation and data loggers to obtain more accurate measurements of operating conditions.

Continuously energized power cables located in randomly-filled, heavily loaded cable trays may be subjected to unexpectedly high operating temperatures due to internal ohmic heating. If these actual operating temperatures are significantly higher than the maximum recommended operating temperature for the cable, it can have an adverse effect on the expected operating life of the cable. If the cable is an EQ cable and the actual operating temperature exceeds the assumed maximum operating temperature at which the cable has been qualified, the qualified life may be adversely affected. In cases such as this, periodic measurements of the actual temperature in the heavily-loaded cable tray should be obtained to verify that critical design parameters have not been exceeded. Enhanced visual inspection using infrared imaging condition monitoring equipment may also be used to detect overheating in heavily loaded cable trays containing continuously energized power cables

Many cable circuits, or portions of those circuits, may not be directly accessible for visual inspection during environmental characterization walkdown. Cables may be routed through conduits, bundled together into heavily loaded cable trays, covered cable trenches, direct buried, or routed through underground duct banks making it physically impossible to visually inspect them. The cable engineer must then make a technical judgement on how best to estimate the cable operating conditions or environments through the use of alternate or indirect methods. He may choose to walkdown the ground surface above the route of an underground circuit, for example, to verify that there are no potential sources of oil, greases, hydraulic fluid, or other chemicals that could leach into the soil along the route of a direct buried cable or into underground cable duct banks and cause degradation of cable insulating materials. Conditions in inaccessible sections may be estimated from conditions at adjacent accessible sections of a cable circuit.

Further guidance on plant walkdowns that can be applied to cable systems environments can be found in Section 6 of IEEE Std. 1205-2000, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment in Nuclear Power Plants," [Ref. 34] and EPRI TR-109619, "Guideline for the Management of Adverse Localized Equipment Environments," Appendices A and B [Ref. 35]. Annex D.4 to IEEE Std. 1205-2000 [Ref. 34] presents an extremely useful description and analysis of nuclear power plant environmental conditions and environmental stressors as applied specifically to insulated electric cables. Section 2 of EPRI TR-109619 provides useful discussions on the types and causes of environmental stressors that can also be applied to cable systems [Ref. 35].

The end result of the CM program element 3 characterization of cable operating environment activities will be baseline environmental measurements, data, inspection results, and identification and location of adverse operating environments for cables selected for monitoring in the CM program. The information for each cable circuit is documented in the CM program database and will be available for review by the cable engineer under CM program element 9.

4.3.2 Monitoring Cable Operating Environments

After the initial walkdown and characterization of a cable system's operating environment(s), the cable engineer can use the results to establish a schedule for periodic monitoring and verification of operating environments (see subsection 4.7). The cable engineer can then identify those global and local stressors that could potentially cause a significant increase in the rate of aging degradation or other damage to a cable (see cable CM program element 4, discussed in subsection 4.4). The cable engineer will use the environmental information to determine, and document in the database, the frequency for the performance of periodic cable inspections and condition monitoring testing, the frequency for periodic monitoring and verification of global environmental conditions, and the frequency for monitoring the status of any adverse local environmental "hot spots" (local adverse stressors) that have previously been identified.

For cable circuits, or portions of circuits, that are routed through mild environments with no identified localized adverse environments, the frequency for periodic walkdowns and verification review of the operating environment may be very low. For higher risk cable circuits that have exposure to identified localized adverse environments, the periodic environmental review and walkdown verification will be conducted on a much more frequent basis. The frequency may also be modified, at the discretion of the cable engineer, based on results of periodic condition monitoring inspections and testing (program element 7, discussed in subsection 4.7), industry-wide and in-plant operating experience and failure history (program element 8, discussed in subsection 4.8), or other factors.

Periodic monitoring of cable environments provides assurance that actual conditions in the field are as they had been specified in the original design of the plant, and that the service life of cables operating in these areas will be as specified. This is especially important for EQ-required cable circuits where the qualified life of the cable is based on testing and analysis of cable performance operating in a specified set of operating conditions, such as temperature and radiation exposure. If actual conditions vary from the limits upon which the qualification analysis was based, the qualified life of the cable will be affected. Localized adverse environments can also result in accelerated aging degradation in the locale of the exposure that could have an impact on the overall qualified life of the cable.

For non-EQ cables, design life is based on the manufacturer's maximum recommended cable operating temperature. The cable design life will be shortened by exposure to locally adverse environments such as steam lines, hi-temperature piping and valve bodies, missing or improperly installed thermal insulation, proximity to area space heaters, or proximity to high power lighting fixtures that cause accelerated aging degradation. Newly installed equipment and other modifications to implement plant power upgrades can sometimes add enough heat load to the environment that it could affect local temperature and overall building temperature. Consequently, cable operating environments must be monitored on a periodic basis to determine whether any changes have occurred that could make service conditions more severe, and to identify any new adverse local conditions that may have developed since the previous inspection.

During the review of the results of the periodic environmental walkdown, the cable engineer may determine that some adverse condition has developed that may require more detailed monitoring. The cable engineer may then decide to install supplemental instrumentation and data loggers to obtain more accurate measurements of operating conditions. For example, higher than expected operating temperatures may be occurring in heavily-loaded cable trays or conduits containing continuously-energized power cables as a result of internal ohmic heating. In order to quantify the extent and severity of the problem, the cable engineer may decide to add temperature monitoring instrumentation to track the actual operating temperature to which cables in the tray are exposed, or he may initiate periodic enhanced visual inspection using infrared thermal imaging to monitor the condition.

4.3.3 Monitoring Inaccessible/Underground Cable Circuits

Special consideration should be given by licensees to the problem of monitoring the operating environment for cable circuits routed through inaccessible underground cable ducts and conduits, covered cable distribution trenches, and manhole vaults. As discussed below, underground cable ducts, conduits, and vaults have proven to be a persistent problem throughout the nuclear industry because they can frequently become flooded resulting in power and control cables operating in wetted and completely submerged conditions for extended periods of time. Most electric cables used in nuclear power plants are designed to operate intermittently under high humidity or wetted conditions. However, the majority of these electric cables are not qualified to operate continuously in a fully submerged state unless the manufacturer has explicitly stated in the cable specification that they have been specifically designed, tested, and qualified for continuous submerged operation.

Since most of these underground distribution systems are largely inaccessible, the wetted and flooding conditions remain undetected for extended periods of time. Eventually, power and control cables that are not designed to operate in the submerged state will experience early failures, often resulting in significant safety consequences. Several of these incidents have been brought to the attention of licensees in NRC Information Notice 2002-12, "Submerged Safety-Related Cables" [Ref. 7] and, more recently, in NRC Generic Letter 2007-01, "Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients" [Ref. 1]. Generic Letter 2007-01 made the observation that cable insulation degradation due to continuous wetting or submergence could affect multiple underground power cable circuits at a plant site; should one of these medium-voltage cables fail, the resulting high-level fault currents and transient voltages would propagate onto the immediate power distribution system and potentially fail other systems with degraded power cable insulation.

A similar set of circumstances can arise in above-ground conduits that are susceptible to water intrusion but lack sufficient drainage such that the cables routed within the conduits operate in a submerged condition for extended periods of time. Since the cable circuits within the conduit are inaccessible for visual inspection, the condition can go on unnoticed until early failure of the cable occurs. This variation of the submerged circuits problem was brought to the attention of licensees in NRC Information Notice 89-63, "Possible Submergence of Electrical Circuits Located Above the Flood Level Because of Water Intrusion and Lack of Drainage," [Ref. 36].

If the underground cable circuit includes a cable splice, long-term submergence of the splice can also result in unexpectedly early failure of the cable system if the splice is not specifically qualified for continuous submerged operation. If a splice is not installed correctly, failure could occur even more quickly in the presence of moisture or standing water. NUREG/CR-6788, "Evaluation of Aging and Qualification Practices for Cable Splices Used in Nuclear Power Plants," [Ref. 5] describes numerous incidents of moisture and water intrusion-related splice failures in nuclear power plant applications. The report also provides an informative discussion of the common stressors and failure mechanisms that can lead to splice failures.

The chief failure mechanisms affecting power cables operating in the submerged state over extended periods of time are described in NUREG/CR-6794, "Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants," [Ref. 3] as follows:

> "Exposure to moisture can also degrade power cables. This can occur for cables installed below grade in ducts or conduits that are susceptible to water intrusion, or for cables buried directly in the ground. Cables exposed to water while energized are susceptible to a phenomenon called 'water treeing' in which tree-like micro-cracks are formed in the insulation due to electrochemical reactions. The reactions are caused by the presence of water and the relatively high electrical stress on the insulation at local imperfections within the insulating material, such as voids and contaminant sites, that effectively increase the voltage stress at that point in the insulation." Figure 4.2 shows an illustration of a water tree formation in the insulation of a cable.
>
> "The occurrence of water treeing is well known in XLPE, however, it also is known to occur in other insulating materials, such as EPR, polypropylene, and PVC [Ref. 37]. Water trees increase in length with time and voltage level, and can eventually result in complete electrical breakdown of the cable insulation. Discharges leading to micro-cracks can also occur at voids and contaminants in the insulation without the presence of water. This is known as "electrical treeing" in which discharges occur due to ionization of the air or gas in voids, and the energy of the discharge causes breakdown of the insulation and the formation of micro-cracks also resembling trees."
>
> "Moisture can also cause corrosion of the various metallic components in the cable, such as metallic shields or the conductor. In some applications where moisture intrusion is to be mitigated, cables with a lead sheath will be used. The lead sheath makes the cable impervious to moisture, provided it is properly sealed at splices and terminations. If such cable is installed in concrete ducts, free lime from the concrete can be a concern since it will form an alkaline environment which can corrode the lead sheath [Ref. 38]."

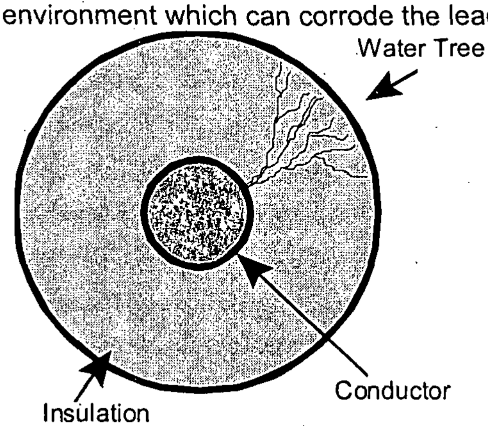


Figure 4.2 Cablecross-section illustrating water tree formation [Ref. 3]

EPRI TR-103834, "Effects of Moisture on the Life of Power Plant Cables" [Ref. 39], provides additional operating experience (pre-1994) and discussion on the effects of moisture, wetting, and submergence on the service life of medium-voltage and low-voltage cables. Several condition monitoring techniques for the detection of moisture are also presented and their advantages and disadvantages are discussed.

