NUREG/CR-6794
BNL-NUREG-52673

Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants

Brookhaven National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at http //www nrc gov/reading-rm html Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, in the Code of *Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402–0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer,
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address http://www nrc gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

NUREG/CR-6794
BNL-NUREG-52673

Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants

Manuscript Completed: August 2002
Date Published: January 2003

Prepared by
M. Villaran, R. Lofaro

Contributors: E. Grove, P. Soo

Brookhaven National Laboratory
Upton, NY 11973-5000

S. K. Aggarwal, NRC Program Manager

Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code W6822

ABSTRACT

An aging assessment of safety-related power cables used in commercial nuclear power plants has been performed to determine the effects of aging degradation. This study is based on the review and analysis of past operating experience, as reported in the Licensee Event Report, Nuclear Plant Reliability Data System, and Equipment Information and Performance Exchange databases. In addition, documents prepared by the Nuclear Regulatory Commission that identify significant issues or concerns related to power cables have been reviewed. Based on the results of the aforementioned reviews, predominant aging characteristics are identified and potential condition monitoring techniques are evaluated. The results of the aging assessment were then used to evaluate environmental qualification practices for power cables to determine if all significant aging mechanisms are appropriately addressed.

TABLE OF CONTENTS

Page No.

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

As a result of the Nuclear Regulatory Commission (NRC) staff's activities on plant license renewal, a number of issues were raised related to the qualification process and EQ was identified as an area that required further review. Research was subsequently performed in this area focusing specifically on low-voltage instrumentation and control (I&C) cables. I&C cables were the initial focus since they are used extensively in nuclear power plants and they were judged to be the most susceptible to aging degradation. However, other classes of safety-related electrical equipment are also susceptible to aging degradation and should be studied to address issues related to their current qualification practices. Power cables are among the equipment identified for additional study.

Power cables have a number of similarities to I&C cables in that one or more metallic conductors insulated with a polymeric material are used to provide a conductive path for an electric circuit. Grounding conductors may be included in multi-conductor configurations. The polymers used to insulate the conductors are typically the same as those used on low-voltage cables, although their thickness is greater to provide the additional dielectric strength required for higher operating voltages. The service environments in which power cables operate are also similar to those for I&C cables. However, there are a number of differences that make a separate study of power cables important.

Power cables have larger conductors to accommodate the higher current, on a continuous basis, typically found in power applications. The continuous current flow in power cables is accompanied by ohmic heating in contrast to the low current, intermittent duty of I&C cables, which experience negligible internal heating. Power cables used to energize medium- and high-voltage equipment, such as pump motors and switchgear, must operate at voltages and currents that are significantly higher than I&C cables. This results in an increased stress on the cables, which could accelerate aging degradation due to internal ohmic heating. In addition, the higher voltages these cables experience make them susceptible to unique aging mechanisms, such as treeing, that low-voltage cables would not experience.

In addition, placement in conduit, raceways, underground ducts, and cable trays will affect the service conditions under which the cables must operate. Routing in densely filled cable trays, enclosed ducts, or fire-wrapped cable trays, together with other continuous duty power cables, will result in elevated operating temperatures. Cable ducts that run below grade or beneath floor level will normally be susceptible to seepage and water intrusion that can lead to the failure of power cables.

Safety-related power cables are susceptible to aging degradation, therefore, it is important to develop an in-depth understanding of how the various types of power cables degrade with time, and what impact this degradation may have on their performance. In light of this, the NRC Office of Nuclear Regulatory Research sponsored this research program to perform an assessment of the aging effects and qualification practices for medium-voltage power cables.

The objectives of this research program are: (1) to characterize the effects of aging on power cables and determine how these aging effects impact performance and accident survivability based on recent operating experience, (2) to evaluate the adequacy of current qualification practices for safety-related power cables in terms of how well they address the aging effects identified, and (3) to evaluate the feasibility of in situ condition monitoring of power cables in terms of what techniques are currently available and how effective they might be at determining the current condition of a cable and predicting future performance under accident conditions.

A review and evaluation of past work and events related to power cables has been performed to characterize the effects of aging on power cable performance and reliability. The following observations are made from this review and evaluation:

- Power cables are constructed of materials that are susceptible to age degradation. This degradation can and has resulted in failure of cables, if it becomes severe. In all cases reviewed in this study, the cable insulation was the subcomponent that failed as a result of aging degradation.

- Power cables are used in both safety-related and non safety-related applications in nuclear power plants and their failure can have a significant impact on plant operation. Examples include the loss of function of safety-related equipment or reactor trip. Less severe consequences are challenges to safety systems and a loss of redundancy of one or more safety system trains.

- The predominant aging mechanism for power cable failure is moisture intrusion, which can degrade the dielectric properties of the insulation and result in water treeing. Other important aging mechanisms are embrittlement of the insulation due to elevated temperatures, and chafing or cutting of the insulation due to vibration or cyclic movement of the cable.

- The number of power cable events found in the various databases is relatively small, suggesting that power cable failures are infrequent. However, there may be a number of power cable events that were judged to be of insufficient importance to report by the utility. As the age of the installed base of power cables in nuclear power plants increases, there is the potential of seeing more power cable failures resulting from age-related degradation.

- The failure mode most commonly found is "ground fault," in which the cable faulted to ground from one or more of its conductors. Other less frequent failure modes are phase-to-phase fault, in which the cable faulted from one conductor to another conductor, or "low resistance," which indicates that the dielectric properties of the insulation had degraded to an unacceptable level.

While the number of failures is relatively low, the data indicate that power cables are susceptible to aging degradation that can lead to failure. Since power cables are not typically replaced on a periodic basis, unless there is a problem with the cable, as plants age and the cables' cumulative exposure to aging stressors increases, the amount of aging degradation will increase. This could lead to an increase in the number of power cable failures in later years of plant life. This suggests that an aging management program to monitor and mitigate the effects of aging may be beneficial.

Aging management of power cables should be based on the implementation of one or more condition monitoring techniques to closely monitor their condition. Based on the review and evaluation of condition monitoring methods, in situ monitoring of medium-voltage power cables appears to be feasible. The following recommendations are made with respect to the establishment of a monitoring program:

- An in situ monitoring program should include the use of several different CM methods. The method chosen for a particular cable should be based on the construction of the cable, as well as its application and installation.

- Visual inspection should be considered as a first step for all cables that are accessible. This is an inexpensive, easy-to-perform technique that can provide valuable information on the condition of a cable, as well as the location of any potential problem areas along the length of a cable run. While qualitative information only is provided, it can be used to make an informed decision as to whether additional more intrusive testing is required.

- Care should be exercised in the use of dc high voltage electrical tests since past work has shown the potential for this type of test to cause premature failure of cables.

Using the results of this aging assessment, power cable qualification practices were evaluated to determine if aging is adequately addressed. The evaluation of current qualification practices for power cables resulted in the following observations:

- The present methods for qualification of electric cables adequately anticipate the effects of thermal and radiation-related aging degradation on the polymeric materials. However, for power cables operating at high current loads, generating significant internal heating, and in densely-filled trays, ducts, conduits, or raceways with other power cables, the effects of the total thermal loading of the cable may not be fully accounted for in those instances where power cables are tested together with low-voltage I&C cables.

- To ensure that all applicable aging stressors are identified and addressed in qualification tests, it may be beneficial to reference an appropriate aging management guidance document, such as IEEE Standard 1205-2000, in the governing IEEE qualification standards (323 and 383).

- Two of the power cable qualification tests reviewed specifically addressed the effects of long-term immersion, while energized, on cable insulation performance. This indicates that the industry acknowledges the importance of this stressor on power cable aging and performance, however, most of the tests reviewed for this study did not include these stressors.

- None of the power cable qualification tests included in the review specifically addressed the effects of vibration/cyclic movement either as a factor in preconditioning or as a separate performance test. Since vibration and water immersion are application-specific variables, they may not normally have been included in general qualification testing for cables. Vibration/cyclic movement for power cables may be addressed as part of the qualification for another piece of equipment, e.g., motor leads feeding a large electric motor.

- Currently accepted standards permit the qualification of various configurations of electric cables based on simple analysis or their similarity to other cables of the same materials or construction that have already passed environmental qualification type tests. During previous research it was found that factors such as cables with insulated conductors of different diameters and thicknesses, single versus multiconductor cable configurations, and bonded versus unbonded jackets performed differently during qualification testing even though they incorporated the same insulation and jacket materials. Consequently, qualification by simple analysis and similarity of materials may not be appropriate in every case.

ACKNOWLEDGMENTS

The authors would like to acknowledge the technical support and guidance provided by the NRC Program Manager, Satish Aggarwal, in the performance of this study. We would also like to thank Edward Grove and Peter Soo of Brookhaven National Laboratory for their support in the performance of the data reviews for this study. Also, we would like to thank Charles Hofmayer for his review and comments on this manuscript.

Our appreciation is also extended to Susan Signorelli for her assistance in the preparation of this document.

ABBREVIATIONS

AWG .... American Wire Gauge
BNL .... Brookhaven National Laboratory
CM .... Condition Monitoring
CSPE .... Chloro-Sulfonated Polyethylene (also known as Hypalon®)
DBE .... Design Basis Event
DOR .... U.S. NRC, Division of Operating Reactors
EAB .... Elongation-at-Break
EPDM .... Ethylene Propylene Diene Monomer
EPR .... Ethylene Propylene Rubber
EPIX .... Equipment Performance and Information Exchange System
EQ .... Environmental Qualification
ESF .... Engineered Safety Feature
I&C .... Instrumentation and Control
LER .... Licensee Event Report
LOCA .... Loss of Coolant Accident
MSLB .... Main Steam Line Break
NPRDS .... Nuclear Plant Reliability Data System
NRC .... Nuclear Regulatory Commission
OITM .... Oxidation Induction Time
PSIG .... Pounds per Square Inch Gauge
PVC .... Polyvinyl Chloride
QA .... Quality Assurance
RES .... U.S. NRC, Office of Nuclear Regulatory Research
SR .... Silicone Rubber
TDR .... Time Domain Reflectometry
XLPE .... Cross-Linked Polyethylene
XLPO .... Cross-Linked Polyolefin

1. INTRODUCTION

1.1 Background

The Environmental Qualification (EQ) Rule documented in Title 10 of the Code of Federal Regulations, Part 50, Section 49 (10 CFR 50.49) requires that safety-related electric equipment that is installed in a harsh environment in a nuclear power plant must be qualified. The qualification program must address aging effects, and it must provide assurance that the equipment will be able to perform its intended function during and following a design basis event, even at the end of its qualified life.

As a result of the Nuclear Regulatory Commission (NRC) staff's activities on plant license renewal, a number of issues were raised related to the qualification process and EQ was identified as an area that required further review. Research was subsequently performed in this area focusing specifically on low-voltage instrumentation and control (I&C) cables. I&C cables were the initial focus since they are used extensively in nuclear power plants and they were judged to be the most susceptible to aging degradation. However, other classes of safety-related electrical equipment are also susceptible to aging degradation and should be studied to address issues related to their current qualification practices. Power cables are among the equipment identified for additional study.

Power cables have a number of similarities to I&C cables in that one or more metallic conductors insulated with a polymeric material are used to provide a conductive path for an electric circuit. Grounding conductors may be included in multi-conductor configurations. The polymers used to insulate the conductors are typically the same as those used on low-voltage cables, although their thickness is greater to provide the additional dielectric strength required for higher operating voltages. The service environments in which power cables operate are also similar to those for I&C cables. However, there are a number of differences that make a separate study of power cables important.

Power cables have larger conductors to accommodate the higher current, on a continuous basis, typically found in power applications. The continuous current flow in power cables is accompanied by ohmic heating in contrast to the low current, intermittent duty of I&C cables, which experience negligible internal heating. Power cables used to energize medium- and high-voltage equipment, such as pump motors and switchgear, must operate at voltages and currents that are significantly higher than I&C cables. This results in an increased stress on the cables, which could accelerate aging degradation due to internal ohmic heating. In addition, the higher voltages these cables experience make them susceptible to unique aging mechanisms, such as treeing, that low-voltage cables would not experience.

In addition, placement in conduit, raceways, underground ducts, and cable trays will affect the service conditions under which the cables must operate. Routing in densely filled cable trays, enclosed ducts, or fire-wrapped cable trays, together with other continuous duty power cables, will result in elevated operating temperatures. Cable ducts that run below grade or beneath floor level will normally be susceptible to seepage and water intrusion that can lead to the failure of power cables.

A recent event at the Davis-Besse nuclear power station demonstrates that power cables are susceptible to aging degradation that can lead to failure, and thus underscores the importance of aging management for medium-voltage power cables. On October 2, 1999, the number 2 component cooling water pump at Davis-Besse tripped due to a ground fault on Phase 'A' to the 4,160 volt motor. The safety-related, Class 1E, three-phase 5 kV Okonite power cable used to energize the pump motor was found to have failed. This cable was constructed of an ethylene propylene rubber insulation encased within a protective neoprene outer jacket.

The failed cable was examined and was found to have cracks throughout the outer jacket, along with heat damage to the outer jacket on approximately 175 feet of the 265 foot cable run. The cable was located in a 4 inch PVC conduit embedded in the concrete floor of the turbine building. The 90 foot section of cable that is elevated at the circuit breaker end of the circuit was in good condition and showed no signs of damage. Subsequent investigation found that the cable failed due to moisture intrusion into the cable insulation, which resulted in grounding of the conductor. Moisture also resulted in severe corrosion and loss of 5 of 7 strands of the cable ground conductor.

As this event clearly demonstrates, safety-related power cables are susceptible to aging degradation, therefore, it is important to develop an in-depth understanding of how the various types of power cables degrade with time, and what impact this degradation may have on their performance. In light of this, the NRC Office of Nuclear Regulatory Research sponsored this research program to perform an assessment of the aging effects and qualification practices for medium-voltage power cables.

In past studies performed on electrical equipment aging [1, 2], the typical aging stressors and failure mechanisms to which power cables are susceptible have been assessed based on available operating data. The current study built upon these past results using more recent operating experience to determine whether the predominant aging mechanisms that they had identified are still the most important, or if any previously unidentified aging characteristics that could affect performance have now become apparent as plants continue to age. Since aging effects typically become more pronounced with increased age, the review of recent operating experience for this study was necessary to confirm the findings of the earlier studies and identify newly-emerging trends. The results were then used to evaluate current qualification practices for power cables to determine whether aging is adequately addressed and if any improvements are warranted.

1.2 Objectives

The objectives of this research program are: (1) to characterize the effects of aging on power cables and determine how these aging effects impact performance and accident survivability based on recent operating experience, (2) to evaluate the adequacy of current qualification practices for safety-related power cables in terms of how well they address the aging effects identified, and (3) to evaluate the feasibility of in situ condition monitoring of power cables in terms of what techniques are currently available and how effective they might be at determining the current condition of a cable and predicting future performance under accident conditions.

1.3 Scope

This study examines medium-voltage power cables (2kV to 15 kV) used in safety-related applications in nuclear power plants, including control power cables in switchgear and motor control centers. The boundaries of the study will encompass the cable components, including the conductors, the insulation, and the outer jacket. Connectors will not be included in this study since they are a separate equipment category and have their own unique materials of construction and aging mechanisms.