In GL 2007-01, licensees were requested to provide failure history information for power cables within the scope of 10 CFR 50.65 (the Maintenance Rule) and a description of inspection, testing, and monitoring programs to detect degradation of inaccessible or underground cables supporting systems within the scope of 10 CFR 50.65. The licensee responses to the requested information were analyzed and described by the NRC in a summary report [Ref. 8]. The summary report indicated that 93% of the cable failures analyzed occurred on normally energized power cables. More than 46% of the failures were reported to have occurred while the cable was in service and more than 42% were identified as "testing failures" in which cables failed to meet testing or inspection acceptance criteria. The failure data showed a trend toward early failure, the majority occurring in the range of 11-20 years of service and 21-30 years of service; this is shorter than the plants' original 40-year licensing period. The NRC staff noted in its conclusions that "...the predominant factor contributing to cable failures at nuclear power plants appears to be the presence of water/moisture or exposure to submerged conditions."

The data in Reference 8 also showed that more than 36% of the reported failures occurred on power cables of 2000Vac or less. These data indicate that long-term submergence in water and moisture intrusion can drive insulation degradation mechanisms that can affect the dielectric strength of insulation materials in both low- and medium-voltage cables, even when they are normally deenergized.

In the summary report of licensee responses to GL 2007-01 [Ref. 8], the NRC further concluded and recommended that:

> "Licensees have identified failed cables and declining insulation resistance properties through current testing practices; however, licensees have also reported that some failures may have occurred before the failed condition was discovered. Although the majority of in-service and testing failures have occurred on cables that are normally energized, the staff is concerned that additional cable failures have not been identified for cables that are not normally energized or tested. The NRC staff recommends that the licensees should also include normally deenergized cables in a cable testing program. It appears that no manufacturer or insulation type is immune from failure. In addition, licensees have identified failures and/or declining performance capabiolity of both shielded and unshielded cables."

Clearly, underground cable environments needed to be monitored for the presence of moisture or standing water. However, due to the inaccessibility of these cable circuits, indirect methods for inspection and measurement must be considered. Visual inspection for moisture or standing water, or the signs of flooding, such as accumulations of sand, mud, and silt or flooding high water marks, could be performed at accessible manhole vaults or cable pull boxes along the length of an underground duct bank. Site survey data on the elevations of the manhole vaults along the underground cable duct bank can then be used to determine whether manhole flooding has affected connected cable ducts. If available, site hydrological data on water table depth and how the water table is affected by site precipitation or the water surface level in nearby bodies of water can also be used to determine where underground cable flooding may be occurring. Illuminated borescopes, such as those used for internal inspection of pipelines, can be routed down into underground duct banks or conduits to visually inspect for standing water or the signs of flooding, such as accumulations of sand, mud, and silt. Cable conduits that are above flood level elevation, but are susceptible to moisture intrusion, such as described in Information Notice 89-63 [Ref. 36], can be checked for water accumulation using ultrasonic inspection at low points.

Some of the condition monitoring tests for cables performed for implementation of element 7 of the cable CM program, described in subsection 4.7, can be used to detect and locate the presence of water along the length of an electric cable. Time domain reflectometry (TDR), the ECAD inspection system, and the newer line resonance analysis (LIRA) technique, which are described in Section 3 of this report, may be able to accomplish this.

The results of electrical property measurement CM tests from program element 7 that can detect water treeing or the degradation of insulation dielectric strength resulting from water treeing could be reviewed as another indirect method for determining whether it is or has been operating in a submerged condition. CM measurement techniques such as insulation resistance/polarization index testing, dc high potential testing, and VLF withstand testing, can be used to check the condition of cables that may be exposed to water. Test results indicating weakened dielectric strength, or trends of unusually rapid deterioration of dielectric strength between successive testing periods, could be an indication of power cables operating in a submerged condition over extended periods of time.

The output results of the CM program element 3 monitoring of cable operating environment activities will be periodic environmental measurements, data, and inspection results for global and local cable operating environments for those cables selected for monitoring in the CM program. The periodic environmental monitoring information for each cable circuit is documented in the CM program database. These data, together with the baseline environmental characterization information, and will be available for review by the cable engineer under CM program element 9, in order to make decisions on managing cable operating environments.

4.3.4 Managing Cable Operating Environments

The next step for the cable engineer, performed under CM program element 9 (see subsection 4.9), will be to review the results of the periodic cable systems environmental monitoring activities on a regular basis. The periodic environmental inspection and monitoring data can be compared to the baseline environmental data to identify any significant changes in the operating conditions to which cables systems are exposed, or to note the emergence of new locally adverse environments, not previously identified. The cable engineer will use this environmental information, together with CM inspection and test results (from CM program element 7), operating experience information (from CM program element 8), and other information in the database, to decide how to best manage the evolving changes in operating conditions or locally adverse cable environments in order to mitigate or minimize the effects that the severe stressors can potentially have on cable degradation, performance, and service life.

If unanticipated or locally adverse cable system operational environments are detected through periodic monitoring of cable environments or other reported observations, the cable engineer can implement one or more of the following responses for the affected cable(s), consistent with its safety significance:

- perform more frequent CM testing and environmental inspections to more closely monitor the cable condition

- add more CM tests that will more closely monitor the status of the specific aging mechanisms associated with the environmental stressors and the cable condition

- perform more frequent periodic review and condition assessment of the affected cable's condition (program element 9) and initiate corrective actions as required

- protect the cable from the adverse environment to reduce or eliminate the effects of the associated stressors

- identify the root cause of the adverse environmental condition and implement modifications, maintenance, or other corrective actions to address and correct the root cause of the adverse condition

It should be emphasized that the occurrence of cable system operating environments or locally adverse conditions that are unanticipated or more severe than the original plant design may constitute a design deficiency of the cable system, specifically, a potential violation of GDC 1, 4, 17, and 18. NRC regulations, such as 10 CFR 50, Appendix B, (quality assurance), the maintenance rule (10 CFR 50.65), and environmental qualification regulations (10 CFR 50.49), require that programs and administrative controls be established to monitor and detect degraded conditions on a regular basis and to promptly implement effective corrective actions and design modifications, consistent with its safety significance, so that any further cable degradation is minimized. A cable system must be designed to meet all applicable regulations and to perform its intended function in the plant environment under all anticipated operational occurrences and design basis events.

Further guidance and a suggested methodology for management of adverse localized equipment environments that can be applied to cable systems environments can be found in Section 3 of EPRI TR-109619, "Guideline for the Management of Adverse Localized Equipment Environments" [Ref. 35].

4.4 Identification of Cable Stressors and Aging Mechanisms

The fourth element of the cable CM program is the identification of stressors affecting cable systems and their associated aging/failure mechanisms. By identifying these stressors, and quantifying their severity, the cable engineer can determine the primary aging and failure mechanisms that will affect each cable circuit. These are the processes that the cable CM program inspection and testing activities must be able to detect and monitor, since they can cause degradation or other damage that may, over time, lead to the ultimate failure of a cable system. This information may then be used by the cable engineer, in cable CM program element 5, to select the most effective CM inspection and testing techniques for detecting and monitoring the anticipated aging/failure mechanisms.

Subsection 2.2.2 of this report describes the FMEA analytical approach applied to identify the piece-parts of an electric cable (e.g., insulation, jacket, conductor) and to analyze the stressors that can affect the material(s) in each piece-part of a particular type of cable in a specific application and operating environment. The aging and degradation mechanisms caused by exposure of cable materials to various stressors can cause a steady, and sometimes rapid, degradation of the cable insulation integrity, performance, and dielectric strength. Since the degradation process can eventually result in one of the cable failure modes, it is essential that the stressors, and the aging and degradation mechanisms that they can cause, be identified early and periodically monitored by the cable CM program activities. Corrective actions can then be implemented to prevent early in-service cable failures.

The FMEA process was applied to the common materials that make up the piece-parts of typical electric power cables and I&C cables used in nuclear power plants. Anticipated in-service environmental stressors, such as those listed in subsection 4.3.1, are analyzed to identify the potential aging and degradation mechanisms that can affect the common cable materials used to construct the piece-parts of the cable. Anticipated in-service operational stressors are similarly analyzed. Table 2.1 presents a general summary of the stressors and associated potential aging and degradation mechanisms identified in the FMEA for typical medium-voltage power, low-voltage power, and I&C cables used in nuclear power plants. The table should apply to the majority of cables in a plant, and with a minor reanalysis, can be adapted to accommodate most of the variations in materials, construction, and configurations that will be encountered in nuclear power plant cables.

Guidance on the identification of environmental and operation stressors acting on medium- and low-voltage cables and I&C cables is presented in subsection 2.2.2. Discussion and guidance regarding the aging and degradation mechanisms affecting these cables is given in subsection 2.2.3.

Similarly the FMEA process was used to analyze electric cable splices and cable termination connections. Table 2.2 presents a general summary of the stressors and associated potential aging and degradation mechanisms identified in the FMEA for typical medium-voltage power, low-voltage power and I&C cable splices and termination connections used in nuclear power plants. Since there are numerous variations in types of splices, configurations, and applications, each group should be analyzed to identify unique failure modes, stressors, and degradation mechanisms. Likewise, there are so many variations in cable terminations that may be encountered, each group and application should be considered.

Guidance on the identification of environmental and operation stressors affecting cable splices and cable termination connections for medium- and low-voltage cables and I&C cables is presented in subsection 2.2.2. Discussion and guidance regarding the aging and degradation mechanisms affecting splices and termination connections for these cables is given in subsection 2.2.3.

The environmental characterization and monitoring walkdown inspections described previously in subsections 4.3.1 and 4.3.2 (program element 3), the cable baseline visual CM inspection described in subsection 4.6.1 (program element 6), and the periodic CM visual inspections described in subsection 4.7 (program element 7) will provide the primary means for identifying the environmental and operational stressors to which a cable will be exposed during its normal anticipated service. Tables 2.1 and 2.2 can be used to identify applicable aging and degradation mechanisms that are likely to affect the individual cables, splices, and termination connections.

The end result of the process for identification of stressors and aging mechanisms for cable systems in CM program element 4 is a listing of the likely anticipated stressors and associated aging mechanisms that will affect each cable system that is to be monitored in the cable CM program. These stressors and aging mechanisms are documented in the cable CM program database for each cable. The information will next be used by the cable engineer to select a group of condition monitoring inspection and testing techniques in CM program element 5 that can best be used to detect and monitor anticipated stressors and associated aging mechanisms. These inspection and testing techniques will be used to establish the baseline condition of a monitored cable (program element 6) and then to periodically assess and monitor the status of cable condition (program element 7).

4.5 Selection of CM Techniques

The fifth element of the cable CM program is the selection of condition monitoring inspection and testing techniques that can be used to detect, quantify, and monitor the status of the aging mechanisms that are causing the degradation of cable systems. By selecting CM techniques that are best suited to the detection and monitoring of the anticipated stressors and associated aging and degradation mechanisms identified, the cable engineer can more accurately monitor the condition of critical plant cables, assess their operating condition, and implement corrective actions to manage aging and degradation in those cables that are found to be experiencing stressors and aging/degradation rates beyond specified design conditions. Realistic and timely assessment of cable condition is the best means for managing cable degradation and avoiding unexpected early cable failures.

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.

As described in subsection 3.1, 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 judgement 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].

Section 3 of this report describes several of the most commonly used cable condition monitoring inspection and testing techniques available to plants for managing cable aging and degradation. These are summarized in Table 3.1, grouped by whether the inspection or test is performed in situ on electric cables in the plant or are laboratory-type tests performed on representative material specimens in a controlled laboratory setting. The advantages and limitations of the various techniques are indicated in Table. 3.1. The table also indicates the types of aging and degradation mechanisms that each CM technique is best suited to detect and monitor.

These CM test techniques may be performed to measure and assess:

- *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)

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 described previously in subsection 4.4 for CM program element 4. The cable engineer can then use his engineering judgement to establish a suite of condition monitoring inspection and testing techniques that can detect, quantify, and monitor the anticipated degradation effects for the selected cables. These inspections and tests would be repeated periodically, and at designated monitoring locations along the length of the selected cable circuit (at the point of locally adverse environments(s), for example), at a frequency determined by the cable engineer. The periodic inspection and test results, may then be compared to the baseline measurements, established for the cable circuit in CM program element 6 (described in subsection 4.6), to periodically review and assess the up-to-date condition and status of the cable circuit as described in subsection 4.9.

Consider as an example, a safety-related, low-voltage instrumentation circuit consisting of a 2/C #12 AWG EPR-insulated cable with overall CSPE jacket originating at a pressure transmitter in the turbine-driven RCIC pump area of a BWR secondary containment and terminating at an analog trip system cabinet in the electrical equipment room of the control building. Baseline environmental survey of the cable route (CM program element 3) showed that the cable passed through mild, dry environments, in ladder-type cable tray or metal conduit, throughout most of its length with no splices, no adverse local environments, and no extreme installation stressors, such as long vertical runs or sharp bends, were noted. However, at the pressure transmitter in the RCIC pump area, elevated temperature and radiation levels were observed during normal operation. Vibration at the transmitter was also a possible stressor for the cable and the cable termination, but this occurred very infrequently during pump operation for testing or emergency operation of the system. Following the initial baseline cable condition visual inspection and environmental walkdown (cable CM elements 6 and 3), a reasonable frequency for subsequent visual CM inspection for the instrumentation cable circuit in this example might be once every 5 to 10 years because of the mild environment over most of the cable's route. However, because of the elevated temperature and radiation stressors at the transmitter end of the cable, the polymer insulation and jacket material in this section of the cable should be visually inspected as part of the quarterly or 18-month technical specification calibration and functional surveillance test procedure for the pressure transmitter. The results of the calibration and functional surveillance tests would also provide one indication of cable condition. In addition, the cable engineer may elect to routinely perform polymer indenter tests of the cable insulation and jacket at the accessible portions of the cable at the transmitter or perhaps a junction box in the RCIC pump area. If visual inspection, surveillance tests, or indenter/hardness tests indicate an unusual rate of degradation, the cable engineer could add a periodic material density test, OIT, or EAB to more closely monitor thermal and radiation effects on insulation condition. Note that these last CM techniques are destructive tests that would require removing a small piece of insulation from the end of the cable insulation at the transmitter terminations, or from sacrificial materials test specimens that had been previously placed in the RCIC pump area specifically to monitor polymer condition.

The guidance provided in Table 3.1 enables the cable engineer to select those CM inspection and testing techniques that are best suited to the detection, assessment, and monitoring of the types of cable aging and degradation mechanisms that are anticipated or are occurring in the various types of cables and cable applications in nuclear power plants. Table 3.2 presents a cable CM technique selection matrix summarizing the most common cable aging stressors and aging mechanisms linked to the various potential CM techniques that can be used to detect them. Further information describing the selection and performance of many different types of cable CM techniques, including in situ methods as well as laboratory tests, can be found in: Section 3 of NUREG/CR-6704 [Ref. 9], Volume 2; Section 5 of SAND96-0344 [Ref. 2]; IEEE Std. 400-2001, "IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems" [Ref. 13]; IEEE Std. 400.1-2007, "IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage" [Ref. 17]; IEEE Std. 400.2-2004, "IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)" [Ref. 14]; IEEE Std. 400.3-2006, "IEEE Guide for Partial Discharge Testing" [Ref. 18]; and Section 6 and Annexes A, C, and D.4 of IEEE Std 1205-2000, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations" [Ref. 34].

Once the most suitable CM inspection and testing techniques have been selected for a particular cable system, the cable engineer will perform a baseline visual CM inspection of the cable to establish the initial installed condition of the cable along the length of its routing through the plant. The initial set of CM tests selected will be performed on the installed cable system and cable materials specimens (if available) to establish the baseline condition of the cable circuits selected for monitoring in the cable CM program. Baseline CM inspection and testing are described in subsection 4.6.

4.6 Establish Baseline Cable Condition

The performance of baseline cable CM inspection and testing is the sixth element of the cable CM program. This activity establishes benchmark values for measured cable parameters, physical condition, and appearance at the time of installation (or the beginning of a cable monitoring program). The cable CM inspection and testing techniques that are used to establish baseline cable condition were selected in cable CM program element 5 where it was determined that they were the methods best suited to identify, quantify, and monitor the status of the aging mechanisms that are causing the degradation of a particular cable system. The results of subsequent periodic performances of these cable CM inspections and tests (cable CM program element 7, described in subsection 4.7) may then be compared to the baseline values to assess cable condition (cable CM program element 9, described in subsection 4.9).

4.6.1 Baseline Visual CM Inspection

The baseline visual inspection of a cable system consists of a walkdown of the entire length of a selected cable circuit to assess the installed physical condition of the accessible portions of a cable, cable splices, and cable accessories. Similar to the discussion of the cable environmental walkdown inspection described in subsection 4.3.1, the baseline cable CM inspection is accomplished by:

- review of the design, specification, and installation documentation for the cable circuit, in order to locate the routing of the cable circuit throughout the plant;

- review of existing environmental survey information from programs such as radiation protection and environmental qualification in order to quantify the environmental conditions to which a cable circuit is exposed;

- in situ measurements of environmental conditions; and

- initial walkdown visual inspection of the accessible portions of the cable circuit to document the physical installation and condition of the cable, and to identify any installation and construction activities damage, operating and maintenance activities damage, and any adverse localized installation conditions, such as sharp bends, long vertical rises, physical contact with SSCs, or other conditions that could potentially affect the performance of the cable, splices, terminations, or other cable accessories.

Since the baseline cable CM visual inspection is so similar in purpose to the baseline cable environmental walkdown inspection described in subsection 4.3.1, it is recommended that these activities be performed at the same time and incorporated into the same procedure. Both activities will make use of cable design, specification and installation documentation, require the review of cable circuit routing information, and require a physical walkdown of the same accessible sections of each cable circuit.

A procedure for baseline and periodic cable CM visual inspection should be developed so that the inspections are conducted in a standardized, detailed manner. Cable attributes that are to be documented include: 1) color, including changes from the original color and variations along the length of the cable route, and sheen; 2) surface damage, including cracks (location, length, and depth, scrapes, gouges, deformations, and indentations, 3) visible surface contamination, including dirt, chemical deposits, surface tracking, 4) rigidity, 5) adverse localized installation conditions such as sharp bends, long vertical rises, physical contact with SSCs, and 6) proximity to adverse localized environments and stressors. Procedural standardization of the qualitative observations made during a baseline CM inspection of a cable system will make them more useful for comparison to qualitative observations obtained during subsequent periodic cable CM visual inspections.

The observations and results from the environmental walkdown described in subsection 4.3.1 are an important part of the assessment of the cable condition. Information on the general environmental conditions to which a cable is exposed can be used by the cable engineer to establish the frequency for subsequent periodic visual inspections. In addition, the identification of localized adverse environmental conditions, the proximity to sources of heat, radiation, and vibration, and other factors related to the installation of a cable circuit can highlight the locations of vulnerable sections of an otherwise mild-environment cable circuit that should be monitored on a more frequent basis. Items to be noted include the proximity to heat sources such as high temperature steam lines, large uninsulated valve bodies, unit area heaters, and high powered lighting fixtures. Storage tanks and piping carrying steam, borated water, hydraulic fluid, or other chemicals above, or in proximity to, cable circuits are potential sources of high temperature/pressure steam leakage, high temperature exposure, wetting or flooding, and exposure to reactive chemicals. Physical contact between polymer-insulated cables and structures, plant equipment, piping, thermal insulation, worker stepping points, and other objects can deform, abrade, or degrade the performance of the cable insulating materials. Vibration of electrical cables can occur at the cable terminations to electric drive motors or at the terminations to instruments mounted on or near operating machinery or large pipelines.

As noted in subsection 4.3.1 for the environmental walkdown inspection of a cable circuit, accessibility issues should be noted in the baseline visual CM inspection. Many cable circuits, or portions of those circuits, may not be directly accessible for visual inspection during the environmental characterization walkdown. Cables may be routed through conduits, bundled together into heavily loaded cable trays, covered cable trenches, direct buried, or routed through underground duct banks making it physically impossible to visually inspect them. The cable engineer must then make a technical judgment on how best to estimate the cable operating conditions or environments through the use of alternate or indirect methods. He may choose to walkdown the ground surface above the route of an underground circuit, for example, to verify that there are no potential sources of oil, greases, hydraulic fluid, or other chemicals that could leach into the soil along the route of a direct buried cable or into underground cable duct banks and cause degradation of cable insulating materials. Conditions in inaccessible sections may be estimated from conditions at adjacent accessible sections of a cable circuit. Accessibility at manholes, cable pull boxes, junction boxes, or conduit elbows and fittings may provide a means to physically inspect portions of an otherwise inaccessible cable run.

As discussed in the special section on inaccessible underground medium-voltage cable runs that could potentially be exposed to moisture or complete submergence (see subsection 4.3.2), the cable engineer must positively identify, either by direct visual inspection or by one or more of the alternative inspection methods suggested previously, those sections of an underground cable run that are susceptible to water intrusion or submergence. These sections of the cable circuit must then be monitored on a more frequent basis to detect unusual rates of cable degradation that could result in early failure.