2. SUMMARY OF PAST RESEARCH ON POWER CABLES

Aging and condition monitoring of medium-voltage power cables has been of interest for some time and has been studied in the past. As part of the current study, a literature search and review was performed to identify past work on this topic. The objective of this effort was to determine what research had already been performed and use that as a starting point for the current study. In this way, any duplication of effort would be avoided and insights gained from past research could be incorporated into the current study.

The following paragraphs provide a summary of the most relevant studies identified from this literature search and review.

2.1 NUREG/CR-5461, "Aging of Cables, Connections, and Electrical Penetration Assemblies used in Nuclear Power Plants," Sandia National Laboratories, July 1990 [1].

This study sponsored by the U.S. NRC is based on a review of LERs (1980-1988) and NRC documents (e.g., Information Notices, Bulletins, etc.). It provides an aging assessment of electrical cables (low-voltage only), cable connections (including splices), and electrical penetration assemblies used in commercial nuclear power plants that was performed for the NRC under the Nuclear Plant Aging Research (NPAR) program.

A review of operating experience from LERs was found to provide relatively few events, thus, little information on failure causes or mechanisms was obtained. However, information from past qualification testing was evaluated to identify the following failure mechanisms:

- mechanical degradation, which could allow moisture intrusion,
- reduced insulation resistance due to high temperature and pressure during accident conditions, and
- reduced insulation resistance due to moisture absorption and swelling

The study concluded that cables are highly reliable devices under normal plant operating conditions, with no evidence of significant failure rate increases with age. In regard to condition monitoring, cables receive minimal testing and maintenance attention due to their relatively high reliability and the lack of effective test techniques. When testing is performed, the test used is usually insulation resistance.

2.2 SAND96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cable and Terminations," Sandia National Laboratories, September 1996 [2].

This study sponsored by the U.S. Department of Energy is based on a review of information from LERs (1980 to 1994), NPRDS (1975 to 1994), EPRI NUS cable database (1993 version), NRC documents (e.g., Information Notices, Bulletins, etc.) up to 1993, and visits/interviews with experts from 3 host utilities. The report provides an aging assessment of electrical cables (low-voltage I&C and medium-voltage power cables), and cable terminations (including splices) used in commercial nuclear power plants that was performed for DOE/EPRI. Recommended methods for effective detection and mitigation of aging effects in commercial nuclear power plant electrical cables are provided.

The report concluded that the number of failures of electric cables is extremely low in proportion to the amount of installed cable. However, it was noted that the data are limited in that there are no accident performance data, and operating experience was limited to plants that are typically less than 20 years old.

Simultaneous wetting and exposure to operating voltage was identified as the predominant aging-related failure cause for medium-voltage cables. The potential failure causes identified are the following:

- installation damage,
- maintenance damage,
- long-term wetting while energized

The review of operating experience found that the most prevalent failed subcomponent in medium-voltage cables was the insulation, and the predominant failure mode was grounding or short circuit. Most of the reported failures were detected during operation.

In regard to condition monitoring, visual inspection was recognized as a technique that is warranted to provide a qualitative assessment of cable condition while in service. Other available monitoring techniques are the following:

- insulation resistance/polarization index,
- capacitance measurement
- time-domain reflectometry,
- power factor measurement,
- ac/dc high-potential testing

The study concluded that aging management activities should focus on those cables in susceptible locations. For medium-voltage power cables, this would include those cables located in areas where they are exposed to wetting or submersion. In addition, an accurate characterization of plant operating environments was recommended to assist in the identification of components requiring further attention. At the time of this study it was concluded that there were no known techniques capable of effective monitoring of aging of the dielectric properties of the cable without potentially causing degradation due to the test itself.

2.3 EPRI Report NP-7485, "Power Plant Practices to Ensure Cable Operability," prepared by Ogden Environmental and Energy Services Co., July 1992 [3].

This report prepared for the Electric Power Research Institute (EPRI) presents information on the construction, installation, qualification, reliability, and maintenance of low-and medium-voltage electric cables in nuclear power plants. A review of trouble reports and past operating experience was performed, along with interviews of industry experts to identify past problems with these cables. It was found that very few cable problems have occurred. The predominant cause of failures that did occur were the following:

- physical damage after installation,
- cable abuse during installation,
- poorly made terminations, and
- long-term wetting

The most significant potential aging mechanism for medium-voltage cables is ionization of any air or gas trapped in voids or imperfections in the cable insulation due to the high electrical stresses imposed. This ionization can cause partial discharges to occur in the voids that can lead to deterioration of the insulation and "treeing".

The report noted that failures of medium-voltage cables have been experienced, particularly in underground locations where wetting is possible while the cable is energized but unloaded. This represents the worst case condition for the cable since electrical stresses are present, however, no ohmic heating occurs that would drive moisture out of the insulation. However, the operating experience review found that the majority of failures reported were related to termination problems.

Although it is rare, another type of failure noted in past experience involves overheating of the cable due to ambient temperatures well above the cable design temperature. This has been found to occur due to poor installation practices, such as installing a cable in close proximity to a high temperature feedwater line.

In regard to condition monitoring, the report concluded that useful condition monitoring and troubleshooting techniques were not currently available at the time of the study. Some utilities consider high-voltage testing to be detrimental to the cable and do not use such tests, while other utilities do use them in some cases. Condition monitoring techniques available at the time of this study that are applicable to medium-voltage cables are the following:

- ac or dc high-voltage testing,
- partial discharge testing,
- time-domain reflectometry/spectrometry,
- ground plane enhancement techniques, such as ionized gas, and
- insulation resistance/polarization index
- compressive modulus,
- oxidation induction,

Visual inspection of cables was recognized as a useful technique for providing a qualitative measure of cable condition, particularly in harsh environment areas. In particular, visual inspections are considered very useful for examining cables and leads attached to the following equipment:

- pressurized water reactor primary loop resistance temperature devices that experience significant heating from circulating reactor water,
- motor operators for valves on hot piping systems,
- continuously energized solenoid valves,
- main steam isolation valve limit switches, and
- motors that run for long periods during normal operation

Identification and control of hot-spots in the plant was also recognized as an effective technique to manage the effects of aging on electric cables.

2.4 EPRI Report TR-103834, "Effects of Moisture on the Life of Power Plant Cables," August 1994 [4].

In this EPRI sponsored study, the effects of moisture on medium- and low-voltage electric cables was assessed through interviews with plant personnel and the review of plant-specific operating experience. The plant survey included both fossil and nuclear power plants. For medium-voltage cables it was found that 34 failures have occurred in over 1000 plant-years of operating experience, indicating these components are very reliable. It should be noted that, while some of the fossil plants were over 50 years old, the minimum plant age was 20 years old for approximately 900 of the 1000 plant-years of operating experience reviewed.

Moisture effects, such as water treeing, were one of the failure causes identified, however, installation damage was the primary cause of failure in the 34 events noted, accounting for over half of the failures. Of the 34 failures, 22 of the cables were installed in underground locations. The failure causes identified are the following:

- manufacturing defects, such as voids or inclusions,
- long term wetting,
- shipping, storage and installation damage,
- poorly prepared terminations and splices,
- inadvertent damage to the cable by field equipment, and
- dc high-potential testing

As noted, dc high-potential testing is believed by some utilities to cause damage to the cable that can lead to failure. Of the 24 utilities surveyed, only five performed dc hi-potential testing as a routine maintenance test, and of those five, two planned to discontinue it due to concern with damage to the cables. Testing of medium-voltage cables is typically performed at the factory to demonstrate an acceptable manufacturing process, and after installation for acceptance testing. The plant survey also indicated that little if any in-service condition monitoring was performed on medium-voltage cables on a regular basis at the time of the study. Condition monitoring techniques that are commonly used on medium-voltage cables are the following:

- insulation resistance (acceptance test, in-service test),
- partial discharge (factory test),
- ac or dc hi-potential testing (acceptance test, in-service test, and factory test)

The study concluded that one of the most effective means by which failures of medium-voltage cables can be mitigated is by maintaining drainage of underground conduits in which these cables are installed. Longevity of the cables will be improved by reducing long-term wetting, particularly for cables that are not designed to be impervious to water. Even cables that are designed to be impervious to water would benefit from reduced wetting since they might have damaged jackets or armor that could allow water to reach and/or penetrate the insulation.

3. DESCRIPTION OF POWER CABLES

In this section, a description of power cables is presented including the various subcomponents of a typical power cable and the materials of construction. Common applications, design ratings, manufacturers, operating environments, and aging stressors are also discussed.

3.1 Subcomponents and Materials of Construction

The basic construction of medium-voltage power cables includes a metallic conductor covered with a polymer insulation. Several insulated conductors may be bundled in a multi-conductor cable. Shielding, drain wires, ground wires, and semi-conductor layers are also used in certain power cable designs. A typical medium-voltage power cable construction is shown in Figure 1.

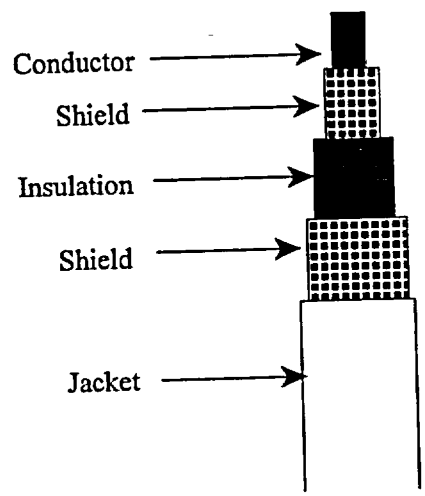


Figure 1: Typical power cable construction

The conductors are typically made of copper, due to its good conductivity, relatively stable thermal properties, and desirable mechanical properties. The copper is sometimes "tinned" to minimize surface oxidation and improve its solderability in making connections. The use of aluminum as a conductor material is also found in some applications and is based mainly on its favorable conductivity-to-weight ratio (the highest of the electrical conductor materials), its ready availability, and the lower cost of the primary metal. However, the 36% difference in thermal coefficients of expansion and the differences in electrical and physical properties demand special consideration in the design of connectors used with aluminum conductors [5]. In particular, when aluminum is exposed to air, an oxide film forms on the surface. This increases electrical resistance and could result in overheating of the connection. Special compounds must be used to remove and mitigate the formation of these films. Also, since aluminum is relatively soft, it is subject to cold flow when under compressive force, such as in a bolted connection. This could result in degradation of the contact in connectors over long periods of time. To mitigate this, spring loaded connectors are usually used with aluminum cables where reliability is a concern.

Sizing of the conductor is based on obtaining the appropriate voltage drop for the circuit, as well as maintaining an operating temperature at the conductor surface that is suitable for the insulating material. As current flows through the conductor, resistance to the flow causes internal ohmic heating of the conductor. As the conductor size increases, the resistance to current flow decreases and, therefore, the less ohmic heating is produced. The ampacity of the conductor is a measure of its current carrying capacity and is used to determine the operating surface temperature of the conductor. The conductor must be sized to the correct ampacity to ensure that the surface temperature does not exceed the maximum operating temperature of the insulation. Ampacities for various power cable sizes and designs are available in standards developed by the Institute of Electrical and Electronics Engineers (IEEE) [7] and the Insulated Cable Engineers Association (ICEA) [8]. For cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) insulating materials, a maximum temperature of 90°C is typically used [6]. Other insulation materials may have a lower maximum operating temperature. Table 1 provides the maximum conductor temperature for various insulating materials. It should be noted that the thermal rating of a cable is not related to the environmental qualification temperature of the cable; they are two distinct temperature values and are not always the same.

Table 1: Maximum conductor temperature for insulating materials [6]

Insulation Material	Maximum Conductor Temperature °C (°F)
Natural Rubber	60 (140)
Polyvinyl Chloride	70 (158)
Polyethylene	70 (158)
Butyl Rubber	85 (185)
Ethylene Propylene Rubber	90 (194)
Cross-linked Polyethylene	90 (194)

Conductor insulating materials are typically polymers, with XLPE and EPR being the most commonly used. For special applications, such as very high temperatures or radiation exposure, other materials may be used. Examples are silicon rubber for very high temperature applications, and polyimides, such as Kapton®, for high radiation exposure. These applications represent a very small percentage of the cable population in a nuclear power plant.

For cables rated at 5 kV or above, shielding is used to increase the uniformity of the voltage stress and contain the electric field within the insulation. This reduces the potential for partial discharges that can damage the insulation. An extruded semi-conducting polymer shield is commonly placed over the outer surface of the conductor, and over the outer surface of the conductor insulation. This minimizes the potential for corona discharge by filling any air gaps. A shield may also be placed around the overall bundle of conductors in a multi-conductor configuration. This outer shielding is typically a copper tape or a semi-conducting tape that is wound around the bundle of insulated conductors.

The outer jacket on a power cable primarily provides protection to the internal components of the cable during installation. As a secondary function, it provides protection from the external environment during service. The jacket is typically constructed of a polymer material, such as Neoprene or chlorosulfonated polyethylene (CSPE).

In some applications where mechanical damage is a concern, a metal shield or armor can be applied to the cable. This armor can be made of aluminum or lead, or it can be a metallic tape that is wrapped around the conductor bundle. This armor provides increased protection from mechanical damage during installation, and from inadvertent damage during its service life, such as from maintenance or repair activities. The armor does not provide an electrical shielding function. In cases where armor is used, the outer jacket of the cable is usually placed over the armor to protect it from corrosion.

3.2 Applications, Design Ratings, and Manufacturers

Medium-voltage power cables are used in both safety-related and non-safety-related applications in nuclear power plants to transmit power between electrical distribution equipment, and to supply power to various electrical loads. Typical loads supplied by medium-voltage power cables are the following:

- Auxiliary transformers
- Medium-voltage buses
- Electrical switchgear
- Medium-voltage load centers
- Large motors
- Motor-generator sets
- Emergency diesel generators

Common voltage ratings for nuclear plant medium-voltage power cables are 5 kV, 8 kV, and 15 kV, however, the actual operating voltages are always lower than the design voltage. For example, a 5 kV cable might be operated at 4.16 kV. an 8 kV cable at 6.9 kV, and a 15 kV cable at 13.8 kV. In some cases, 15 kV cables may be used for 4.16kV applications to provide additional margin against failure, and to improve reliability and increase service life. Typical operating voltages are shown in Table 2.

Table 2: Typical operating voltages for power cables

Cable Voltage Rating	Cable Operating Voltage
5 kV	4.16 kV
8 kV	6.9 kV, 4.16 kV
15 kV	13.8 kV, 6.9 kV, 4.16 kV

There are a number of manufacturers that supply power cable to the industry. While the cable designs are usually similar, and the different manufacturers may produce cables with the same generic type of insulation, it should be noted that the specific formula used to make the insulating material will differ from one manufacturer to another. This can result in significantly different properties and aging behavior for the same generic type of insulating material. Table 3 shows some of the major manufacturers of power cables used in U.S. nuclear power plants [3].

Table 3: Major power cable manufacturers [3]

- American Insulated Wire (AIW)
- Aanconda
- Boston Insulated Wire (BIW)
- Brand Rex
- Cablec
- Eaton
- Ericsson
- General Electric
- ITT Surprenant
- Kerite
- Okonite
- Rockbestos
- Samuel Moore
- Simplex

3.3 Operating Environments and Aging Stressors

Power cables can be installed in various locations in the plant, including underground ducts and conduits, above ground raceways, and cable trays. The installation location will affect the service conditions under which the cables must operate and could impact the aging degradation rate of the cable. Routing in densely filled cable trays, enclosed ducts, or fire-wrapped cable trays, together with other continuous duty power cables, could result in elevated operating temperatures that could increase the rate of degradation for the cable. Cable ducts that run below grade or beneath floor level will normally be susceptible to seepage and water intrusion that can lead to the failure of power cables.