Further guidance on plant walkdowns and visual inspection that can be applied to cable systems and their operating environments can be found in Section 6 of IEEE Std. 1205-2000, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment in Nuclear Power Plants" [Ref. 34], and EPRI TR-109619, "Guideline for the Management of Adverse Localized Equipment Environments," Appendices A and B [Ref. 35]. Annex D.4 to IEEE Std. 1205-2000 [Ref. 34] presents an extremely useful description and analysis of nuclear power plant environmental conditions and environmental stressors as applied specifically to insulated electric cables that can serve as useful guidance for cable CM visual inspection walkdowns of cable systems.

4.6.2 Baseline CM Tests

Subsection 4.5 described the process for selection of CM tests that were best suited to detect, quantify, and monitor the status of aging mechanisms that may lead to the degradation of cable systems in the program. It also described the desirable attributes to be found in the ideal CM technique (listed in subsection 3.1), one of these being the capability to "...measure property changes or indicators that are trendable and can be consistently correlated to functional performance during normal service," and another being the reproducibility of test results "...that are not affected by, or can be corrected for the test environment..."

In order to fully realize the goals of trendability and reproducibility, the quantitative test results from the cable CM test methods that are being used to monitor the cable in the program must be referenced back to a reliable set of initial values representing the condition and properties of the cable, as installed in the plant, at the start of its normal service life or when the CM program was initiated. This initial set of test data is the baseline CM test data.

For non-destructive tests and measurements, the first performance of a particular CM test serves as the baseline value or data set for that CM test. Preferably, these measurements are performed at the time that the cable system is installed or first put into service. However, if a cable that has already been in service is added to the cable CM program or if a new CM test has been added to an existing cable, the first performance of that CM test can be considered a baseline, and then subsequent measurements performed using that CM test technique are referenced against that first performance set of baseline measurements. All subsequent performances of that CM test may then be compared to the baseline measurement to provide a plot of the changes of the measured parameters or properties over time. Over time the data may show changes that correspond to aging or degradation of the cable materials in response to environmental or operational stressors. If a clear time-related trend is manifested for the measured cable parameter or property, these data may help the cable engineer to project future values of the cable parameter or property, and estimate remaining useful life for the cable system.

If the CM tests selected to monitor a cable are destructive-type tests, requiring sacrificial materials specimens to measure the property or parameters of the cable material (e.g., the elongation-at-break (EAB) which requires standard "dogbone" insulation or jacket material specimens), the sacrificial materials testing specimens must be prepared from samples of the cable from the same reel, or the same purchase lot, if possible. This will ensure that the age of the test specimen materials since the time they were manufactured is the same as the age of the materials on the installed cable that is being monitored. The formulation of the materials in the test specimens will then be more likely to match the formulation of the materials in the installed specimen. The exact formulation for a polymer material is proprietary information and manufacturers may often change content, quantities, and additives without notice and change the overall trade-name for the polymer material. The best way to account for this in a CM testing program is to prepare sacrificial test specimens from the same reel that the installed cable was taken from, or if that is not possible, then at least from cable manufactured at the same time.

Ideally, destructive testing would require that a sufficient quantity of sacrificial test specimens be prepared to allow baseline CM testing and periodic CM testing for that method throughout the installed life of the cable. The specimens prepared for future periodic CM testing would have to be placed in the plant at the most severe locally adverse environment for the selected cable or groups of cables using the same types of materials. By testing materials specimens that have been exposed to the most severe plant environments in which cables of that type are located, the cable engineer can estimate the "extreme limit" of aging-related degradation for cables using that particular material. The level of degradation of the materials in other cables of that type, operating in less severe environments for the same amount of time, should then be less than for the "extreme limit" specimens. It may be possible to extrapolate the remaining life of cables in less severe environments using CM data from cables in the most severe environment.

Other alternatives for obtaining baseline sacrificial materials test specimens would be: unused cables of the same type, purchased at the same time, from warehoused supplies of cable; spare cables of the same type that are located along a similar route as the cable(s) to be monitored; disconnected cable circuits, of the same type, that are "abandoned in place" and that are located along a similar route as the cable(s) to be monitored.

The end results of the CM program element 6 baseline visual cable inspections and CM tests will include cable physical condition information, the locations of adverse localized environments, the locations of actual and/or potential physical damage to the cable, and quantitative baseline CM test data covering cable properties and condition measurements. The baseline information for each cable circuit is documented in the CM program database and will be available for review by the cable engineer under CM program element 9.

4.7 Perform Cable CM Inspection and Testing

The performance of periodic cable CM inspection and testing is the seventh element of the cable CM program. The implementation of this program element involves the routine performance of inspection and testing procedures to provide a periodic assessment of the physical condition and appearance of a cable system, the status of the cable circuit's operating environments (including locally adverse environments), and the quantitative measurement of the properties, operating parameters, and performance parameters that indicate the condition of the cable systems included in the plant's cable CM program. The data and results obtained from the periodic testing and inspections are documented in the cable CM program database.

The CM program elements described in the preceding subsections provide the background and foundation for the cable CM program. The cable CM inspection and testing techniques that are used to establish baseline cable condition were selected in cable CM program element 5 where it was determined that they were the methods best suited to identify, quantify, and monitor the status of the aging mechanisms that are causing the degradation of a particular cable system. Once the types of cable CM inspections and test procedures have been selected, the controlling procedures have been developed and put into place, and the initial baseline cable CM inspections and tests have been completed, what remains is the routine implementation of the periodic cable CM inspection and testing program.

This activity is very similar to existing nuclear power plant programs for the performance of plant technical specifications surveillance testing and plant preventive maintenance (PM) activities. It is anticipated and recommended that the periodic performance of cable CM inspection and testing activities for CM program element 7 be incorporated into the existing plant preventive maintenance program either as new PM activities or as an expanded part of existing PM activities. The timely performance of the cable CM inspections and tests are ensured by incorporating these activities into the format of the existing plant PM program. The plant PM program structure thus provides for the scheduling and administrative controls to implement the activities for CM program element 7.

The performance frequency for the CM inspection and testing of each cable that is to be monitored under the cable CM program is initially determined by the cable engineer based upon experience and the results of the environmental baseline inspection and the baseline CM inspection and tests. Certain sections of a cable circuit may require CM inspection and testing at even shorter intervals than the performance frequency for the overall remainder of the cable if they have been identified in walkdown inspections as being exposed to locally adverse environmental conditions (more severe aging and degradation stressors). The normal CM frequency and the augmented frequency for more severely stressed cable locations should all be identified and documented on the cable CM program database.

Periodically, the cable engineer will review the results of periodic CM inspections and tests for each cable and compare them to the baseline observations and test data as part of CM program element 9 (see subsection 4.9). Based on this review of test results and observations, and the observation of any trends in the plot of quantitative testing results data versus time, the cable engineer may choose to modify the performance frequency for the periodic CM tests and inspections for entire cables or sections of the cables exposed to more severe environmental stressors. The cable engineer may also elect to add (or delete, as warranted) additional CM tests to provide more detailed monitoring of a particular aging mechanism or cable condition parameter. These changes should be controlled and documented in the cable CM program database.

The results of the periodic CM inspection observations and CM test data obtained under cable CM program element 7 are all consolidated and documented in the program database (CM program element). These data and information are available to the cable engineer to support the formalized periodic review and assessment of the condition of each cable system monitored under the cable CM program. The periodic review and assessment activity constitutes CM program element 9 and it is discussed in subsection 4.9.

4.8 Operating Experience

The eighth element of the cable CM program is the review of cable-related operating experience and incorporation of applicable information into the program. By actively reviewing industry-wide operating experience regarding cables, a plant can be alerted to deficiencies or defects in specific cable types or configurations, inadequate or damaging installation practices, testing techniques that can potentially damage cables, useful new testing techniques, manufacturing defects, or misapplications of cable types. Regular review and analysis of cable failures or cable-related problems in one's own plant can sometimes reveal adverse performance trends or otherwise point to emerging problem areas that can be monitored more closely and/or corrected in a timely fashion before the occurrence of an early cable failure.

All nuclear plants are required to have a program or other measures in place to address corrective actions, in accordance with 10 CFR 50, Appendix B, Criterion XVI. An effective corrective action program promptly identifies, corrects, and documents failures, malfunctions, deficiencies, deviations, defective material and equipment, nonconformances, or other conditions adverse to quality that occur in a nuclear power plant. The corrective actions program can provide the means for analyzing problems, finding root causes, developing corrective actions, and implementing solutions.

The corrective action program and process can be used to provide an effective means for identifying and correcting cable-related problems that occur in the plant. The cable engineer should periodically review and analyze these cable-related failures, problems, and other deficiencies to try to identify adverse performance trends or otherwise point to emerging problem areas. Corrective actions can then be developed and implemented to address cable-related problem areas. Corrective actions in response to industry and in-plant operating experience may then be incorporated as modifications or additions to the cable CM program. These could include: more frequent monitoring of certain cable types or materials; root cause analysis of cable failures; augmented monitoring for unusual rates of cable system degradation or adverse local environments; added CM tests for certain cables and configurations that have experienced higher failure rates; or special tests or inspections to address specific cable-related problems.

Nuclear power plants typically have industry operating experience programs in place to regularly review and analyze industry-wide failures, incidents, operating experience, or other events to determine applicability to their plant. Information regarding applicable operating experience is added to the corrective action program and/or directed to the responsible plant organization for follow-up analysis.

Sources for current nuclear industry operating experience regarding cables would include: NRC information notices, generic letters, circulars, and bulletins; Licensee Event Reports (LERs); 10 CFR Part 21 reports; the NRC website (www.nrc.gov); cable and cable splice manufacturers' technical bulletins and instruction manuals; cable test equipment manufacturers' technical bulletins; international cable testing standards; and technical research literature on cable systems.

Historical cable-related operating experience can be obtained from the Nuclear Plant Reliability Data System (NPRDS) for events up through 1996, the Equipment Performance Information Exchange (EPIX) database for events occurring since 1997, and the LER database. Several NRC-sponsored research programs included sections dedicated to the assessment and analysis of operating experience related to cables, cable splices, and terminations. Some of these, which are listed in the references section of this report, include:

NUREG-1760	fuse holders and connections
NUREG/CR-6384	electric cables research, operating, and qualification experience
NUREG/CR-6704	electric cables research and qualification testing experience
NUREG/CR-6788	cable splices
NUREG/CR-6794	power cables
NUREG/CR-6950	medium-voltage power cables, switchgear electrical bus connections, circuit breaker connections, power transformer terminations, instrument transformer terminations
SAND96-0344	electrical cables, splices, and terminations

In addition, utility organizations such as the Electric Power Research Institute (EPRI) have sponsored research programs on electric cables, splices, and terminations that included sections dedicated to the assessment and analysis of cable-related operating experience. Some of these reports, which are available to member utilities, are listed in the references section of this report.