A power cable can be very long with one circuit traversing several different areas of the plant. Therefore, one cable run can be exposed to several different environments. It should be noted that nuclear safety-related medium-voltage power cables are not installed inside the containment of any currently operating commercial nuclear power plant in the United States, therefore, radiation exposure for these cables is typically minimal [3].

Due to the relatively higher voltages and currents at which medium-voltage power cables operate, they are susceptible to aging mechanisms such as internal ohmic heating and corona discharge that are unimportant in low-voltage instrumentation and control (I&C) cables. Exposure to elevated temperatures can also be caused by the location, such as for cables installed in close proximity to high temperature steam lines. Aging due to elevated temperatures will cause the various polymers used to insulate the cables to degrade, resulting in loss of elongation, embrittlement, and eventual cracking over long exposure periods.

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 phenomena 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 2 shows an illustration of a water tree formation in the insulation of a cable.

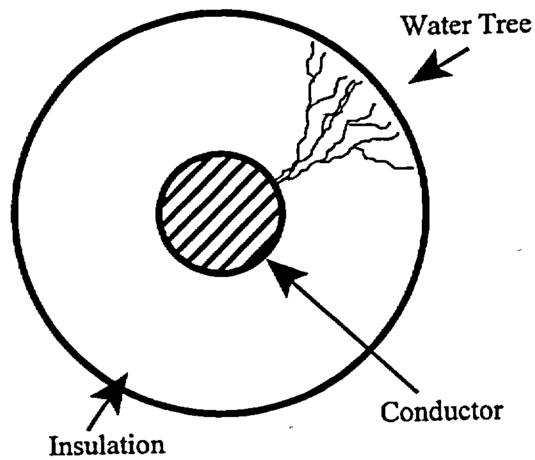


Figure 2: Cable cross section illustrating water tree formation

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 [6]. 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 [9].

In general, aging degradation of the insulating material is of the most concern for medium-voltage power cables. The other subcomponents are also susceptible to aging degradation due to the various stressors to which they are exposed, however, their degradation rate is usually minimal. Table 4 summarizes the potential environmental stressors, degradation mechanisms, and aging effects for medium-voltage power cables.

Table 4: Summary of potential aging mechanisms and aging effects for medium-voltage power cables

Subcomponent	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comment
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 internal ohmic heating and external environment
	• 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	• Partial discharge • Electrical treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	Insulation must contain voids or other imperfections.

Table 4: Summary of potential aging mechanisms and aging effects for medium-voltage power cables (continued)

Subcomponent	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comment
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 to 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 or abuse during maintenance, testing activities	• Mechanical damage including crushing, bending, cutting, abrasion	• Loss of structural integrity • Increased intrusion of moisture and contaminants to cable interior	Only applicable to cables installed in accessible locations.

Table 4: Summary of potential aging mechanisms and aging effects for medium-voltage power cables (continued)

Subcomponent	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comment
Jacket (continued)	• Various polymer materials (e.g., CSPE, Neoprene)	• Vibration	• Mechanical damage including cutting, abrasion	• Loss of structural integrity • Increased intrusion of moisture and contaminants to cable interior	Applicable to portion of cables near terminations at connection to load.
Conductor	• Copper • Aluminum	• Wetting due to moisture intrusion	• Corrosion • Oxide formation	• Increased resistance to current flow • Increased ohmic heating	
	• Copper • Aluminum	• Vibration	• Metal fatigue • Loosening of connectors	• Loss of structural integrity • Degraded connector contact	Applicable to portion of cables near terminations at connection to load.
	• Aluminum	• Compressive forces	• Cold flow • Loosening of connectors	• Loss of contact on connectors • Increased resistance to current flow • Increased ohmic heating	Applicable to aluminum conductors with static mechanical connectors

Table 4: Summary of potential aging mechanisms and aging effects for medium-voltage power cables (continued)

Subcomponent	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comment
Shield	• Copper tape	• Wetting due to moisture intrusion	• Corrosion • Oxide formation	• Loss of structural integrity • Increased insulation degradation due to partial discharges	
	• Semi-conducting polymers	• Elevated temperature • Elevated radiation fields	• Embrittlement • Cracking	• Loss of structural integrity • Increased insulation degradation due to partial discharges	
Sheath	• Lead	• Alkaline environment (e.g., free lime from concrete ducts)	• Corrosion	• Loss of structural integrity • Increased intrusion of moisture and contaminants to cable interior	

4. PAST EVENTS RELATED TO POWER CABLE FAILURES DUE TO AGING

A search was performed of NRC documents, including Generic Communications, Information Notices, Bulletins, Generic Letters and Regulatory Issue Summaries to identify issues and/or significant events related to power cables. Since past studies reviewed documents up to 1994, this search covered the period January 1994 to July 2001.

4.1 Summary of Past Power Cable Events

A total of five events were identified from the review of NRC documents that provide relevant information for this study. They are summarized in the following paragraphs.

4.1.1 Headquarters Daily Report, December 3, 1997

This report notes an event at the Monticello Nuclear Plant on November 25, 1997 in which an electrical fault occurred in a power cable running from the plant to the off-gas storage building. The cable fault resulted in a forced plant outage. No information is provided on the aging mechanism or failure mode of the cable.

4.1.2 SECY 96-043, February 28, 1996, Weekly Information Report - Week Ending February 23, 1996

This report notes an event at the Lasalle Nuclear Plant, Unit 2, in which a control power cable to the main power transformer cooling fans failed causing a manual scram of the plant. The cable failed as a result of water intrusion into the conduit carrying the cable and freezing during the extreme cold weather at the site. The water intrusion was determined to be caused by a missing cap on the conduit from the original construction. This is not considered an aging-related event, however, it does demonstrate the potential plant effects of failed power cables.

4.1.3 Oconee Inspection Report 99-12, September 21, 1999

This report documents the results of an NRC inspection of the Oconee plant to determine whether their aging management programs adequately support their application for license renewal. Based on a sample of electrical cable inspection results and a review of potential problem reports, it was concluded that aging management programs are warranted for electrical cables and connectors. The following are examples of the degradation noted during the inspection:

- cable degradation from thermal and radiation embrittlement,
- mechanical damage from flexing of the cables,
- cables subjected to submergence
- rust on flex conduit and braided metal jacketing of cables, and
- degradation due to chemical stressors

A review of the applicant's problem investigation process database identified 500 events related to cables and connections over a six year period from 12/93 to 6/99. A review of 63 events from this sample found 55% that were age-related events. Specific areas of concern identified are areas in the plant that were found to be conducive to aging effects related to heat, radiation, moisture with boric acid exposure, and submergence. In one instance in 1980, a 4 kV cable to a service water pump failed. It was found to have minor jacket damage and there was water in the buried conduit containing the cable. The failure was attributed to moisture intrusion.

An additional observation noted in this report is that the applicant is using partial discharge testing on underground cables to detect insulation degradation. This is a fairly new technique which uses increasing step voltages applied to the cable conductor while electronically monitoring for indications of insulation weakness. Voltages over 200% of nominal operating voltage were used.

4.1.4 Headquarters Daily Report, December 3, 1999

This report discusses an event at the Davis-Besse Nuclear Plant on October 2, 1999 in which a component cooling water pump tripped due to a phase-to-ground fault on a 3-phase power cable. The failed cable was manufactured by Okonite, and consisted of three twisted AWG #2/0 single conductors with a bare AWG #4 copper ground. The conductor was insulated with ethylene propylene rubber, and had a semi-conductor tape, a tinned copper tape shield, and a neoprene jacket over it. The cable was installed in a 4-inch PVC conduit that runs partially underground. It was in service for 23 years. A failure analysis found severe corrosion of the copper ground conductor and cracking of the neoprene outer jacket. The degradation was attributed to intrusion of ground water into the cable over a period of time. Although the cable is water resistant, it is not water proof, and water had permeated through the EPR insulation.

4.1.5 Preliminary Notification Report PNO-III-98-051, November 2, 1998

This report documents an event at the Prairie Island Nuclear Plant on October 29, 1998 in which a control rod drive power cable suffered an electrical fault. As a result, a control rod dropped causing an automatic reactor trip. This was the third instance in two years at this plant that a control rod dropped due to a faulted power cable. It was decided that all of the control rod drive power cables would be replaced. No information on the aging mechanism or failure mode is provided.

4.2 Evaluation of Past Events

The events identified from a review of NRC documents demonstrate that power cables are susceptible to age degradation that can result in failure. As seen, failure of these power cables can have a significant impact on plant operation, including the loss of function of safety-related equipment or reactor trip. The predominant aging mechanism identified from these events is moisture intrusion, which degrades the dielectric properties of the insulation. It is noteworthy that the number of reported power cable events is relatively small, suggesting that power cable failures are infrequent. This observation is supported by findings in other studies.

5.0 RESULTS OF OPERATING EXPERIENCE REVIEW AND ANALYSIS

To supplement the operating experience review performed in past studies, an updated search and review of more recent operating experience was performed. The Licensee Event Reports (LER), Nuclear Plant Reliability Data System (NPRDS) and Equipment Performance and Information Exchange (EPIX) system databases were searched to obtain operating experience related to power cables. The results are discussed in the following paragraphs.

5.1 Operating Experience from Licensee Event Reports (LERs)

The LER database contains reports from utilities to the NRC regarding events that directly or indirectly impact the safe operation of nuclear power stations. As such, the database does not include equipment failures that have no impact on plant safety. The reporting requirements are specified in 10 CFR 50.73. The events reported cover any and all equipment and systems in the plant that impact safety, and are not necessarily focused on aging degradation or equipment failures. Various field and keyword searches of the database can be performed to focus on a particular category of equipment, however, each LER must be reviewed to determine if a failure occurred and if age degradation was a cause of the failure.

A search of the LER database was performed covering the period from January 1994 to July 2001 to identify events related to aging or failure of electric cables in general. The search criteria were purposely made broad to ensure that no relevant events were omitted. The search generated 93 events, which were reviewed to identify age-related power cable incidents. A total of three events out of the 93 were identified that were relevant for this study. This low number of events suggests that power cable failures are infrequent, which is consistent with results from previous studies. The relevant LERs are discussed in the following paragraphs.

5.1.1 LER 25596002, "Initiation of Technical Specifications Required Shutdown Due to Safeguards Cable Fault - Supplemental Report"

This LER addresses an event at the Palisades Nuclear Power Station in January 1996 in which a medium voltage feeder cable from a safeguards bus developed a phase-to-phase fault. The cable was installed in an underground conduit. The cable failure caused a loss of the safeguards bus, which forced a shutdown of the reactor due to technical specifications requirements. Upon inspection of the failed cables, bare copper was noted on one location of the 'Z' phase, and a 9-inch section of the 'X' phase conductor was exposed all the way around the cable. The damage location was determined to be in a straight section of conduit inside a duct bank. A borescope inspection of the conduit showed carbon buildup near the fault location along with markings indicating the presence of water in the conduit. It was concluded that the cause of the cable failure was localized water and contaminant treeing in the Ethylene Proplyene Rubber (EPR) cable insulation. Localized foreign matter and voids were found to be present in samples of the cable insulation, which acted as initiation points for the treeing. The failed cables had been in service approximately 7 years at the time of failure.

5.1.2 LER 21996009, "Actuation of Engineered Safety Features Caused by a Loss of Power due to a Cable Fault"

This LER addresses an event at the Oyster Creek Nuclear Power Station in October 1996 in which a three-phase underground medium-voltage feeder from the emergency diesel generator to a 4,160 Vac bus developed a ground fault. The unit was shutdown in a refueling outage, however, the cable failure led to a loss of the bus and a subsequent full reactor scram signal. It was determined that the Phase 'C' feeder cable had faulted to ground. The damaged cable was replaced. Similar events occurred at this plant in 1988, 1977 and 1975. No information is provided on the aging mechanism or failure cause for this event.

5.1.3 LER 31598040, "ESF Actuation and Start of Emergency Diesel Generators 1CD and 2CD due to Faulted Underground Cable"

This LER addresses an event at the Cook Nuclear Plant in August 1998 in which a 12 kV underground power cable failed due to age degradation and caused the loss of the station service transformer. The emergency diesel generators started as a result. The cable was rated at 15 kV and was used for power distribution in the switchyard. The cable insulation was polyethylene with a life expectancy of 30 years. Plant experience has found that the polyethylene cable typically lasts approximately 25 years. No information is provided in the report on the aging mechanism or failure cause. A new cable, constructed of tree-retardant cross-linked polyethylene with a moisture resistant jacket, was installed.

5.2 Operating Experience from Nuclear Plant Reliability Data System (NPRDS) Reports

The NPRDS database includes reports of equipment failures provided by participating nuclear power plant utilities. Not all utilities report to the NPRDS database, therefore, it is not a comprehensive source of operating experience representative of the entire nuclear power industry. However, it does provide useful information on the types of failures that have occurred. The reports do not focus specifically on age-related events, however, aging is one of the failure cause categories in the database. A limitation of the database is that there is no standardized procedure for developing a report. Different report writers may interpret the event circumstances differently, thereby introducing a degree of subjectivity into the reports regarding the cause of failure and the component that failed. Therefore, a careful review of each report is necessary to obtain useful information from the database. The NPRDS database contains data from approximately 1982 through December 1996. Starting in 1997 it was replaced by the EPIX system.

A keyword search of the NPRDS database was performed from January 1994 to December 1996 to identify events related to "cable"(s). As with the LER database, broad search criteria were used to ensure that no relevant events were omitted. The search generated 179 events, which were reviewed to identify age-related power cable incidents. A total of three events out of the 179 were identified as being relevant for this study. This low number of events is consistent with the LER results and also suggests that power cable failures are infrequent.

Due to the sparsity of data, a supplemental search of the NPRDS database was performed for power cable events prior to 1994. A field search for "power cables" was used and this yielded an additional five events; three of which were age-related. These events were also reviewed and included in this evaluation.

The relevant NPRDS events are discussed in the following paragraphs.

5.2.1 Nine Mile Point-1, September 1994

In September 1994 it was found that the drive motor for one of the reactor recirculation pump motor-generator sets had a low resistance to ground. The cause was determined to be degradation of the insulation on one of the generator output leads. This was determined to be due to the high load currents over 25 years of operation causing the Vulkene I insulation to deteriorate. The generator leads were replaced. Since the pump was out of service for maintenance, there was no significant effect on plant performance.

5.2.2 Nine Mile Point-1, November 1994

In November 1994 it was found that the drive motor for one of the reactor recirculation pump motor-generator sets had a low resistance to ground. The cause was determined to be degradation of the insulation on one of the motor leads. This was due to the high load currents over 25 years of operation causing the Vulkene I insulation to deteriorate. The motor leads were replaced. Since the pump was out of service for maintenance, there was no significant effect on plant performance.

5.2.3 River Bend-1, July 1995

In July 1995 a ground fault occurred on a component cooling water pump motor causing failure of the pump. Redundant pumps were available, therefore, plant operation was not affected. The ground fault was determined to be caused by degradation of the insulation on the pump motor power leads. Pump vibration caused abnormal wear and chafing of the motor lead insulation in the motor-mounted junction box, resulting in a short circuit to ground and burnout of the motor windings. The failed motor was replaced and a modified junction box was installed to prevent future cable damage. No information is provided on the cable type or insulation material.

5.2.4 North Anna-1, September 1988

In September 1988 a ground fault occurred on a transfer bus resulting in a loss of redundancy for the AC power supply. The ground fault was determined to be caused by a faulted cable from a reserve station transformer. The cable had worn through the outer jacket to the shield in a section of the cable, resulting in the ground. The main conductor was not exposed. The cause of the failure was attributed to aging and chafing of the cable jacket due to wind moving the cable against a bushing. The cable was repaired and returned to service. The 4,160V power cable was manufactured by Boston Insulated Wire, and was constructed of silicon rubber insulation with a polyethylene jacket. It had been in service approximately 10 years at the time of failure.

5.2.5 Oyster Creek-1, July 1988

In July 1988 a substation transformer primary feed cable failed. The protective relay opened the main breaker, thus, AC power was lost. The plant was shutdown, therefore, no significant effect on plant operation occurred. Examination of the failed cable found pinhole indications, which were attributed to age. The 5kV power cable was manufactured by General Electric and was constructed of EPR insulation and jacket. It had been in service approximately 19 years at the time of failure.

5.2.6 Oyster Creek-1, March 1977

In March 1977 a ground fault occurred in one of the leads between an electrical bus and the diesel generator circuit breaker. This caused a trip of the breaker and a loss of the bus. A power reduction was necessary as a result of this event. It was determined that the cable faulted to ground due to age-related degradation of the cable insulation. The 4,160V power cable was manufactured by General Electric, and was constructed of cross-linked polyethylene insulation with a polyethylene jacket. It had been in service approximately 8 years at the time of failure.

5.3 Operating Experience from Equipment Performance and Information Exchange (EPIX) System Reports

The EPIX system replaced the NPRDS system starting in January 1997 and contains similar information. As for the NRPDS, not all utilities report to the EPIX database, however, it does contain useful information from a cross section of nuclear power plants.

The EPIX database was searched to identify age-related power cable events. The search included all component types in the database and all records from January 1997 to August 2001. The search was focused on the piece parts "cable," "cable connector," "connector," "insulation," and "power cable" to capture all potentially relevant events. The search identified a total of 27 events that met the search criteria. Each of these events was reviewed, and only three dealt with failures of power cables. Each of the events is discussed below.

5.3.1 Farley-1, November 1998

This report addresses an event at the Farley Nuclear Power Station in November 1998 in which the electric cable motor leads on a control rod drive mechanism cooling fan were found to be degraded during an outage. The degradation was determined to be due to repeated determination/retermination of the leads over the life of the motor. As an interim corrective action, the damaged leads were taped and an attempt was made to start the motor, however, the motor caught fire. The damaged leads should have been properly repaired or replaced. No information is included in this report to determine the type of cable used for the motor leads or their age. The plant was in a refueling outage at the time of this event, therefore, there was no significant effect on plant operation.

5.3.2 Prairie Island-1, June 1998

This report addresses an event at the Prairie Island Nuclear Power Station in June 1998 in which the field leads for several control rod drive gripper coils were found to be degraded with one cable having a short to ground. The failed cable resulted in a reactor trip from full power. The cables used Tefzel-insulated conductors with a Mylar wrap and a Hypalon outer jacket. The Hypalon jacket on several cables was found to be brittle and covered with a whitish dust. These cables are located underneath the reactor core, and those cables near the center of the core were found to be the most degraded. This area experiences the highest temperatures and radiation. A contributing cause of failure is believed to be moisture intrusion into the cables, possibly through the connectors at the cable ends, which caused several of the cables to short to ground. These cables were to be replaced.

5.3.3 Prairie Island-1, November 1998

This report is similar to the previous one and addresses an event at the Prairie Island Nuclear Power Station in November 1998 in which the field leads for a control rod drive gripper coil failed. The failed cable resulted in a reactor trip from full power. The failed cable used Tefzel-insulated conductors with a Mylar wrap and a Hypalon outer jacket. All similar cables were replaced with cables of a higher temperature rating as a result of this event.

5.4 Analysis of Operating Experience

To provide a quantitative evaluation of power cable aging events, the past operating data were analyzed to identify the predominant aging characteristics. Due to the paucity of data, all events from the LER, NPRDS, and EPIX databases were combined for this analysis.

A review of the events shows that, in all cases, the power cable subcomponent that failed was the insulation. This is consistent with other studies, which identify insulation as the subcomponent of most concern from an aging standpoint.

Several aging mechanisms were identified from the data, including water treeing, chafing of the insulation, and embrittlement. In many cases, insufficient information was available to determine the specific aging mechanism, and the failure was attributed to general "aging degradation." The distribution of aging mechanisms is shown in Figure 3.

Similarly, the aging stressors resulting in failure were identified from the past operating experience. These include elevated temperature, moisture, and vibration/cyclic movement of the cable. The distribution of stressors is shown in Figure 4.

The failure mode most commonly found from the data was "ground fault," in which the cable faulted to ground from one or more of its conductors. Other less frequent failure modes were phase-to-phase fault, in which the cable faulted from one conductor to another conductor, or "low resistance," which indicates that the dielectric properties of the insulation had degraded to an unacceptable level. The distribution of failure modes is shown in Figure 5.

An important aspect of any component failure is the effect it has on plant operation. The more severe the effect on plant operation, the more important it is to ensure that failures of that component are mitigated to the greatest extent possible. For power cables, the failures identified in past operating experience show that several events resulted in significant effects on plant operation, including tripping of the reactor and challenges to engineered safety features. Other effects include a loss of redundancy for a specific system, and reduced power operation. When power cable failures occur during plant shutdown there is typically no significant effect on plant operation reported. The distribution of failure effects for power cables events reviewed herein is shown in Figure 6.

Table 5 summarizes the events identified from the operating experience review.

Table 5: Summary of age related power cable events identified from past operating experience

Event	Subcomponent Failed	Aging Mechanism	Failure Mode	Plant Effect
LER 25596002	Insulation	Water Treeing	Phase-to-phase fault	Reactor shutdown
LER 21996009	Insulation	NA	Ground fault	ESF actuation reactor trip signal
LER 31598040	Insulation	Age degradation	Ground fault	ESF actuation
NPRDS Event at Nine Mile Point-1 (September 1994)	Insulation on recirc. pump motor-generator output leads	Age degradation due to high load currents	Low resistance to ground found during maintenance	No significant effect
NPRDS Event at Nine Mile Point-1 (November 1994)	Insulation on recirc. pump motor leads	Age degradation due to high load currents	Low resistance to ground found during maintenance	No significant effect
NPRDS Event at River Bend-1 (July 1995)	Insulation on component cooling water pump leads	Chafing of the insulation due to vibration	Ground fault	No significant effect
NPRDS Event at North Anna-1 (September 1988)	Insulation on underground feeder cable	Chafing of the insulation due to wind movement of the cable	Ground fault	Loss of redundancy
NPRDS Event at Oyster Creek (July 1988)	Insulation on substation transformer feeder cable	Age degradation resulting in pin holes	Ground fault	No significant effect
NPRDS Event at Oyster Creek (March 1977)	Insulation on feeder cable from diesel circuit breaker to electrical bus	Age degradation	Ground fault	Reduced power level

Table 5: Summary of age-related power cable events identified from past operating experience (continued)

Event	Subcomponent Failed	Aging Mechanism	Failure Mode	Plant Effect
EPIX Event No. 235 at Farley-1	Insulation on control rod drive cooling fan motor leads	Age degradation due to repeated determination and retermination	Ground fault	No significant effect
EPIX Event No. 42 at Prairie Island-1	Insulation on field leads for control rod drive gripper coils	Degradation due to moisture intrusion; Embrittlement due to high temperature and radiation conditions	Ground fault	Reactor trip
EPIX Event No. 72 at Prairie Island-1	Insulation on field leads for control rod drive gripper coils	Degradation due to moisture intrusion; Embrittlement due to high temperature and radiation conditions	Ground fault	Reactor trip

Notes: LER data cover the period 1994 - 2001
NPRDS data cover the period 1975 - 1996
EPIX data cover the period 1997 - 2001

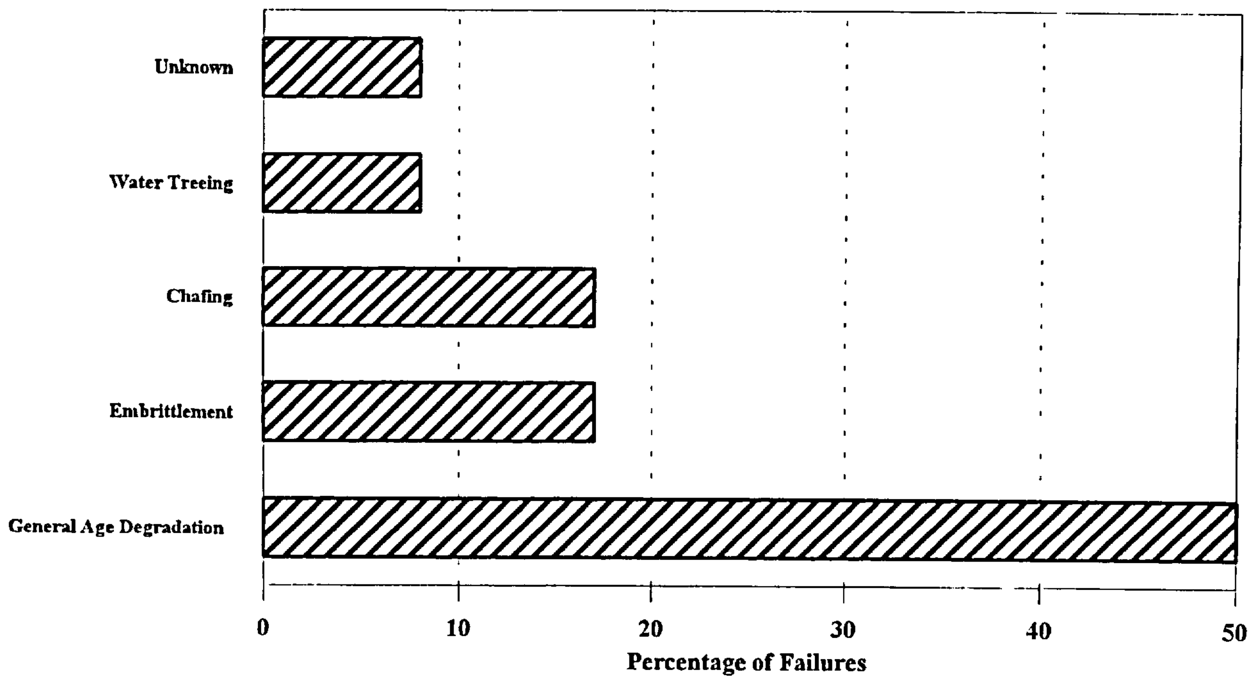


Figure 3: Distribution of power cable aging mechanisms

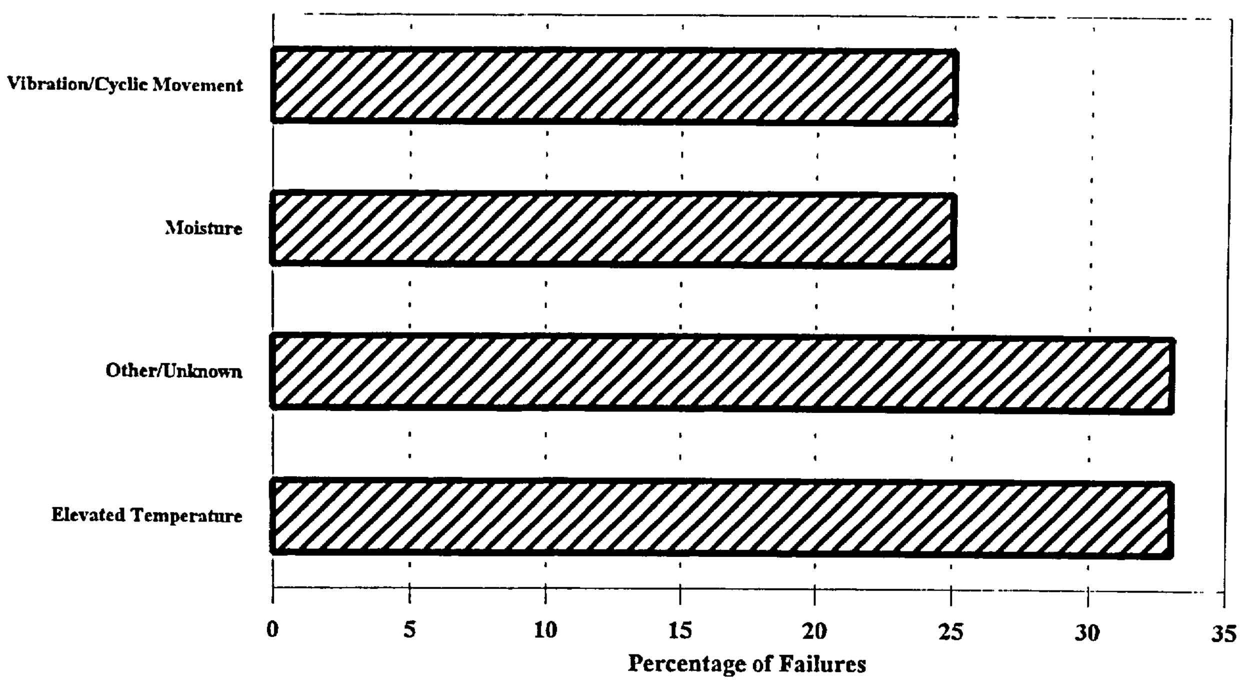


Figure 4: Distribution of power cable aging stressors causing failure

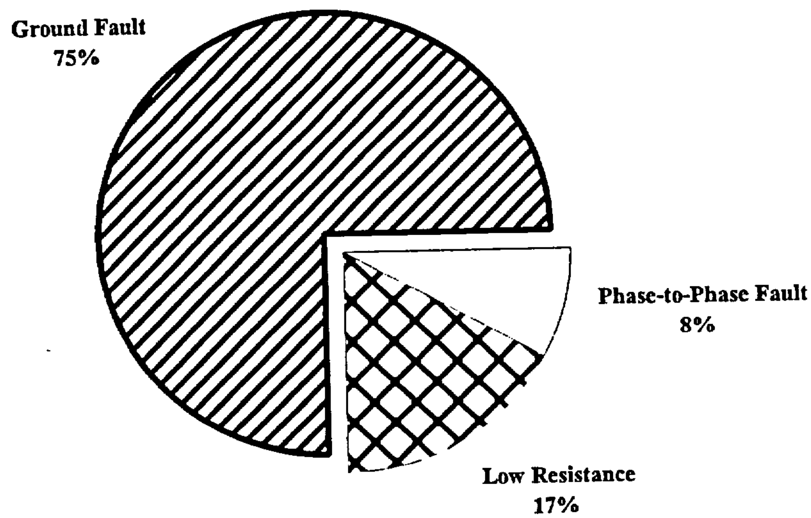


Figure 5: Power cable failure modes

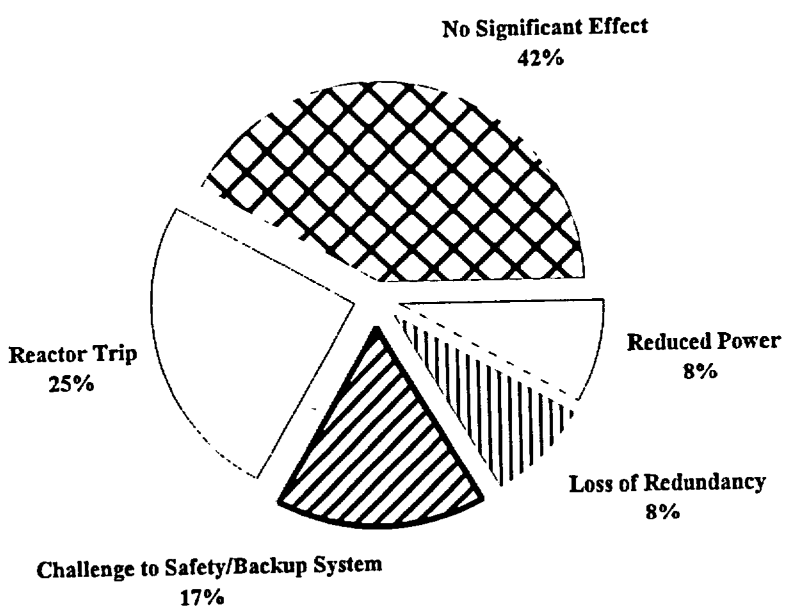


Figure 6: Effect of power cable failures on plant performance

6. REVIEW OF CONDITION MONITORING TECHNIQUES

Condition monitoring of an electric cable involves the observation, measurement, or trending of one or more indicators, which can be correlated to the condition or functional performance of the cable, with respect to an independent parameter, such as time or cycles. In a research program sponsored by the NRC [10], attributes of an ideal CM technique were identified as the following:

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

CM measurements are intended to provide information that can be used to determine the current ability of a cable to perform within specified acceptance criteria, as well as to make predictions about its future performance and accident survivability. To predict future performance, it is most important 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.