The end result of the review and incorporation of industry-wide and in-plant electric cable operating experience would be to enhance, augment, or modify the cable CM program in order to address cable issues that are applicable to the plant and to identify, analyze, and implement corrective actions for adverse performance trends or emerging problem areas in the plant before the occurrence of an early cable failure.

4.9 Periodic Review and Assessment of Cable Condition

The periodic review and assessment of the condition of cables that are being monitored under the cable CM program is the ninth element. The purpose of this element is to perform a formal periodic review that brings under consideration all of the inspection and CM testing results, inspection and testing data trends, surveillance and PM test results, applicable operating experience, and operating environment conditions and trends in order to establish an assessment of the present condition for each cable in the program.

4.9.1 Periodic Review and Assessment

The formal periodic review and assessment element of the cable CM program is the activity where the results and inputs from all the other elements of the program that are being gathered together and documented in the cable program database are evaluated and analyzed in order to make an experienced, informed, assessment of cable condition. No single CM inspection or test alone can provide a complete picture of cable condition, nor can successful functional testing, under the limited and controlled loadings and conditions of such testing, fully predict cable function under the more severe, demanding, extended conditions of full power or emergency operation. The periodic cable condition review and assessment allows the cable engineer to use his engineering judgment to weigh all the contributing factors (CM inspection and testing, functional testing, environmental factors, data trends, in-plant and industry-wide operating experience) to determine the condition of a cable at the time of the analysis in terms of material degradation, performance, and remaining service life.

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. Each plant cable circuit may traverse a number of different environments and localized conditions along its length. Many condition monitoring techniques (e.g., EAB, compressive modulus, density) are localized indicators of condition at the specific place (and even a specific point on the cable jacket's surface) along a cable circuit where the measurement is made; cable properties measured at multiple points may show the cable to be in sound condition, but a measurement made only inches away at a more severely stressed section could show otherwise. Furthermore, the criteria used to define cable functional condition or accident survivability for a particular circuit are application-specific. Consequently, engineering judgements 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]. Results and data from the periodic CM inspection and testing activities described in subsections 4.6 and 4.7 (CM program elements 6 and 7) provide input to the cable engineer regarding bulk cable properties, insulating material condition and properties, and rates of degradation.

It has also been shown that the operating environment in which a cable operates can have a significant effect on the performance and operating lifetime of a cable. Since a cable can traverse several different operating environments throughout the length of its route through the plant, the effect of the various environmental conditions must be considered. Of even more significance may be the identification and monitoring of locally adverse operating environments that can drive cable aging and degradation mechanisms that could end in unexpectedly early cable failures. Periodic monitoring inspections and measurements of cable system operating environments, described in subsections 4.3.1 and 4.3.2, provide valuable information to the cable engineer in his evaluation of the state of the cable operating environment, exposure to locally severe conditions, and the types and severity of cable stressors.

The functional performance of a cable, as revealed by instrument and control system calibration and functional surveillance test, system and equipment performance tests, or other related technical specification surveillance testing and preventive maintenance program testing, can provide useful information and trends to the cable engineer as part of his overall assessment of a cable's condition. Such testing alone can only tell part of the total story, since the cable circuit may appear to be operating normally during periodic functional testing right up until the time it fails, even though cable CM visual inspection and/or tests performed at the same time would indicate significant overall and/or localized degradation. When called upon to operate under the stresses encountered during an emergency, (i.e., fully loaded equipment, more extreme environmental conditions, extended operation in a heavily loaded state), however, such a cable could fail unexpectedly.

Finally, operating experience (CM program element 8 described in subsection 4.8) can provide very important input to the cable engineer as part of his periodic assessment of cable condition. Industry-wide occurrences, application-related cable problems, commonly-encountered manufacturing defects, or common performance shortcomings of cables used at other plants must be evaluated and in-plant applicability determined so that these common problems are addressed in a timely manner. In-plant cable failures and other cable-related operating experience should be reviewed and evaluated for applicability to in-plant cable systems. From the experienced cable engineer's viewpoint of the impact that various operating experience incidents can have on plant cable systems, his review and analysis of these cable-related failures, problems, and other deficiencies may reveal adverse performance trends or otherwise point to emerging problem areas. During the periodic cable condition assessment the cable engineer can fully determine the applicability and impact of operating experience on each cable system or groups of cables operating under similar circumstances.

4.9.2 Managing Cable Operating Environments and Degradation Effects

An important part of the periodic review and assessment of cable condition under CM program element 9 is the development of recommendations for the management of cable operating environments and the associated aging and degradation mechanisms that are affecting each cable in the program. Based upon the periodic review and assessment of present cable condition, the cable engineer can make an estimate of the remaining service life of a cable given the present condition of the cable, existing cable operating environments, and rates of degradation of cable properties and performance parameters.

If the estimated remaining service life of the cable is much greater than the operating life of the plant, including the design bases accident conditions, the cable engineer may decide to continue the present environmental inspection and monitoring activities, at their present performance frequencies, to periodically confirm that the operating environments of the cable do not become more severe and that no local adverse environmental conditions have developed. In this case, the cable engineer would most likely continue to perform the same visual inspections and CM tests on the cable, at the same performance frequencies, to periodically confirm that the physical condition of the cable does not change significantly and to monitor for any adverse trends in the measured cable properties and performance parameters.

If adverse environmental changes have occurred, the more severe cable stressors and associated aging and degradation mechanisms could cause increased rates of degradation in the cable, possibly shortening its service life. Should the estimated remaining service life of a cable be approximately equal to, or less than the remaining operating life of the plant, the cable engineer must recommend and implement activities to manage cable aging degradation and operating environments and/or to repair or replace the degraded cables. All of the cables selected for monitoring in the program are important to the safe operation of the plant, so the timely implementation of corrective action strategies will help to avoid unexpected early cable failures.

Cable aging degradation can be managed by modifying the performance frequencies for the cable visual inspections and CM tests. More frequent inspections and measurements will keep the cable engineer better informed of the recent status of cable condition and performance parameters. Adverse trends of measured cable parameters or increased rates of degradation can be monitored and detected sooner. The cable engineer may also decide to augment the existing CM inspections and testing with additional CM tests to provide more comprehensive data to monitor specific aspects of cable condition or to provide more information on critical cable parameters. Cables that have indicated adverse performance trends or increased rates of degradation will also be tagged for more frequent periodic review and condition assessment under CM program element 9.

Another action available to the cable engineer for the management of cable aging is the management of the cable operating environments. By controlling or reducing the severity of environmental and operating stressors acting on a cable system, the degradation process can be controlled or slowed, thereby maintaining the estimated service life.

As discussed in subsection 4.3.3, if unanticipated or locally adverse cable system operational environments are detected through periodic monitoring of cable environments or other reported observations, the cable engineer can implement one or more of the following responses for the affected cable(s), consistent with its safety significance:

- perform more frequent CM testing and environmental inspections to more closely monitor the cable condition

- add more CM tests that will more closely monitor the status of the specific aging mechanisms associated with the environmental stressors and the cable condition

- perform more frequent periodic review and condition assessment of the affected cable's condition (program element 9) and initiate corrective actions as required

- protect the cable from the adverse environment to reduce or eliminate the effects of the associated stressors

- identify the root cause of the adverse environmental condition and implement modifications, maintenance, or other corrective actions to address and correct the root cause of the adverse condition

It should be emphasized that the occurrence of cable system operating environments or locally adverse conditions that are unanticipated or more severe than the original plant design may constitute a design deficiency of the cable system, specifically, a potential violation of GDC 1, 4, 17, and 18. NRC regulations, such as 10 CFR 50, Appendix B, (quality assurance), the maintenance rule (10 CFR 50.65), and environmental qualification regulations (10 CFR 50.49), require that programs and administrative controls be established to monitor and detect degraded conditions on a regular basis and to promptly implement effective corrective actions and design modifications, consistent with its safety significance, so that any further cable degradation is minimized. A cable system must be designed to meet all applicable regulations and to perform its intended function in the plant environment under all anticipated operational occurrences and design basis events.

Finally, if cable visual inspections and CM tests indicate that a monitored cable is in such a degraded state that it is at risk for early cable failure, the cable engineer will recommend either maintenance/repair or replacement. Repairs can be made to damaged sections of a cable to restore the dielectric strength of the cable insulation or, if access allows, damaged sections of the cable can be cut out and replaced with new cable sections spliced into the cable circuit. If degradation of the cable is widespread, the entire cable may have to be replaced with a new cable run or use an existing spare cable, if any are available along the same cable route.

5. CONCLUSIONS AND RECOMMENDATIONS

The important observations and recommendations from this study to evaluate cable condition monitoring techniques and develop the essential elements of an effective electric cable condition monitoring program are summarized in this section.

5.1 Conclusions

A cable condition monitoring program is needed for the following reasons:

- The 10 CFR Part 50 regulations require licensees to assess the condition of their components, to monitor the performance or condition of SSCs in a manner sufficient to provide reasonable assurance that they are capable of fulfilling their intended functions, and to establish a test program to ensure that all testing required to demonstrate that components will perform satisfactorily in service is identified and performed. Recent incidents involving early failures of electric cables and cable failures leading to multiple equipment failures, as cited in IN 2002-12, "Submerged Safety-Related Cables" [Ref. 7], and Generic Letter 2007-01, "Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients" [Ref. 1], may indicate that licensee approaches to cable testing, such as in-service testing, surveillance testing, preventive maintenance, maintenance rule, etc., do not fully characterize the status of cable insulation condition nor provide information on the extent of the aging and degradation mechanisms that can lead to cable failure.

- 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. Portions of a cable circuit may pass through areas experiencing more harsh environmental conditions, such as high temperature, high radiation, high humidity, or flooding of underground cables. There has been concern that such local adverse environmental stressors can cause excessive aging and degradation in the exposed sections of a cable that could significantly shorten its qualified life and cause unexpected early failures.

- In-service testing of safety-related systems and components can demonstrate the integrity and function of associated electric cables under test conditions. However, in-service tests do not provide assurance that cables will continue to perform successfully when they are called upon to operate fully loaded for extended periods as they would under normal service operating conditions or under design basis conditions. In-service testing of systems and components does not provide specific information on the status of cable aging degradation processes and the physical integrity and dielectric strength of its insulation and jacket materials.

- Analysis of the summary of licensee responses to GL 2007-01 [Ref. 8] inquiries on licensees' experiences regarding cable failures and cable CM activities, revealed wide variations to the approaches and comprehensiveness of cable testing activities. Analysis of the reported cable failures also indicated a trend toward early cable failures occurring prior to the end of the original 40-year license period. These data prompted the NRC to consider whether "...licensees should have a program for using available diagnostic cable testing methods to assess cable condition."