Various research programs have evaluated CM techniques to determine their effectiveness for monitoring the condition of electric cables. In the current study, a review and evaluation of promising condition monitoring techniques was performed to determine their effectiveness for in situ use on medium-voltage power cables. This evaluation was performed based on available information and test data from past work. No new testing was performed.

In this evaluation, several condition monitoring techniques judged to be promising for medium-voltage power cables are described in terms of the theory behind it and how it was performed. Information is also provided on any special equipment required to perform the technique. The technical basis for judging it to be promising is also discussed. The techniques are categorized as mechanical, electrical, or chemical based on the cable property measured.

6.1 Mechanical CM Techniques

In this category, CM techniques that measure a mechanical property of the cable insulating system are discussed. The theory for these techniques is that, as a cable ages, there will be a measurable change in the mechanical property of the insulation. By measuring and trending this change, and correlating it with a known measure of cable performance, the condition of the cable may be determined.

6.1.1 Visual Inspection

Visual inspection of cables provides a qualitative assessment of the cable condition. It is an in situ test that is inexpensive and relatively easy to perform, and can provide useful information for determining cable condition. In a research program sponsored by the NRC [10] visual inspection was evaluated in terms of its effectiveness for in situ monitoring of electric cables. For this evaluation, visual inspections of various test specimens were performed prior to testing (baseline), as well as periodically throughout pre-aging and LOCA simulation processes. The results obtained throughout the research program were compared to those obtained from the baseline visual inspection to determine if visible changes in the cable can be correlated to degradation occurring as a result of aging.

The visual inspections were performed in a standardized, detailed manner in accordance with test procedures. The only pieces of equipment used were a flashlight, magnifying glass and a tape measure. Cable attributes that were inspected visually 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 was qualitatively determined by squeezing and gently flexing it.

Visual inspection was found to be a very effective technique for providing a qualitative assessment of a cable's condition. While no quantitative data is obtained, the results can be used to provide an assessment of how fast a cable is degrading under the operating conditions to which it is exposed. This technique can be used to evaluate the general condition of a cable and to determine if more extensive testing is required to further characterize its condition. In most cases, cables that appeared to be in good physical condition through visual inspection showed acceptable electrical performance under accident conditions.

The major advantage of the visual inspection is that it is easy to perform and it does not require any expensive test equipment. A standardized procedure should be developed to ensure that a consistent inspection approach is used and that all of the important cable attributes are inspected. The level of experience of the inspector is also an important factor in determining the success of a visual inspection. In medium- and high-voltage cables, indications such as surface tracking, deposits, or burn marks may indicate insulation degradation or periodic exposure to water.

The most serious limitation of this technique is that the cable to be inspected must be accessible and visible. In some cases, cables may be installed in closed conduits or buried beneath other cables in a cable tray. In these cases, visual inspection would not be directly useful. Also, even for visually accessible cables, usually only the jacket can be seen. Therefore, inspection of the insulation would probably not be possible. However, visual inspection of representative cables that are accessible could be used to provide an indirect measure of the condition of the inaccessible cables. Also, in those cases where the cable insulation is not directly accessible, visual inspections can still be useful to determine if the cable is being subjected to unanticipated environmental conditions, such as submergence due to water intrusion for cables installed in underground conduits. If such conditions are identified, corrective actions can be taken before degradation of the cable occurs.

Visual inspection may also be used to examine the condition of cable insulation of previously identified "hot spot" locations in the plant. Cables passing in the vicinity of these known high temperature, high radiation, or other extreme environmental stressors, are subject to higher rates of degradation than in other parts of the plant. Visual inspection of cables in "hot spots" during plant shutdowns can guide plant maintenance personnel in decisions regarding further CM testing, repair, or replacement of affected cables.

In spite of its disadvantages, visual inspection should be considered a fundamental part of any cable condition monitoring program. While it does not provide quantitative data, it does provide useful information on the condition of the cable that is easy and inexpensive to obtain, and that can be used to determine if further investigation of the cable condition is warranted.

6.1.2 Compressive Modulus (Indenter)

Compressive modulus is a material property defined as the ratio of compressive stress to compressive strain below the proportional limit. As cable insulation and jacket materials age they tend to harden, which will cause the compressive modulus of the materials to increase. By monitoring this change in compressive modulus, an estimate of the degradation rate of the material can be made.

To monitor changes in the compressive modulus, the Ogden Indenter Polymer Aging Monitor (Indenter) was used in a low-voltage electric cable research program sponsored by the NRC [10]. This device presses a probe into the material being tested 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 controlled by a portable computer and appropriate software, which controls the travel of the probe to prevent damage to the cable.

In the low-voltage electric cable research program [10], indenter measurements for both cable jacket and conductor insulation materials were performed during the initial baseline testing, and at pre-determined CM hold points. Measurements were obtained at four different angles (0°, 90°, 180°, and 270°) circumferentially to account for the differences in the readings taken directly above a conductor, as opposed to readings taken above the space between conductors. The additional measurements also account for any variations in the materials. Each of the individual modulus measurements at the different angles were arithmetically averaged to obtain the mean compressive modulus for each cable specimen. For the insulation measurements, a minimum of three locations were tested for each conductor, and the results were averaged to obtain the mean compressive modulus for each color of insulation.

In Figure 7, compressive modulus results for XLPE insulating material are shown as a function of accelerated aging to simulate 20, 40 and 60 years of service life [10]. As aging increases, the modulus shows a corresponding increase. These results suggest that indenter measurements are suitable for monitoring aging degradation of this material. Similar results were obtained for EPR insulating material.

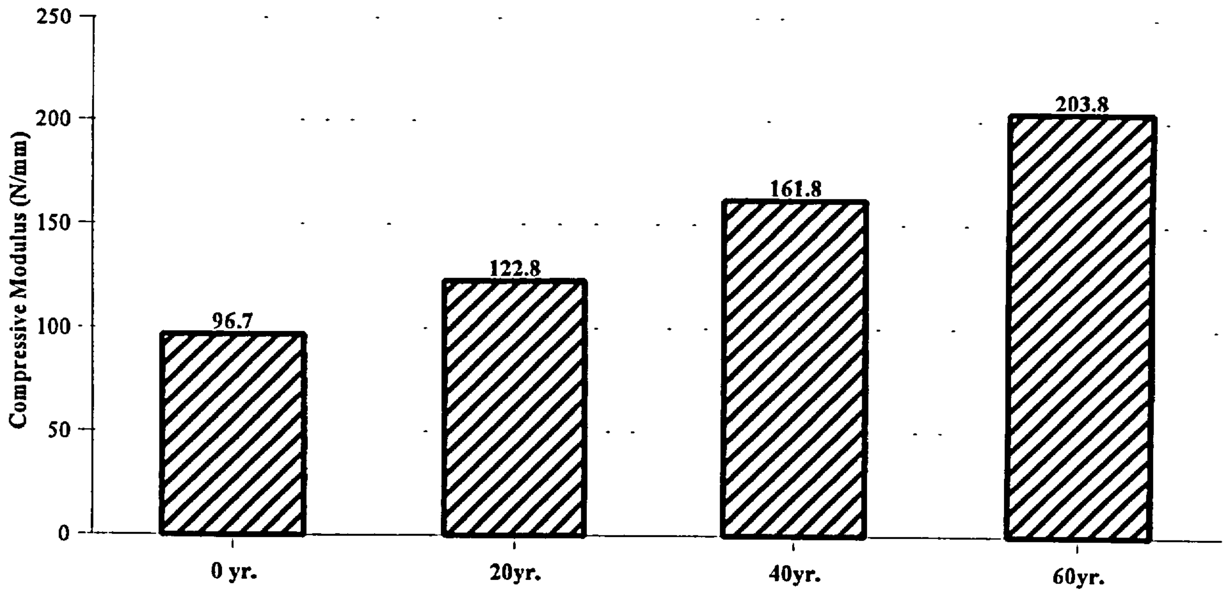


Figure 7: Average compressive modulus for XLPE insulation from Rockbestos specimens pre-aged to simulate 0, 20, 40 and 60 years of service life [10]

20 yrs = 648.5 hrs @ 302°F + 26.1 Mrad
40 yrs = 1,301.2 hrs @ 302°F + 51.5 Mrad
60 yrs = 1,363.8 hrs @ 302°F + 77.0 Mrad

The indenter was found to be easy to operate and capable of producing repeatable results. It can be operated by one person in the laboratory, though in situ testing in a nuclear power plant would require two persons. Over the course of the six test sequences, the indenter was used to obtain over 15,000 data points on over 100 cable specimens [10]. Over this period, only one operational problem was noted, resulting in the replacement of the electric motor. This failure was easily identified by widely-varying modulus results and did not affect any of the data.

In many instances, cables are not easily accessible in nuclear plants. Often they may be stacked in cable trays or run through conduits, which severely limits access to perform CM testing. For cables which are accessible, the indenter can be used to determine the modulus of the outer jackets. For those cables that are not accessible, it is neither desirable nor possible, in some instances, to excessively handle the cables to permit indenter testing. To monitor the modulus of individual jackets or insulation, access would be needed at a termination point. This is not the optimum situation, since the termination points may be physically located in a different plant location and exposed to very different ambient conditions than the remainder of the cable. For cables operating at medium to high voltages, the cables to be tested should be de-energized prior to in situ testing with the indenter. This highlights the potential benefit of using test coupons, which could be strategically located throughout the plant and used for CM. However, in the absence of test specimens, there may be no alternative, and CM must be performed where cables are physically accessible.

The indenter was found to be a non-destructive test which did not affect the continued operation of the cable. The indenter software prevented the probe from penetrating the material being tested, from leaving residual marks, or from causing any other type of damage. It is suitable for use on various materials (XLPE, EPR, Hypalon® and Neoprene®). However, not every material produced significant age-induced changes that could easily be correlated with thermal or radiation exposure. For low levels of aging, relatively small modulus changes were seen, which, in the absence of baseline measurements, might be difficult to correlate with aging. Cable construction and manufacturer were also found to produce different modulus results for the same aging. The results obtained were found to correlate well with EAB measurements, which is an indication of this technique's usefulness. It can also provide an alternative to EAB, which by its nature requires specially prepared samples and is a destructive test.

From the results of the low-voltage cable testing program, it was determined that the indenter is an effective mechanical monitoring technique, which can be used in situ or in the laboratory. The changes in a polymer's compressive modulus reflect the condition of the material, and can be an important indicator of remaining life. Dramatic increases in modulus are indications of extreme exposure to temperature and radiation, which can be used to determine replacement schedules for the whole, or individual sections of the cable.

6.1.3 Infrared (IR) Thermography

The use of infrared thermography for non-destructive, non-contact inspection of electrical equipment has grown considerably since the 1980's. The theory of infrared thermography is simple; by using a thermal detection or imaging system, it is possible to detect, measure, and/or display the infrared, or heat radiation emitted by an object that is invisible to the unaided human eye. 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.

There are two generic choices available for electrical inspection equipment: spot meters and imagers. Both are capable of accurately measuring infrared radiation emitted from a thermally hot electric cable, electrical connection, cable splice or termination, circuit breaker, transformer, fuse or other electrical equipment. The spot meter converts the infrared radiation measured by the instrument into a numeric value or radiometric temperature. Obtaining a reading simply requires aiming the spot meter at the spot to be monitored, typically aided by a laser guided pointing device. If the spot is within the measurement resolution and corrected for emissivity, accurate temperature data can be obtained. Infrared spot meters are inexpensive but they require some skill, knowledge, and experience by the operator in order to assure that accurate, repeatable, and usable data are obtained.

Imagers convert the infrared radiation data into a visual image or thermogram. These devices can portray hot spots when temperature differences are as small as one tenth of a degree F, if emissivities are high. Focal plane array, or FPA imagers can provide an image quality of up to 320 lines by 244 picture elements (pixels) per line. Each pixel is capable of providing a thermal image as well as a temperature at a high resolution that enables the user to clearly resolve smaller temperature differentials. Some of the higher scale devices are calibrated so that radiometric temperatures can be made directly in the image. The imaging instruments are teamed with internal microprocessors and large capacity storage devices, such as PCMCIA memory cards, that enable them to store the data digitally, preserving temperature accuracy, when importing the data to a personal computer. Thermal imaging software on the personal computer provides the user with a full menu of image manipulation, analysis, and display options. Features include multiple color palates, multiple isotherms, and the ability to change display temperature limits. Values for emittance, atmospheric attenuation, and background radiation can also be input into some software programs to provide greater accuracy for observed temperatures. Image subtraction features allow one image to be automatically subtracted from another "normal" reference image to provide a difference between the two. Trending options allow several images to be automatically analyzed over a period of time and the associated temperature data to be graphed. References 11 and 22 provide additional information on IR thermography.

Figure 8 depicts a typical infrared imaging thermogram of the three phases of a cable connection to a piece of electrical equipment [11]. The color scale at the left of the thermogram defines the temperatures represented by the colors in the image of the cables while operating at full load. The right-hand cable in the pair of conductors in the phase 'A' connection (left side of the image) shows evidence of overheating due to a poor connection as compared to the other normal phase connections shown in the image. The overheating may be caused by loose lugs, a loose crimp connection, or corrosion at the electrical contact surfaces.

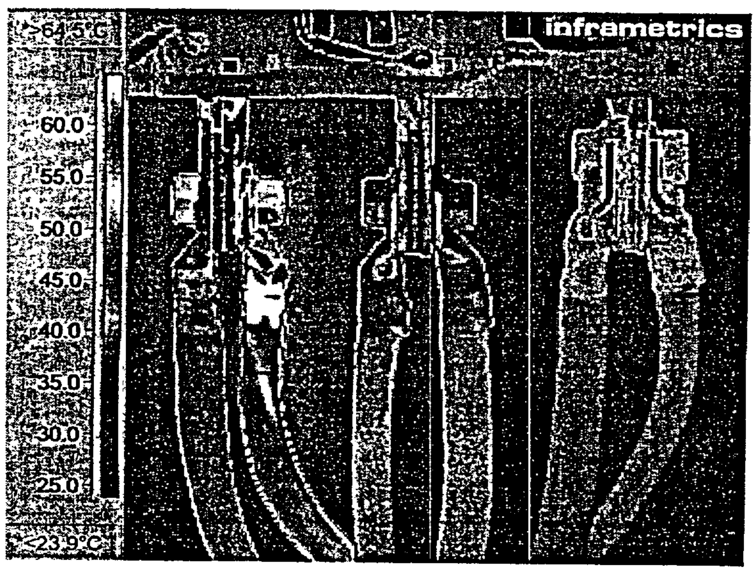


Figure 8: Infrared thermogram showing cable lug overheating due to poor connection [11]

Infrared imaging is considered a powerful tool for the condition monitoring of electric cable systems. The high resolution temperature detection capabilities of the instruments combined with image storage and analysis software make it possible to provide accurate trendable data. While the newer FPA imagers have become more sophisticated, they have become smaller, less expensive, and more user friendly. Special training, knowledge, and experience are required for successful use and analysis of data.

6.2 Electrical CM Techniques

Electrical testing of cables can provide a direct measure of an electrical circuit's performance. These tests are typically performed by attaching the test equipment to one end of a cable, which eliminates the access problem faced by other test methods. There are two categories of electrical tests that can be performed: 1) destructive tests, which can be used to find and repair potential failure sites before placing a circuit in service, and 2) non-destructive tests, which can be used to provide an indication of the level of degradation of a circuit. For purposes of this evaluation, only non-destructive electrical tests are considered since they are the only ones that would be appropriate for in situ testing in nuclear power stations.

Within the non-destructive category, electrical tests can be further divided into direct current (dc) tests and alternating current (ac) tests. Each has advantages and disadvantages, and there is no general agreement on which is best. While dc tests are typically the most simple to perform, due to the relatively small and inexpensive test equipment required, they may not be appropriate for all power cable applications. The dc tests do not produce the same electrical stress for cables used in ac applications, therefore, they may not detect defects caused by ac service conditions. Also, past tests on cables with extruded insulation found that dc tests that cause flash over can cause the cables to fail prematurely when returned to service due to the relatively high voltages required [12, 13]. Guidance for performing dc tests on power cables is provided in IEEE Standard 400-1991 [14] and IEEE Standard 4-1978 [15].

The use of ac tests is considered by some to be more suitable for power cables in ac applications since the stress applied to the insulation is similar to that experienced under service conditions. In the past, the use of ac tests was difficult due to the relatively large, expensive test equipment required to obtain the test voltages required. This limitation has largely been mitigated with the use of resonant test sets. Guidance on performing ac tests on power cables is provided in IEEE Standard 62-1978 [16] and IEEE Standard 4-1978 [15].

The following paragraphs describe both dc and ac tests that can be used to evaluate the condition of medium-voltage power cables in situ.

6.2.1 DC High Voltage Test

Cable insulation can, without damage, sustain application of dc potential equal to the system basic impulse insulation level for very long periods. In contrast, the application of ac over potential will result in degradation of most insulating materials. Therefore, high dc potential is normally used for repetitive field testing of cable insulation. The voltage levels used for such testing must be high enough to indicate incipient failure of weakened insulation that may fail in service, but not so high as to damage sound insulation [17].

The methods and procedures to be used for making high voltage measurements in situ are presented in detail in IEEE Std. 400-1991, "IEEE Guide for Making High-Direct-Voltage Tests on Power Cable Systems in the Field" [14]. Generally, the cable systems to be tested should be disconnected from equipment and clear from ground. Conductors that are not being tested should be electrically grounded. By disconnecting the cable system from all other electrical equipment, the leakage current measured during the test is that from the cable and splices. Leakage current should be monitored and recorded during the application of test voltage and watched for rapid changes that could signal approaching insulation failure [17]. The test voltage may be raised continuously up to the maximum test voltage, or it may be raised in steps, pausing for a minute or more at each level to allow the capacitive current and the dielectric absorption current to subside.

The advantage of step testing is that the one minute pause at each level allows a stabilized current to be recorded that reflects the leakage current for the cable system at that voltage level. If large changes in leakage current are noted at any step it may indicate that the insulation may be approaching failure and the test could be stopped to avoid damage to the cable. If a cable cannot withstand the prescribed test voltage for the designated test period, typically 5 minutes, without an increase in leakage current the cable is considered to have failed the test [17].

For low- and medium-voltage cable systems a megohmmeter may be used to directly measure the insulation resistance. This condition monitoring method was evaluated as part of the low-voltage cable research program sponsored by the NRC [10]. When a dc voltage is applied to a test cable, the total current flowing in the insulation from the conductor to ground is equal to the sum of the capacitive charging current, the dielectric absorption current, and leakage current. These three components of the total current will 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. Once the insulation, which behaves like a capacitor, is energized and charges have aligned across the insulation, these currents will taper off and eventually approach zero. On the other hand, leakage current will start at zero and increase to a steady value in less than a minute. Leakage current will remain steady after this time in good insulation. If the insulation is badly deteriorated, wet, or contaminated, the leakage current will be greater than that found in good insulation and it will 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 applied and taper off in different ways over the next several minutes depending on the condition of the insulation. In good insulation the insulation resistance will gradually increase after the test voltage is applied. Because of this behavior, insulation resistance measurements are taken using a megohm meter first at one minute and again at ten minutes. The ratio of the insulation resistance at ten minutes to the value measured at one minute is called the polarization index.

An important factor that must be considered when making these measurements is that insulation resistance is very sensitive to temperature. It is common practice to correct the readings to a single temperature, such as 15.56°C (60°F) for electric cables, in order to compare measurements taken at different times and to trend the data over an extended period. Another advantage of using the polarization index is that it is not temperature dependent since the temperature correction factor drops out of the calculation.

Insulation resistance is also affected by the length of the electric cable that is being tested. Therefore, the insulation resistance values should be normalized to a standard length to facilitate comparison after temperature correction of the values.

Humidity and the combination of dielectric materials used in the cable insulation can affect insulation resistance measurements. The specimens in the NRC program were stored at controlled temperature and humidity prior to use, and always maintained above the dew point temperature until the time of the actual LOCA simulation exposure. Extreme drying also occurred during the thermal aging process, essentially eliminating any absorbed moisture within the cable materials. With the exception of the initial baseline measurement for some of the EPR-insulated cables, the effect of humidity or absorbed moisture was negligible for these cable materials under the conditions at which the measurements were made, therefore, correction for humidity was not applied.

For the NRC test program, a megohmmeter with the capability of measuring insulation resistance values up to 200 teraohms ($200 \times 10^{12}\ \Omega$) was used to measure and track insulation resistance in the ranges required for these cable specimens. The General Radio Model 1864 Megohmmeter was used to make these measurements in accordance with an approved BNL test procedure. The applied test voltage used for the test program was 500 Vdc.

The advantages of the insulation resistance test are that it is relatively easy to perform and requires inexpensive test equipment. The data showed that corrected insulation resistance decreases in a predictable manner as the insulation ages, and trending of this parameter could be useful as a condition monitoring technique for electric power cables.

6.2.2 Partial Discharge Measurement

Measurement of partial discharge is an ac electrical test that has shown potential for use as a condition monitoring technique on medium-voltage cables. If a sufficiently high voltage stress (the inception voltage) is applied across a cable's insulation, an electrical discharge (also known as partial discharge or corona) can occur in small voids within the insulation, or in air gaps between insulation and a ground plane, such as a shield in the cable. These discharges can cause degradation of the insulation over a period of time due to localized overheating leading to eventual breakdown of the insulation.

Partial discharges, which indicate potential degradation sites, 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 [19].

In research performed by the National Institute of Standards and Technology (NIST) [21], partial discharge measurements were made on intentionally damaged low-voltage (600V) cables constructed of common insulating materials. The inception voltage of the cable was 4,500 volts and measurements were made at 10%, 20%, and 40% above the inception voltage. Figure 9 shows results for measurements at 6,000 volts, which demonstrate that each of the defect locations was detected using the partial discharge measurements.

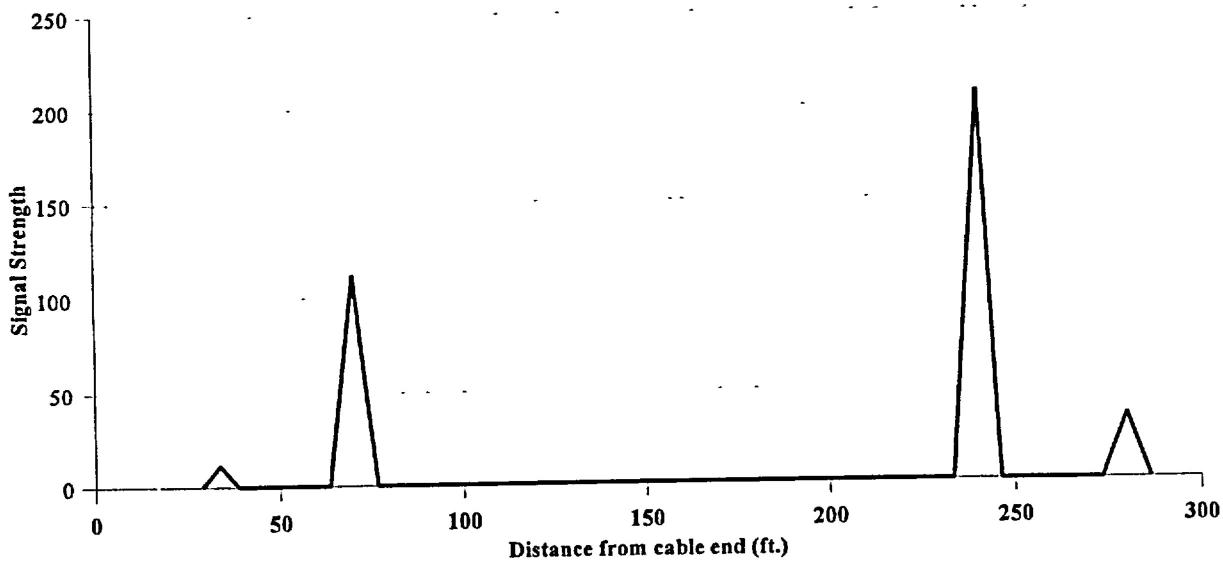


Figure 9: Partial discharge signals at 6,000 volts indicating the location of cable defect sites

This test is commonly used by cable manufacturers to detect defects in cables. However, it has limitations for use in the field since it requires relatively high voltages to be applied to the cable. This would be a concern for in situ testing 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. Techniques for reducing noise interference include the use of independent test voltage sources, power line and high voltage filters, shielding, and the use of bridge detection circuits [18].

6.2.3 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is a condition monitoring technique that is often used in nuclear power stations to periodically assess the condition of instrumentation, control, and power cables that are located in areas of the plant that are normally inaccessible, such as in high temperature and high radiation zones. The TDR works on the same principle as radar. A non-destructive pulse of energy is transmitted down a cable from one end. When that pulse reaches the far end of the cable, a fault along the cable, or some other problem that causes a change in the electrical impedance of the cable, part or all of that pulse energy is reflected back to the source where the instrument is located. The TDR measures the time it takes for the signal to travel down the cable to where the impedance change is located, and return back. The TDR then converts this time of propagation to a distance, and depending on the type of display used, can present this information as a waveform and/or a distance reading.

The simplest form of TDR will display the distance to a fault or the first major change in the cable impedance. More useful information is provided by a TDR that displays the actual waveform or "signature" of the cable on a CRT or LCD. This type of display can show the outgoing pulse transmitted down the cable from the instrument and any reflections that come back to the TDR that are caused by discontinuities or impedance variations along the length of the cable. The magnitude of the impedance change will determine the amplitude of the reflected pulse. The latter method has been used by BNL to verify the integrity of cables in its test programs and to monitor insulation degradation during experiments involving naturally aged cables and cables that have been subjected to accelerated artificial aging.

A simplified representation of TDR reflectograms are shown in Figure 10. In the upper reflectogram, an incident pulse is transmitted from one end of a cable whose far end has also been disconnected. A partial open circuit condition along the length of the cable is detected as an attenuated positive pulse at cursor 2. The magnitude of the reflection correlates to the severity of the discontinuity which caused it. The distance from the TDR to the location of the discontinuity is determined from the abscissa which may be calibrated to true distance depending upon the characteristic propagation velocity and configuration of that cable type. In the lower reflectogram, a partial short circuit condition exists as indicated by the attenuated negative pulse at cursor 2; the distance from the TDR to the location of the discontinuity is again determined from its location along the abscissa on the reflectogram.

Any time two or more metallic conductors are run in close proximity, either in the same multiconductor cable or in the same tray, conduit, or raceway, that cable will present an electrical impedance to an ac current. The impedance will depend on numerous factors, including, but not limited to, conductor spacing, dielectric (insulation) material type and thickness, temperature, or moisture. The TDR is capable of detecting and indicating changes in the electrical impedance caused by a variety of circumstances. Using the characteristic velocity of propagation for a given type of cable, which can also be determined by using the TDR, the distance in feet or inches to any discontinuity can be determined and/or displayed on the signature waveform for the cable.

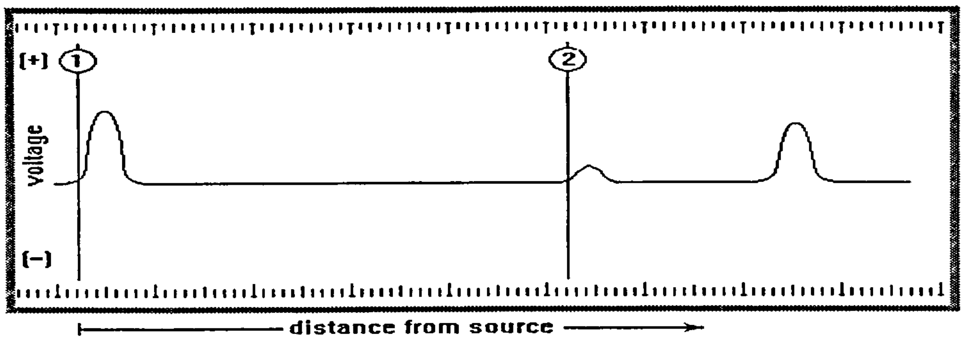
Some of the problems that a TDR can be used to detect, measure, and physically locate are:

- cable damage (kinks, bends, cuts, abrasion)
- water or moisture intrusion or submersion
- change in cable type
- improper installation (crushed, kinked, or pinched cables)
- bad splices or unknown splices

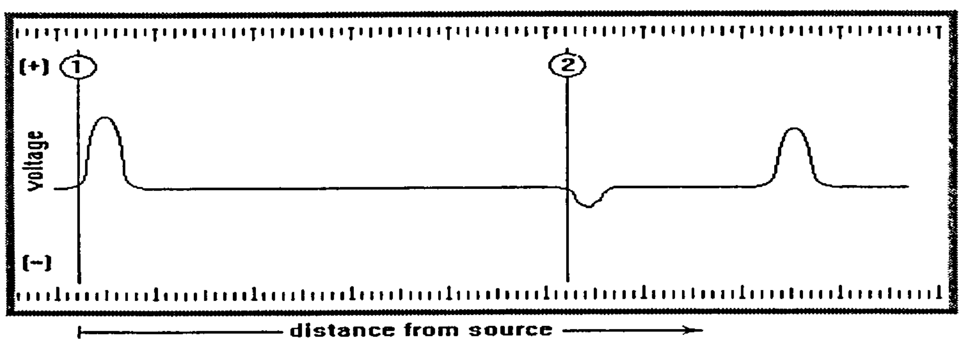
- opens or short circuits in a cable
- severity of faults or damage
- location of an in-line component
- problems causing excessive loss of ac or radio frequency signals

TDR testing may be used to provide initial verification of cable integrity and proper initial installation. In situ baseline cable TDR waveform signature for a given cable can then be used to comparatively monitor and trend in-service degradation over time. Once the characteristic velocity of propagation for specific insulating materials and cable configurations have 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.