5.2 Recommendations

This research study developed recommendations for a comprehensive cable condition monitoring program consisting of nine essential elements that consolidate a core program of periodic CM inspections and tests, together with the results of in-service testing, environmental monitoring and management activities, and the incorporation of cable-related operating experience. The recommended nine essential elements of the cable CM program are listed in Table 5.1 with a summary of the purpose and expected result for each element of the program.

A comprehensive cable condition monitoring program consisting of the nine essential elements listed in Table 5.1 can address the shortcomings of indirectly demonstrating cable integrity and function through in-service testing of systems and components. Some of the features of this program are as follows:

- Condition monitoring inspections and tests provide the means for evaluating the level of aging degradation of electric cables. Portions of a cable circuit that pass through areas experiencing more harsh environmental conditions or local adverse environmental stressors can cause excessive aging and degradation in the exposed sections of a cable that could significantly shorten its qualified life and cause unexpected early failures. Periodic cable condition monitoring inspection and testing can provide cable condition status information and measurements of cable insulation properties, physical integrity, and dielectric strength. Severely damaged or degraded cable insulation can then be identified and repaired or replaced to prevent unexpected early failures while in service.

- The benefits of periodic cable condition monitoring inspections and testing can be further complemented by addressing cable operating environments. Environmental stressors, especially temperature, moisture/flooding, and radiation, can be responsible for causing significant aging and degradation of electric cable insulation and jacket materials. Monitoring and management of the environmental conditions in which cables are operated can help to control or reduce aging stressors.

- Special consideration should be given the problem of monitoring the operating environment for cable circuits routed through inaccessible underground cable ducts and conduits, covered cable distribution trenches, and manhole vaults because they can frequently become flooded resulting in power and control cables operating in wetted and completely submerged conditions for extended periods of time. Unless the installed cables have been procured specifically for continuous submerged or submarine operation, the licensees should ensure that cables installed in duct banks, manholes, bunkers and direct burial applications, are provided with proper drains, sumps, alarms and other protective measures and inspection activities to ensure that they are monitored and maintained in a dry environment.

- The review of cable-related operating experience can play an important role in the assessment and management of electric cable aging and degradation. Industry-wide operating experience can alert licensees to cable manufacturing defects, inadequate installation practices, misapplication of cable types, and other environmental and operation factors. Regular review and analysis of in-plant cable failures or cable-related problems can sometimes reveal adverse performance trends or otherwise point to emerging problem areas that can be monitored more closely and/or corrected in a timely fashion before the occurrence of an early cable failure.

Table 5.1 Recommended Nine Essential Elements of a Cable Condition Monitoring Program

Program Element	Purpose	Expected Result
1. Selection of Cables to be Monitored	To identify and select electric cables that are candidates for inclusion in the cable condition monitoring program.	A listing of the most important cables in the plant whose condition should be periodically monitored and evaluated to provide assurance that they are capable of performing their intended function
2. Develop Database of Monitored Cables	To provide a single centralized source of information for all the cables in the program that can be used by the cable engineer as a tool to access, analyze, and evaluate the data and documentation necessary to make cable condition assessments and to guide the direction of program decisions and activities	A database that will provide essential information to support the implementation of the cable CM testing and inspection activities, and the periodic review and assessment of the condition of individual cables
3. Characterize and Monitor Cable Operating Environments	To verify the baseline design operating environment for a cable, to periodically verify actual environmental conditions and identify local adverse environments (e.g., high temperature or radiation, moisture, submergence) that may have developed, and to manage environmental conditions to mitigate the effects on cables	Baseline environmental operating conditions measurements and inspection results, periodic environmental condition monitoring and verification measurements and results, identification and description of local adverse environments, and activities for managing operating environments to mitigate adverse effects on cables
4. Identify Stressors and Aging Mechanism Affecting Cables in the Program	To identify the stressors and determine the aging mechanisms affecting cables in the program	Listing of the stressors and aging mechanisms affecting the condition of each cable in the program to be used in program element 5 to select the most effective CM inspection and testing techniques for each cable
5. Select CM Inspection and Testing Techniques	To determine the most effective CM inspection and testing techniques to detect and monitor the anticipated aging/failure mechanisms for each cable	An initial listing of cable CM inspection and testing techniques and periodic performance frequency for each cable
6. Establish Baseline Condition of Cables in the Program	To measure and document the baseline condition of each cable in the program using the selected cable CM inspection and testing methods identified in program element 5	Baseline cable condition measurements and inspection results for the techniques selected in program element 5
7. Perform periodic CM Inspection and Testing	To periodically measure and document the condition of each cable in the program using the selected cable CM inspection and testing methods identified in program element 5	Periodic record of cable condition measurements and inspection results for the techniques selected in program element 5
8. Review and Incorporate Cable-Related Operating Experience	To review industry-wide and in-plant cable-related operating experience and incorporate changes to the cable CM program as required to address applicable issues and trends	Incorporate changes to the cable CM program based on review of applicable operating experience
9. Periodic Review and Assessment of Cable Condition	To perform a periodic review of the current cable condition CM inspection and testing results, operating environments CM results, trends of cable properties and condition measurements, and applicable operating experience to establish an up-to-date assessment of cable condition, expected service life, and program changes and activities to manage aging degradation of each cable in the program	A formal periodic assessment of cable condition, expected service life, and program changes and activities to manage aging degradation of each cable in the program

- In the periodic review and assessment element of the program, the cable engineer brings together all of the inspection and CM testing results, inspection and testing data trends, surveillance or PM test results, applicable operating experience, and operating environment conditions and trends in order to establish an assessment of the present condition for each cable in the program. Based upon the periodic review and assessment of present cable condition, the cable engineer can make an estimate of the remaining service life of a cable given the present condition of the cable, existing cable operating environments, and rates of degradation of cable properties and performance parameters.

- The periodic review and assessment element of the program provides the opportunity for the cable engineer to make adjustments to the types and frequencies of CM testing and inspection for individual cable circuits, or specified sections of cable circuits, depending on the present status of the cable condition and operating environments. Recommendations can be made for corrective actions to manage cable aging degradation and environmental stressors.

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APPENDIX A: FIBER OPTIC CABLES

A. FIBER OPTIC CABLES

With the increased availability of digital and computer-based instrumentation and control (I&C) systems, many existing nuclear power stations are considering the replacement of their aged and obsolete original analog instruments and control systems with newer digital I&C technologies. The next generation of nuclear plants now being developed (e.g., the Westinghouse AP-600 and AP-1000, the General Electric ABWR and ESBWR, the Mitsubishi Industries US APWR, and the Areva EPR) make more extensive use of digital controls, instrumentation, and computer-based systems in their original designs. Many of these new digital I&C systems make use of fiber optic cable systems to interconnect the diverse system sensors, controls, and other components.

This section provides a brief description of fiber optic cable materials, construction, and configurations. Discussion and analysis on the failure modes, stressors, and aging mechanisms for fiber optic cables, splices and connectors is presented. Finally, some of the condition monitoring test methods applicable to fiber optic cables are described.

A.1 Construction, Materials, and Configurations

Instead of using the conventional metallic copper or aluminum conductor cables, many of the new digital I&C systems incorporate fiber optic cable systems to link the digital process signals and communications among the various subcomponents in the digital I&C channel. On the functional level the two types of cables are similar. However, where metal conductor-based I&C systems transmit information via electrical pulses or analog electrical waveforms along the metallic conductors in the conventional electric cable, the fiber optic-based channels use light pulses to transmit information along the fiber optic cables to link the various components in the system.

At one end of the fiber optic system channel is a transducer/optical transmitter that translates the signal from its original form at the origin of the cable into a series of light pulses to be transmitted along the fiber optic cable to an optical receiver/transducer at the receiving end. A light-emitting diode (LED) or an injection-laser diode (ILD) can be used for generating the light pulses. Using a lens, the light pulses are funneled into the fiber-optic medium where they travel down the cable. The wavelength of the light source (near infrared) is most often 850nm for shorter transmission distances and 1,300nm for longer distances on multi-mode fiber optic systems. On single mode fiber optic systems, the wavelength of the light source is typically 1,300nm for shorter transmission distances and 1,500nm is used for longer distances. The optical receiver translates the optical pulses into an information signal in a form compatible for use at the receiving end of the fiber optic channel. [Ref. A1]

The fiber optic cable acts as an optical waveguide that transmits light within the cable by the principle of total internal reflection. In its most basic configuration, a fiber optic cable is composed of two concentric layers: the core, through which light is piped, and the cladding. The core and cladding have different indices of refraction with the core having n_1 and the cladding n_2. The light pulses are guided down the fiber optic cable in the core because the core and cladding have different indices of refraction with the index of the core, n_1, always being greater than the index of the cladding, n_2. Light rays entering the fiber optic cable core that strike the core-to-cladding interface at an angle greater than critical angle, $\Theta_c = \arccos(n_2 / n_1)$, are reflected back into the core. Since the angle of incidence is always equal to the angle of reflection the reflected light will be reflected again and again down the entire length of the fiber optic cable. If a light ray strikes the core-to-cladding interface at an angle less than the critical angle, Θ_c, it passes into the cladding where it is attenuated very rapidly with propagation distance. [Refs. A1, A2]

Attenuation is principally caused by two physical effects: absorption and scattering. Absorption removes signal energy in the interaction between the propagating light (photons) and molecules in the core. Scattering redirects light out of the core to the cladding. When attenuation for a fiber optic cable is dealt with quantitatively it is referenced for operation at a particular optical wavelength, a window, where it is minimized [Ref. A2]. The integrity and quality of the core-to-cladding interface are very important to the attenuation of light channeled along the length of a fiber optic cable. Stressors that could erode, physically disrupt, or chemically alter the core-to-cladding interface in any way, will therefore result in greater attenuation of light, through scattering, when traveling from the origin to the receiving end of the fiber optic cable.

There are two basic modes of operation for fiber optic cables: single mode and multimode. A mode is the defined path in which light propagates through the fiber optic core. A light signal propagates through the fiber optic cable core on a single path in the single mode fiber and over many paths through the core in multimode fiber. The mode in which the light travels is dictated by the wavelength, core index profile, and core geometry. Single mode cable is comprised of a single strand of a very slender 8.3μm to 10μm diameter glass fiber through which light signals propagate via one mode, typically with a wavelength of 1310nm or 1550nm. Single mode fiber carries higher bandwidth than multimode fiber and experiences less signal attenuation, but requires a light source with a narrow spectral width. Multimode cable uses a larger fiber, in the 50μm to 100μm diameter range, and can provide a high bandwidth at a high speeds over medium distances. Since the light is dispersed over multiple pathways through the core, signal attenuation and distortion at the receiving end can become unacceptable at distances greater than 3000 feet [Ref. A1].