The advantages of the TDR for in situ testing of medium-voltage power cables are: it is a non-destructive test; it provides useful information on severity and location of a discontinuity; the testing apparatus is only moderately expensive; and data is moderately trendable against historic baseline reflectograms. Some of the disadvantages of the TDR include: the cable must be disconnected in order to perform the test; a high level of training and experience are required of the testing personnel in order to obtain the best results; and transient conditions, such as water immersion, are only detected if they are present during the TDR test.



TDR reflectogram showing incident pulse at cursor 1 at left end [source] with a partial open condition at cursor 2. Reflected pulse from the far end [open circuit] of the cable is at the right.



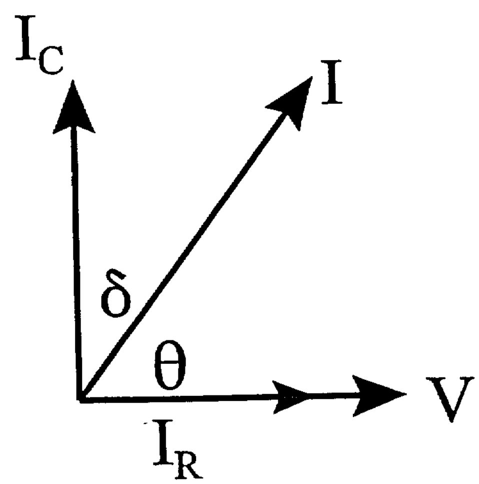
TDR reflectogram showing incident pulse at cursor 1 at left end [source] with a partial short circuit condition at cursor 2. Reflected pulse from the far end [open circuit] of the cable is at the right.

Figure 10: Simplified representation of TDR reflectograms

6.2.4 Dielectric Loss/Power Factor

An electrical measurement that shows promise as a CM technique for medium-voltage cables is the dielectric loss measurement, which measures deterioration of a material's dielectric properties. When a steady-state ac test voltage (V) is applied to an insulated cable, 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 11. The phase angle θ between the applied test voltage (V) and the total current (I) is known as the dielectric phase angle. The compliment of the phase angle is called the dielectric loss angle δ.

The leakage current for electric cables is normally much smaller than the charging current, but it is more sensitive to the condition of the insulation. As insulation deteriorates, it is expected that the leakage current will increase, while the capacitive current remains approximately constant. Thus, the ratio of the magnitudes of (I_R) and (I_C) will increase. As can be seen from Figure 11, this ratio is the tangent of the dielectric loss angle (tan δ). It is called the dielectric dissipation factor and is commonly used as a measure of insulation condition. Similarly, another means of describing insulation condition 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).



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 11: Power factor relationship

In a research program sponsored by the NRC [10], dielectric loss measurements were performed to measure the dielectric phase angle of various common cable insulation materials. Measurements were taken at various stages of aging between the black and white insulated conductors, and between the black and white insulated conductors and the ground. The dielectric loss measurements were taken using a two-channel Hewlett Packard HP 35670A Dynamic Signal Analyzer. An internal source provides the applied ac voltage signal to the test specimens, and an internal disk drive allows the data to be stored for later analysis. The instrument is programmable so the testing routine can be setup, stored on a 3.25" diskette, and reloaded whenever it is needed. For the testing performed in the referenced program, the instrument was programmed to apply the 5 Vac (peak) test voltage at increasing increments of frequency ranging from 0.1 Hz to 5000 Hz, while measuring and recording the dielectric phase angle at each increment. This feature yields very repeatable results.

Figure 12 shows power factor as a function of increasing age for XLPE insulated cables [10]. As shown, a consistent increasing trend in power factor was observed as aging increased. This indicates that this technique may be useful for monitoring the condition of this material. Similar results were found for EPR, another common insulating material.

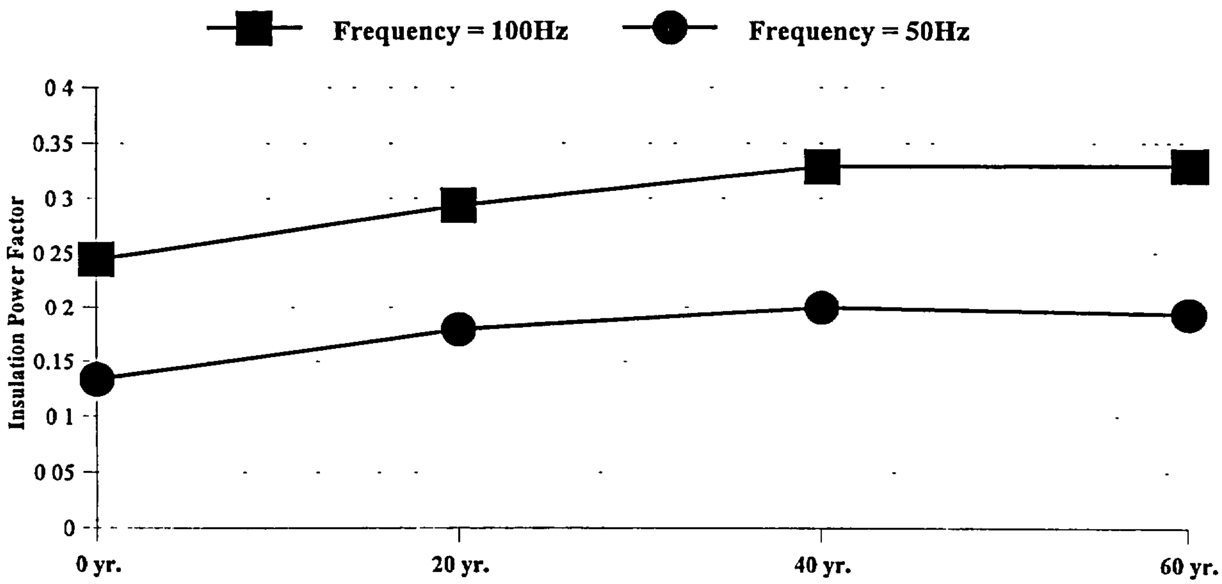


Figure 12: Power factor versus age for XLPE insulation aged to simulate 20, 40, and 60 years of service life [10]

20 yr = 648.5 hr @ 302°F + 26.1 Mrad
40 yr = 1,301.2 hr @ 302°F + 51.5 Mrad
60 yr = 1,363.8 hr@302°F + 77.0 Mrad

Some of the factors which affect the dielectric loss measurement technique include cable length, humidity or moisture within the cable and insulation, and electrical equipment operating in the vicinity of the test cable. For the NRC study, laboratory testing was performed to evaluate and quantify these effects by testing various lengths of cable in a cable tray with other cables in an industrial environment. The effect of 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 making in situ baseline measurements for each cable to be monitored to serve as a standard for comparison with similar measurements in the future. The effect of other operating electrical equipment or energized cables in the same tray was concentrated at the frequency of the operating equipment. In most cases, this was the 60 Hz power frequency and it had a more pronounced effect on longer cables than short ones. This problem can be avoided by making measurements at an applied ac test voltage with a frequency below 50 Hz or above 70 Hz.

The effects of humidity or moisture within the cable and insulation were observed in measurements made on EPR-insulated cables. It was found that the cable specimens exhibited improved dielectric properties after initial thermal aging had driven all moisture and humidity out of the cables. It should be noted that the sudden extreme change in moisture experienced in the laboratory testing would not normally occur in a plant environment. By making baseline measurements against which future condition monitoring results can be compared, the effects of moisture would be minimized under normal plant conditions.

The major 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. Also, no material samples need be taken from the cable.

A disadvantage of the dielectric loss technique is that the cable under test must be disconnected in order to attach the test instrument. However, this can be controlled by test procedures with independent verification steps, as are commonly used for surveillance and maintenance procedures in nuclear power plants.

EPR-insulated cables with bonded and unbonded Hypalon® jackets, in both single and multiple conductor configurations, all demonstrated a measurable trend toward increasing power factor (deteriorating dielectric strength) with greater insulation material degradation. Similarly, XLPE-insulated cables also exhibited the trend toward increasing power factor as the cables were subject to greater degradation during pre-aging. This trend was most pronounced and consistent at applied ac test voltage frequencies in the range from 10 to 500 Hz. The effect was also best observed in measurements from conductor-to-ground. Dielectric loss measurement, particularly when compared to a baseline measurement, was judged to be a good electrical condition monitoring technique for these materials.

6.3 Chemical CM Techniques

CM methods in this category measure a chemical property of the insulating material to determine if there has been any change with exposure to service conditions. The results can then be correlated with a known measure of electrical performance to provide an indication of the condition of the cable. These test are not strictly in situ since a small sample of insulation or jacket material must be obtained from a cable to perform the measurements, however, they are considered non-destructive. Several chemical tests that are applicable to medium-voltage power cables are evaluated in the following paragraphs.

6.3.1 Oxidation Induction Time (OITM)

Most cable insulation formulations include an anti-oxidant to retard the oxidation process during exposure to service conditions. A differential scanning calorimeter (DSC) can be used to measure the time at which rapid oxidation of a test material occurs at a predetermined constant test temperature in a flowing oxygen environment. This is termed the oxidation induction time (OITM). The DSC is an apparatus that supplies heat to an approximately 10 mg sample of insulation or jacket 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 adjacent to the test specimen to act as a control. The difference in heat supplied to the two pans is, therefore, the heat supplied to the sample. 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.

In research sponsored by the NRC [10], various common cable insulation materials were aged, then tested to determine the OITM at various stages of degradation. Figure 13 shows OITM results for XLPE insulating material as a function of accelerated aging. In this test, the aging was relatively severe and resulted in complete depletion of antioxidants after the first exposure (simulation of 20 year service life). Nevertheless, it is seen that OITM decreases as aging increases. Data for EPR show similar trends in which decreases in OITM are observed when the service aging time increases. Since the OITM, which is a measure of the remaining amount of antioxidant in an aged specimen, changes sensitively with aging, it is an acceptable technique for monitoring the kinetics of degradation. The ability to correlate this parameter with electrical performance makes it possible to estimate the residual ductility of cable insulation.

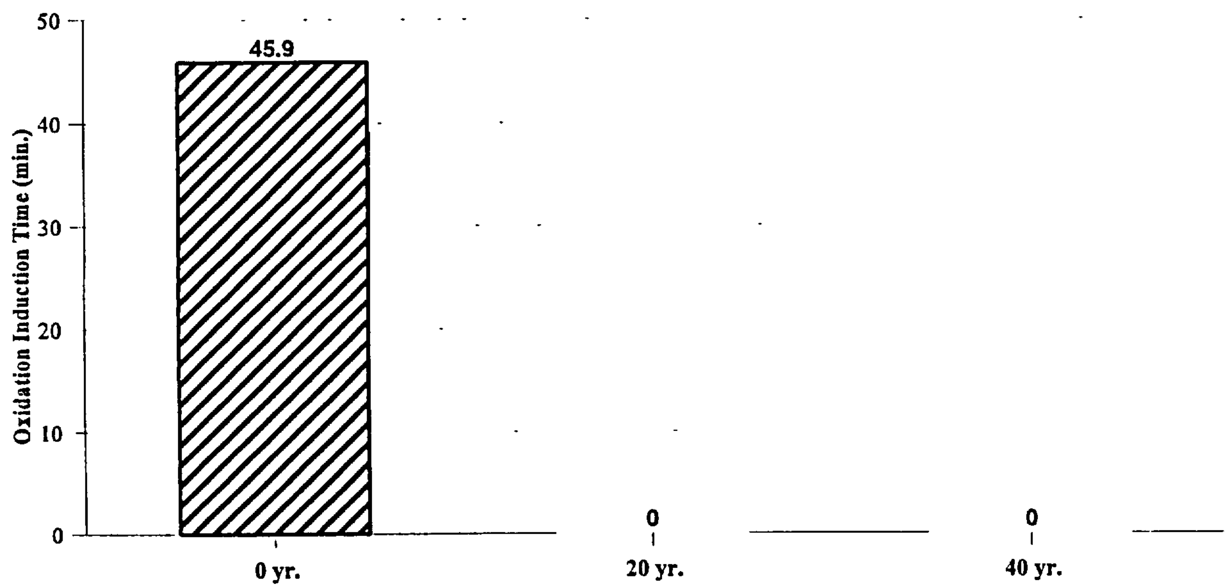


Figure 13: Average OITime at 200°C for XLPE insulation from Rockbestos specimens pre-aged to the equivalent of 0, 20 and 40 years of service life [10]
20 yr = 648.5 hr @ 302°F + 26.1 Mrad
40 yr = 1,301.2 hr @ 302°F + 51.5 Mrad

In summary, OITM is a promising technique for monitoring the condition of electric cables. Results show that aging degradation can be trended with this technique for both XLPE and EPR insulation. While a small sample of cable material is needed to perform this test, the relatively small amount required should be obtainable without impacting cable performance.

6.3.2 Density

When polymers age in the presence of oxygen, oxidation typically dominates the degradation process. As a result, various changes in the polymer structure take place, including cross-linking and chain scission, along with the generation of oxidation products. Several of these processes can result in shrinkage of the material and an increase in the density of the polymer. It has been suggested that measuring and trending the density of a cable's insulating material can be used as a measure of the degree of aging experienced by the cable, and research has been performed to demonstrate the feasibility of this technique [20].

Density measurements can be made using a small piece of material (<1mg). Two different approaches are available. In the density gradient approach, samples are placed into a calibrated liquid column containing a gradient in density. Once the sample reaches equilibrium, the density is determined using a calibration curve for the column. The liquid in the column is typically composed of salt solutions of various densities, or mixtures of ethanol and water.

A more recent approach to measuring density uses 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.

Results on density measurements for typical cable insulating materials have been promising and show a good correlation with other proven techniques, such as elongation-at-break (EAB). Figure 14 shows density measurements for XLPE insulation material as a function of increasing aging. The aging consisted of radiation exposure at 0.0175 Mrad/hr (175 Gy/hr) at 110°F (43°C) in air. As shown, a continuous increase in density was observed as the total radiation dose increased, which was consistent with the decrease in EAB (shown as e/e_o). This suggests that density would be useful as a monitoring technique for this material. Similar results were obtained for other commonly used insulating materials, although some had an induction period during which the change in density was relatively slow.