The fiber optic cable is composed of one of three basic types of material construction: fused silica (glass), polymer (plastic), or polymer-clad silica (PCS). Glass fiber optic cable, consisting of a glass core and glass cladding, has the lowest signal attenuation characteristic (and therefore, the longest transmission distance without the need for optical signal repeaters) but it is more expensive than the other types. The core fiber may be pure silica glass or it may be doped with other elements such as germanium or fluorine to achieve a specified index of refraction (e.g., germanium or phosphorous are added to increase the index of refraction; boron or fluorine are added to decrease the index of refraction) or to optimized the performance characteristics of the glass fiber core operating in high radiation or temperature environments [Refs. A2, A4, A5].

Polymer (plastic) fiber optic cable, consisting of a polymer core and polymer cladding, has the highest signal attenuation characteristic (and the shortest transmission distance capability), but comes at the lowest cost. Plastic fiber optic cable is the largest in diameter, e.g. typical core/cladding dimensions are 480/500μm, 735/750μm and 980/1000μm, which also makes it quite rugged and capable of withstanding abuse. A typical plastic fiber optic cable consists of polymethylmethacrylate (PMMA) fiber core coated with a fluropolymer cladding [Ref. A2]. Poor performance under high temperature and radiation conditions, the limited transmission distance, and flammability problems make it an unlikely choice for nuclear plant applications.

Plastic Clad Silica (PCS) fiber optic cable, consisting of a glass core fiber with a polymer (plastic) coating (usually of a lower index of refraction), has an attenuation characteristic falling between the pure silica fiber cables and the polymer fiber optic cables. The cost of PCS fiber optic cable lies between that of pure glass fiber cables and all-plastic cables, as well. Plastic Clad Silica (PCS) fiber optic cable has a glass core which is often vitreous silica while the cladding is plastic - usually a silicone elastomer with a lower refractive index. The IEC standardized PCS fiber optic cable in 1984 to have the following dimensions: core 200μm, silicone elastomer cladding 380μm, jacket 600μm. Application of connectors on PCS fabricated with a silicone elastomer cladding can require a higher level of skill and training because of the plasticity of the cladding and other application problems [Ref. A2]. Attenuation performance and transmission distance limitations, together with connector application and other difficulties, make the PCS fiber optic cable a less desirable option for nuclear power plant service.

A typical basic fiber optic cable has an additional coating(s) around the cladding called the jacket. The jacket usually consists of one or more layers of polymer. Its role is to protect the core and cladding from physical impacts that might affect their optical or physical properties. The jacket also acts as a physical shock absorber, and it provides protection for the internal optical fiber and cladding from abrasions, solvents, moisture, and other contaminants. The jacket does not have any optical properties that might affect the propagation of light within the fiber optic cable [Ref. A1].

A.2 Failure Modes, Stressors, and Aging Mechanisms

In order to include important fiber optic cables in the electric cable condition monitoring (CM) program it is necessary to identify the similarities and differences between fiber optic cables and the conventional polymer-insulated, metal conductor I&C cables around which the essential elements of the program are designed. The general programmatic structure of the recommended nine essential elements of the cable CM program is compatible with monitoring and evaluation of fiber optic cables. However, the differences in construction of the fiber optic cable, its failure modes, the important failure mechanisms, and the types of inspection and CM testing techniques will be unique as compared to conventional electric cables. Therefore, some minor considerations and adaptations may be called for to incorporate fiber optic cables into program element 3, environmental monitoring, element 4, identification of stressors and aging degradation mechanisms, and element 5, selection of CM inspection and testing techniques. Some modifications may be needed to the database data fields (CM program element 2) to accommodate fiber optic cable characteristics information and test data.

In conventional electric cables, the evaluation of the condition of the electrical insulation is the primary focus when monitoring the cable. The integrity of the conductor, cable splices, and cable termination connections is proven through condition monitoring activities, such as functional testing, visual inspection, Infrared (IR) thermography, and time domain reflectometry (TDR) testing. The major considerations in the evaluation of electric cables are insulation resistance, insulation dielectric strength, aging mechanisms, flexibility, effects of design basis events (DBEs), and fire resistance. In contrast, when evaluating optical fibers, the condition of the cable is assessed by evaluating signal transmission performance. The outer polymer buffer layer does not contribute to the transmission of light signals and serves as physical protection for the optical core and cladding material. The major considerations for evaluating fiber optic cables are monitoring signal attenuation, radiation dose and dose rate, and environmental thermal effects [Ref. A3].

The reliability engineer typically uses the failure modes and effects analysis (FMEA) tool to identify the manner or state in which a structure, system, or component (SSC) fails and the resulting effect that the failure mode will have on the function of the SSC. The piece-parts and subcomponents of the SSC are each analyzed in turn to identify the sub-component materials, stressors, potential aging mechanisms, and the potential effect(s) of the stressors and associated degradation/aging mechanisms on the function and operation of the subcomponent, i.e., will the mechanisms result in the subcomponent's failure.

By identifying these stressors, and quantifying their severity, the cable engineer can determine the aging and failure mechanisms that will cause degradation or other damage that, over time, could lead to the ultimate failure of a cable system. This information can then be used to select the most effective CM inspection and testing techniques for detecting and monitoring the anticipated aging/failure mechanisms.

Using the FMEA methodology applied to fiber optic cable systems, the failure modes, stressors, and significant aging mechanisms must be identified. The condition monitoring inspection and testing methods that are best suited for detecting and monitoring the progress or effects of the significant degradation mechanisms can then be selected. The failure modes for optical fibers include attenuation of signal to unacceptable optical power levels, distortion of the signal (time dispersion) causing an unacceptable bit error rate (BER), or complete loss of signal.

Cable systems in nuclear power plant service are subject to a variety of aging and degradation stressors that can produce immediate degradation or aging-related mechanisms and effects causing degradation of the cable components over time. Stressors can generally be categorized as one of two types based upon their origin: 1) environmental stressors originate from conditions in the environment where a cable system is located or 2) operational stressors that are the result of operational factors such as inspections or operating and maintenance activities in the vicinity of the cable system.

Using the FMEA analytical approach applied to fiber optic cable systems, the piece-parts of a cable (e.g., silica fiber optic core and cladding, protective fiber optic cable jacket, the precision silica fiber connector interface, and the fiber optic cable splice and connector hardware) are each analyzed to identify the constituent material(s). The stressors that can affect the material(s) in each piece-part of a particular cable system and operating environment, are analyzed to determine whether they can produce a degradation or aging mechanism that could eventually lead to one of the failure modes for the fiber optic cable. A general summary of stressors and associated potential aging and degradation mechanisms, adapted from information found in References A3 through A9, is provided in Table A.1 for fiber optic cables, splices, and connectors.

A.3 Fiber Optic Inspection and Testing

Condition monitoring of fiber optic cable systems will include visual inspection and testing using instruments and techniques specifically designed for fiber optic cable systems. Baseline visual inspection and periodic visual inspection for fiber optic cable systems will be quite similar to those described in subsections 3 and 6 for conventional electric cables. Identification of local adverse stressors, such as high temperature, high radiation, high humidity or flooding, is important since these stressors can cause the aging and degradation mechanisms summarized in Table A1, which could have an adverse affect on cable performance. Visual inspection can detect direct mechanical damage, such as physical impacts, bending, abrasion, cutting, contact, deformation, and perforation resulting from installation and maintenance activities in and around the location of a cable. As indicated in Table A.1, mechanical damage is a potential stressor that can affect fiber optic cable systems by direct damage to the optical fibers or, indirectly, by damaging the protective polymer jacket and opening a potential pathway for intrusion of moisture or other contaminants that could degrade the optical properties of the fiber optic core and cladding material.

Testing fiber optics requires special tools and test instruments that must be selected specifically for monitoring the types of fiber optic components and fiber optic cables used in the particular installation being tested. Guidance on various types of fiber optic cable system testing techniques has been developed and incorporated in to testing standards, known in the industry as fiber optic test procedures (FOTPs), sponsored by the Electronic Industries Alliance (EIA) and the Telecommunications Industry Association (TIA). A list of these EIA-TIA fiber optic test procedures can be found on the Fiber Optics Association (FOA) internet website [Ref. A8].

At the time fiber optic cables are installed, spliced, and terminated, they must be baseline tested. In addition to a baseline visual inspection to verify the condition of the installation, typical fiber optic cable system measurements will include a test for continuity and polarity, end-to-end insertion loss, and then troubleshooting for any problems that are identified. Long fiber optic cable runs that include intermediate splices should be checked using an optical time domain reflectometer (OTDR) to verify the location and performance of the individual splices. Baseline measurements of these data can be compared with subsequent periodic measurements of the same type to identify or trend any degradation of the fiber optic cable system. The aging and degradation mechanisms listed in Table A1 can degrade the performance of the cable's optical fiber and intermediate optical cable splices and connectors.

Continuity checking is accomplished using a visual fiber tracer to verify that the optical fibers are not broken and to trace the path of a fiber from one end to another through many connections. The visual fiber tracer looks like a flashlight, or a pen-light, with a simple light bulb or LED source that mates to a fiber optic connector. When attached to a cable, the light from the source will be transmitted through the core of the fiber and will be visible at the far end. If there is no light at the end, there are faulty intermediate connectors or splices, or broken sections of the fiber optic cable [Refs. A8, A9].

Optical power measurement is one of the most important indicators of fiber optic cable performance. The power output of an optical transmitter or the input to the optical receiver are "absolute" optical power measurements; that is, the actual value of the optical power is being measured. Optical power loss is a "relative" power measurement, being the difference between the power coupled into a component like a cable, splice, or a connector and the power that is transmitted through it. This difference in power level before and after the component is called optical loss and defines the performance of a cable, connector, splice, etc. [Refs. A8, A9].

"Loss testing of a cable is the difference between the power coupled into the cable at the transmitter end and what comes out at the receiver end. Testing for loss (also called "insertion loss") requires measuring the optical power lost in a cable (including fiber attenuation, connector loss and splice loss) with a fiber optic light source and power meter (LSPM) or optical loss test set (OLTS). Loss testing is done at wavelengths appropriate for the fiber and its usage. Generally, multimode fiber is tested at 850nm and optionally at 1300nm with LED sources. Single mode fiber is tested at 1310nm and optionally at 1550nm with laser sources" [Ref. A8].

The optical time domain reflectometer (OTDR) is typically used to measure distance and attenuation over the entire length of a fiber optic cable link. It is also used to identify specific points along the link where optical power losses occur, such as splices and connectors.
An OTDR is an optical radar which measures time of travel and the return strength of a short pulse of light launched into an optical fiber. The functional principle is similar to the time domain

Table A.1 Summary of Stressors and Potential Aging Mechanisms for Fiber Optic Cables, Splices, and Connectors

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comments
Fiber Optic Cable Core and Cladding	• Silica fiber (pure and doped)	• Elevated temperature • Elevated radiation fields	• Discoloration • Degradation of core to cladding interface	• Increased signal attenuation • Decrease in optical power transmission • Increased signal time dispersion	-
	• Silica fiber (pure and doped)	• Wetting • Humidity	• Moisture intrusion • Degradation of core to cladding interface	• Increased signal attenuation • Decrease in optical power transmission • Increased signal time dispersion	Moisture intrusion can introduce contaminants onto interface surface; possible fungal contamination
	• Silica fiber (pure and doped)	• Corrosive chemical contamination	• Chemical reactions • Discoloration • Degradation of core to cladding interface	• Increased signal attenuation • Decrease in optical power transmission • Increased signal time dispersion	
	• Silica fiber (pure and doped)	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including crushing, bending, tensile deformation, cracking	• Increased signal attenuation • Decrease in optical power transmission • Increased signal time dispersion • Loss of signal	Breakage of fiber can cause loss of optical signal
	• Silica fiber (pure and doped)	• Installation damage	• Mechanical damage including crushing, bending, tensile deformation	• Increased signal attenuation • Decrease in optical power transmission • Increased signal time dispersion • Loss of signal	Breakage of fiber can cause loss of optical signal

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comments
Cable Jacket	• Various polymer materials	• Elevated temperature • Elevated radiation fields	• Embrittlement • Cracking	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	The primary function of the cable jacket is to provide mechanical protection to the cable during installation. A secondary function is to mitigate intrusion of moisture and contaminants into the interior of the cable
	• Various polymer materials	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage including crushing, bending, cutting, abrasion, gouging, tensile deformation	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	Moisture and contaminant intrusion can result in damage to silica fiber core and cladding as described above
	• Various polymer materials	• Installation damage	• Mechanical damage including crushing, bending, cutting, abrasion, gouging, tensile deformation	• Loss of structural integrity • Increased intrusion of moisture and contaminants into the cable interior	Moisture and contaminant intrusion can result in damage to silica fiber core and cladding as described above
Fiber Optic Cable Connection Interface (Splices and Connectors)	• Silica fiber (pure and doped)	• Contamination by dirt or dust	• Degradation of connection interface	• Decrease in optical power transmission • Loss of signal	
	• Silica fiber (pure and doped)	• Wetting due to moisture intrusion • Humidity	• Degradation of connection interface	• Decrease in optical power transmission • Loss of signal	Moisture intrusion can introduce contaminants onto interface surface; possible fungal contamination
	• Silica fiber (pure and doped)	• Vibration	• Abrasion • Loosening of connectors	• Decrease in optical power transmission • Loss of signal	
	• Silica fiber (pure and doped)	• Corrosive chemical contamination	• Chemical reactions • Discoloration • Degradation of connection interface	• Decrease in optical power transmission • Loss of signal	
	• Silica fiber (pure and doped)	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage to interface surfaces • Misalignment of connection interface	• Decrease in optical power transmission • Loss of signal	Can result from excessive disconnection and reconnection of cable connector

Sub-component	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comments
Connectors (continued)	• Silica fiber (pure and doped)	• Installation damage	• Mechanical damage to interface surfaces • Dirt on interface surfaces • Misalignment of connection interface	• Decrease in optical power transmission • Loss of signal	Result of faulty installation practices.
Fiber Optic Cable Connection Hardware	• Metal connection assembly components • Plastic connection assembly components	• Handling, physical contact, or abuse during maintenance, operation, or testing activities	• Mechanical damage to interface surfaces • Misalignment of connection interface	• Decrease in optical power transmission • Loss of signal	Can result from excessive disconnection and reconnection of cable connector
	• Metal connection assembly components • Plastic connection assembly components	• Installation damage	• Mechanical damage to interface surfaces • Dirt on interface surfaces • Misalignment of connection interface	• Decrease in optical power transmission • Loss of signal	Result of faulty installation practices.
	• Metal connection assembly components • Plastic connection assembly components	• Vibration	• Mechanical damage to interface surfaces • Fatigue damage to connector hardware • Misalignment of connection interface	• Loss of structural integrity • Decrease in optical power transmission • Loosening of connection • Loss of signal	

reflectometer (TDR), described in subsection 3.2.9, used for trouble shooting conventional electric cables. As a light signal propagates the length of an optical fiber, small reflections occur throughout the fiber, becoming weaker as power levels drop with distance. At major breaks, large reflections occur and appear as strong peaks on an oscilloscope display at the instrument. The magnitude and location of the peaks can indicate broken or damaged sections of optical fiber, or indicate degradation, misalignment, or other problems at the site of an optical cable splice or an optical cable connector. The instrument also gives the location of the problem, so that if the site of the problem is accessible, the degraded splice or connector can be cleaned and/or repaired [Refs. A8, A9].

Additional guidance on the use of OTDRs, optical power meters, and other fiber optic test instruments to perform condition monitoring measurements on fiber optic cable systems can be found in References A8 and A9.

Table A.1 indicates that the interconnection joint on an optical cable splice or connector is an area that is susceptible to contamination, damage or misalignment that can degrade the optical performance of the connection. Fiber optic inspection microscopes are used to inspect connectors and to find faults like scratches, polishing defects, and dirt. A properly installed connector will have a smooth, polished, scratch-free finish and the fiber will not show any signs of cracks, chips, or areas where the fiber is either protruding from the end of the ferrule or pulling back into it.

The magnification available on a fiber optic inspection microscope for viewing connectors can typically range from 30 to 400 power, so that an optimum viewing magnification can be selected. Some fiber optic inspection microscopes allow examination of the connector from several angles, either by tilting the connector or adjusting the angle of illumination to optimize the viewing conditions. Adaptors are provided to affix the connector in position to allow inspection. More advanced fiber optic inspection microscopes provide a digital video display of the optical connector end face and software that analyzes the surface finish [Refs. A8, A9].

Further guidance on the installation, inspection, cleaning, and maintenance of fiber optic cable splices and connectors is provided in References A8 and A9.

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APPENDIX B: DEFINITIONS

B. DEFINITIONS

This appendix provides definitions for several of the key terms and phrases used in this report. Some of these are common electric cable terminology in use in the commercial nuclear and electric power industries. Other usages have evolved during the performance of electric cable manufacturing, testing, maintenance, qualification testing, and research. Many of the electric cable terms and phrases are defined in one or more standard industry dictionaries or glossaries of technical terms, such as EPRI Brochure BR-101747, "Common Aging Terminology" [Ref B1], and IEEE Std. 100-2000, "The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition" [Ref B2]. Reference sources are cited as applicable.

B.1 Definitions of Terms and Phrases

Aging Mechanism - specific process that gradually changes characteristics of an SSC with time or use [Refs. B1 & B6]

Alternate AC (AAC) Power Source - an alternating current (ac) power source that is available to and located at or nearby a nuclear power plant and meets the following requirements:

(1) is connectable to but not normally connected to the offsite or onsite emergency ac power systems;
(2) has minimum potential for common mode failure with offsite power or the onsite emergency ac power sources;
(3) is available in a timely manner after the onset of station blackout; and
(4) has sufficient capacity and reliability for operation of all systems required for coping with station blackout and for the time required to bring and maintain the plant in safe shutdown (non-design basis accident) [Ref B3]

Antioxidants (cable insulation) - an oxidation inhibitor included in polymeric electric cable insulation to protect the main polymer compound from oxidation damage

Cable System - an electric cable circuit or group of circuits including the electric cable, terminations, splices, and other accessories

Compressive Modulus - a material property defined as the ratio of compressive stress to compressive strain below the proportional limit [Ref B4]

Condition Monitoring - observation, measurement or trending of condition or functional indicators with respect to some independent parameter (usually time or cycles) to indicate the current or future ability of an SSC to function within acceptance criteria [Ref B1]

Degradation Mechanism - specific process that causes the immediate or gradual deterioration of characteristics of an SSC that could impair its ability to function within acceptance criteria [adapted from Refs. B1 & B6]

Design Basis Event - conditions of normal operation, including anticipated operational occurrences, design basis accidents, external events, and natural phenomena for which the plant must be designed [10 CFR 50.49]

Dielectric Loss Angle - the angle whose tangent is the dissipation factor (See Figure 3.1) [Ref. B2 & B4]

Dielectric Phase Angle - the angular difference in phase between the sinusoidal alternating voltage applied to a dielectric and the component of the resulting alternating current having the same period as the voltage (See Figure 3.1) [Ref. B2 & B4]

Dielectric Strength - the potential gradient at which electric failure or breakdown occurs [Ref. B2 & B4]

Dissipation Factor - the tangent of the dielectric loss angle, Note: For small values of dielectric loss angle dissipation factor is virtually equal to insulation power factor (See Figure 3.1) [Refs. B2 & B4]

Dry (environment) - an operating environment in which an electric cable is generally protected from direct exposure to water and only occasionally may be exposed to moisture, condensation, or high humidity for brief intervals of time

Environmental Conditions - ambient physical states surrounding an SSC [Ref. B1]

Failure Mode - the manner or state in which an SSC fails [Ref. B1]

Harsh Environment - an environment expected as a result of the postulated service conditions appropriate for the design basis and post-design basis accidents of the station [Ref. B2]

Insulation (cable) - the part that is relied upon to insulate the conductor from other conductors or the conductor from ground [Ref. B2]

Insulation Resistance (cable) - the resistance, measured at a specified dc voltage, between a specified conductor and any other conductor or ground [adapted from Refs. B2 and B4]

Jacket (cable) - a thermoplastic or thermosetting covering, sometimes reinforced, applied over the insulation, core, metallic sheath, or armor of a cable [Ref. B2]

Local Adverse Environment - a condition in a limited plant area containing an electric cable system that is significantly more severe than the specified service condition for the electric cable system; the service conditions of interest include normal, abnormal, and error-induced conditions prior to the start of a design basis accident or earthquake [adapted from Ref. B6]

Low-Voltage (power cable) - those cables used on systems operating at 1000V or less [Ref. B2]

Mild Environment - a mild environment is an environment that would at no time be significantly more severe than the environment that would occur during normal plant operation, including anticipated operational occurrences. [10 CFR 50.49]

Ohmic Heating (cable) - the internal heat generated by the flow of current through the electrical resistance of a cable conductor

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

For more than 20 years the NRC has sponsored research studying the aging degradation, condition monitoring, enviromental qualification, and testing practices for electric cables and cable accessories used in nuclear power plants. The essential elements for an effective cable condition monitoring program presented in this report are based upon the results of the NRC's electric cable and equipment research programs, industry guidance and standards, and the experience and observations of the others who have studied or conducted electric cable condition monitoring and qualification testing. The program methodology presented herein provides guidance on the selection of cables to be included in the program, characterization and monitoring of cable operating environments and stressors, selection of the most effective and practical condition monitoring techniques, documentation and review of cable condition monitoring testing and inspection results, and the periodic review and assessment of cable condition and operating environments.

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