20

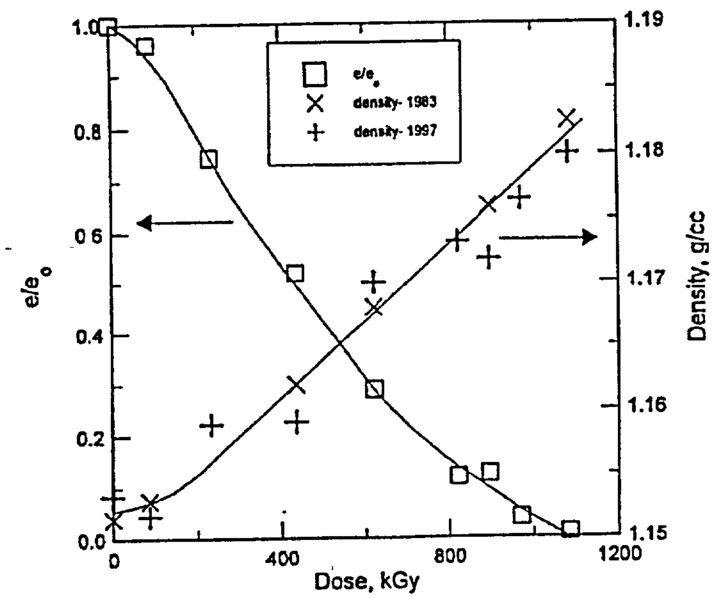


Figure 14: Density and elongation results versus aging dose for XLPE insulation aged at 175 Gy/hr plus 43°C in air [20]

While density measurements may provide a relatively easy and inexpensive means of monitoring the aging degradation of the cable condition, its drawback 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.

6.4 Summary of CM Methods for Medium-Voltage Cables

The review and evaluation of condition monitoring methods found that there are several methods available to monitoring the condition of medium-voltage power cables. Each has its own advantages and limitations, and there is no one technique that can be identified for use on cables for all applications. Table 6 summarizes the various tests available for in situ monitoring of medium-voltage power cables along with their advantages and limitations.

Table 6: Summary of CM Methods for In-Situ Monitoring of Medium-Voltage Power Cables

CM Method	Advantages	Limitations
Mechanical		
1. Visual Inspection	• Simple, inexpensive to perform • Provides useful qualitative information on cable condition	• Requires access to cable under test • Does not provide quantitative data on cable condition • Knowledge and experience produce best results
2. Compressive Modulus (Indenter)	• Relatively easy to perform • Provides trendable data on commonly used cable insulation materials • 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 • High voltage cables must be de-energized during test
3. IR Imaging Thermography	• Relatively easy to perform • Properly corrected data identifies temperature and location of hot spots • Measurements can be made when circuit is operating at full load • Data may be stored and trended • Non-destructive, non-intrusive, does not require cable to be determinated	• Requires high level of training and experience for best results • Measurements made when circuit is operating at full load can be a safety concern • High end imagers and analysis software are expensive • Area to be monitored must be visually accessible
Chemical		
4. Oxidation Induction Time	• 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
5. Density	• 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

Table 6: Summary of CM Methods for In-Situ Monitoring of Medium-Voltage Power Cables (continued)

CM Method	Advantages	Limitations
Electrical		
6. DC High Voltage Test	• 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 • Testing may damage the cable insulation
7. Partial Discharge	• 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 • Testing may damage the cable insulation
8. Time Domain Reflectometry	• Provides useful information for locating defects in cable	• Cable must be determinated to perform test • High level of training and experience required for best results
9. Dielectric Loss/ Power Factor	• 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

7. EQ EVALUATION FOR POWER CABLES

A review of environment qualification test reports and analyses related to electric power cables was conducted. The review examined the typical procedures and test conditions that are used in the industry during qualification testing for electric power cables. These were compared to the approaches used by the industry for the qualification of low-voltage electric cables [10]. Furthermore, industry practices for the qualification of power cables were evaluated in light of the discussions on operating environments and aging stressors affecting power cables (see Section 3.3), along with information gathered during an operational experience review and analysis (see Section 5).

7.1 Considerations for the Qualification of Power Cables

The requirements for environmental qualification of Class 1E electrical equipment, including power cables, are described in IEEE Standard 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, " [23] as endorsed by the US NRC in Regulatory Guide 1.89, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants" [24]. Further detailed direction and procedures for establishing type tests specifically related to the qualification of electric cables are presented in IEEE Standard 383-1974, "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations" [25].

In accordance with the aforementioned requirements, the environmental qualification of power cables must consider the following physical attributes: the cable insulation material, thickness, and application method; the individual conductor jacket and overall cable jacket materials and thicknesses; the construction of the individual conductor, i.e. solid or stranded; the size of the conductor(s) and the individual strands; the type of metal used in the conductor and what coatings, if any, are used; the configuration of the cable, for example, whether it is single or multiple conductor cable, and the inclusion of ground conductors, shields, braids, binding material, and filler materials. Other important cable attributes are the voltage rating and the temperature rating.

The service environment to which the cable will be exposed during both normal operation, as well as, abnormal operating and transient conditions, is another important consideration. If the entire length of a power cable is going to be operated in a mild, low humidity, nuclear plant environment, where there is no possibility for exposure to steam, water, radiation, chemical spray, or other corrosive substances, the specifications are very straightforward. The power cable materials must be compatible with each other and the service environment, the cable insulation must be capable of operating at the voltage levels, including transients, specified for the circuit, and the cable must be capable of carrying the projected load currents without exceeding its thermal rating. The operating ampacity of the cable will be affected by the means of routing the power cable, i.e., whether it is run through cable tray, metallic conduit, cable duct, raceway, etc., outdoors or indoors, and overhead, in air, or underground. The number, type, and loading characteristics of other power cable circuits that share the routing will also affect the ampacity of a power cable.

The qualification of power cables that are to be operated in harsh nuclear environments must include the stressors that may be encountered during a design basis accident at the end of the cable's design life. The aging effects of high temperatures and high radiation for the postulated 40-year service life of the cable must be simulated by accelerated aging techniques similar to the process that is followed for the qualification of low-voltage electric cables [10]. However, unlike low-voltage I&C cables, power cables themselves are a source of internal ohmic heating resulting from carrying often substantial load currents on a continuous basis. In addition, the higher voltages at which a power cable is operated can affect the degradation of the dielectric properties of the insulating materials, as described in Section 3.3. If the effects of internal heating and high operating potentials are determined to be substantial in the intended application, they must be considered and accounted for as part of the preconditioning process in a qualification test.

The adverse effects of sustained exposure to water while power cables are energized at high voltage were described in Section 3.3 and in the operational experience review and analysis (see Section 5). These aging mechanisms must be considered when specifying the preconditioning portions of a qualification test for power cables in those applications where moisture or immersion is likely to be encountered, even though they may be located in mild nuclear environments. In some Class 1E power distribution applications, particularly with underground distribution systems or with conduits or cable ducts that could potentially become filled with water, these aging mechanisms may prove to be the most important consideration in the qualification of a power cable.

Following preconditioning to simulate 40 years of service life, power cables that are located in, or are routed through, a harsh nuclear environment may be exposed to a design basis accident exposure simulation test (LOCA exposure simulation test). The format for this portion of a power cable qualification would be identical to that used for low-voltage electric cables [10], and is described in IEEE Standard 323-1974 [23] and IEEE Standard 383-1974 [25]. The design basis accident profile, as suggested by Appendix B to IEEE Standard 323-1974 [23], would consist of a high temperature and high pressure steam exposure under corrosive chemical spray conditions for a period of several hours up to several months depending on the specific details of the accident analysis. The main difference for power cables, as compared to accident exposure testing for low-voltage cables, is that they will be energized at higher voltages and much higher currents throughout the accident simulation test. In addition, using the guideline of 80V/mil of insulation thickness, the post-LOCA submerged voltage withstand test for power cables will be conducted at much higher applied test voltages than for I&C cables.

7.2 Review of Environmental Qualification Test Reports for Power Cables

More than fifty environmental qualification test reports and analyses for electric cables were reviewed. Thirty-three of these reports were found to include qualifications for one or more power cables. Electric cables were considered to be power cables if they fit one or more of the following criteria: rated at greater than 600V, had a conductor size of #10 AWG or larger, 1/C or 2/C #12 AWG configuration and rated at 600V, or were identified as power cables in the test report specifications. Cables that are #12 AWG can be considered as either power or control cables. When they were tested in multiconductor configurations, e.g. 7/C #12 AWG, they were most likely destined for use as control cables. The single conductor #12 AWG configuration was frequently tested at 480Vac or 600Vac, and a substantial continuous load current (e.g., 15 amperes), indicating that such a cable was intended for use in a power application; in many test reports that were reviewed, the 1/C #12 AWG configuration was specifically identified as a power cable. Using these guidelines for the review, the reports were found to include qualification tests for 66 different power cables.

The environmental qualification test reports for power cables reviewed in this study dated from December 1988 back to 1969. The voltage ratings of the cables being tested ranged from 600V up through 15kV. In those cases where the voltage rating of the cable was not specified in the test report, but an insulation thickness was provided, the voltage rating was estimated from the insulation thickness for purposes of this review. Conductor sizes of the cables ran from #12 AWG up to 750 MCM. The highlights of the power cable test reports reviewed are discussed in the following paragraphs and are summarized in Table 7.

With regard to power cables, the qualification tests could be grouped into three categories: qualification tests that specifically addressed the unique operating requirements and environments of power cables; qualification tests that treated low-voltage electric cables and power cables in the same way because they utilized the same insulation and jacket materials; and older qualification tests that addressed one or more selected requirements or criteria for electric cables, but not all of those identified in IEEE Standards 323-1974 [23] and 383-1974 [25]. Some of the qualification test reports also included cable splices which were applied to and tested as part of the power cable test specimens; these are identified in Table 7. The aging degradation and qualification practices associated with cable splices used in nuclear power plants were addressed in a previous study, as reported in NUREG/CR-6788 [26].

Some examples of qualification tests that specifically address the unique operating requirements and environments of power cables are described below.

NQRN-3 "Nuclear Environmental Qualification Report for Okoguard Insulated Cables and T-95 & No. 35 Splicing Tapes" [30], performed by The Okonite Company in1988 described one 5kV power cable qualification with one 5kV taped power cable splice qualification. The testing was performed in accordance with the guidelines of IEEE Std. 323-1974 [23] and IEEE Std. 383-1974 [25]. One specimen received no preaging and the other was thermally aged for three weeks at 150°C to simulate 40 years of service at 90°C. A total of 200Mrads of service irradiation and accident irradiation was administered at a dose rate of no greater than 1Mrad/hour. A dual peak LOCA profile (two peaks at 345°F/114psig for 3 hours each), similar to that suggested in Appendix A to IEEE Std 323-1974 [23], was employed and the overall exposure cycle lasted for 130 days. The chemistry and spray rate of the accident spray solution was the same as that suggested in Appendix A to IEEE Std 323-1974 [23] and lasted for 30 days; steam and water spray was administered throughout the final 100 days of the simulation. Specimens were energized at 5kV and a current of 80A was maintained for the duration of testing. Electrical testing included: 1) periodic insulation resistance measurements at the beginning and end of each transition, approximately once per week during the extended LOCA simulation, and post-LOCA; 2) post-LOCA capacitance and dissipation factor (percent power factor); 3) post-LOCA submerged ac voltage withstand test in accordance with IEEE Std 323-1974 [23], Section 2.4.4; and 4) a final ac rapid rise breakdown test (dielectric strength test) after all other electrical tests were completed. The test successfully qualified the tested 5kV cable and taped cable splice for a design service life of 40 years at 90°C.

#P-1625-Q "Qualification Data (Type Test Results) of 5-15kV Power Cable" [38], performed for Gilbert Associates, Inc. and others by The Anaconda Company, January 31, 1979. This test included an electrical moisture absorption test of #4/0 AWG power cable, with one specimen at 0V and the other energized continuously at 15kV, while immersed in water at 90°C for 12 months. Periodic electrical measurements were made throughout the test period. A thermal aging Arrhenius study was performed using 100% elongation-at-break measurements for EPR insulation specimens. The results of another qualification program, reported in Franklin Institute Research Laboratories F-C4350-3 (the revision 3 version of Reference 44), for a 600Vac power cable of the same insulation and jackets materials was referenced as the type test for thermal and radiation aging followed by a LOCA exposure in accordance with the guidelines of IEEE Std. 323-1974 [23] and IEEE Std. 383-1974 [25].

Many of the power cable test reports reviewed for this program described cable qualification tests that included low- and medium-voltage power cables together with several low voltage instrumentation and control cables. Preaging for specimens in this category of tests generally consisted of accelerated thermal and radiation aging. This was then followed by accident irradiation and a design basis accident simulation consisting of high temperature/high pressure steam exposure and chemical spray. Power cable specimens were treated no differently than the low voltage I&C cables in these tests, with the exception of the voltage at which the specimens were energized. Some examples of qualification tests that fall into this category are described below.

F-C4033-1 "Tests of Raychem Flamtrol Insulated and Jacketed Electrical Cables Under Simultaneous Exposure to Heat, Gamma Radiation, Steam and Chemical Spray While Electrically Energized" [46], prepared by The Franklin Institute Research Laboratories for Raychem Corporation in January 1975, describes qualification testing for several power, instrumentation, and control cables. The power cable specimens included a Flamtrol™ 1000V insulated 1/C #6 AWG cable and seven Flamtrol™ 1000V insulated 1/C #12 AWG cables in two different constructions. The testing was performed in accordance with the guidelines of IEEE Std. 323-1974 [23] and IEEE Std. 383-1974 [25]. All of the specimens were simultaneously thermally aged for 168 hours at 302°F (150°C) and irradiated to a total dose of 50Mrads while energized at 1000Vac. One of the 1/C #12 AWG cables had been thermally aged for 25 days at 302°F (150°C) and two of the 1/C #12 AWG cables had been thermally aged for 12 days at 320°F (160°C) prior to the simultaneous thermal/radiation aging. All of the specimens were then exposed to a simultaneous steam/chemical spray/radiation, single peak LOCA profile (357°F at greater than 70psig for approximately 10 hours), that lasted for 30 days. The chemistry and spray rate of the accident spray solution was similar to that suggested in Appendix A to IEEE Std 323-1974 [23] and was administered throughout the entire duration of the test. The total accident irradiation administered during the LOCA exposure simulation was 150Mrads. The coaxial splice specimen was energized at 600Vac and 0A for the duration of testing. Electrical testing included: 1) periodic insulation resistance measurements the beginning and the end of each temperature/pressure transition, twice per week during the extended LOCA simulation, and post-LOCA; 2) an in situ preliminary post-LOCA submerged voltage withstand test; and 3) a 40x diameter post-LOCA mandrel bend test, followed by immersion in room temperature tap water and a final post-LOCA submerged ac voltage withstand test in accordance with IEEE Std 323-1974 [23], Section 2.4.4. The Raychem Flamtrol™ 1000V insulated cables successfully passed the post-LOCA electrical testing and were thereby qualified by type test.

#QR-5804 "Report on Qualification Tests for Rockbestos Firewall® III Chemically Cross-linked Polyethylene Construction for Class 1E Service in Nuclear Generating Stations" [31], prepared by The Rockbestos Company, describes qualification testing for several instrumentation cables, thermocouple extension wires, power cables, and control cables. The power cable configuration tested is a 1/C #6 AWG Firewall® III Chemically Cross-linked Polyethylene insulated cable with no jacket, rated at 600V and 90°C. The testing was performed in accordance with the guidelines of IEEE Std. 323-1974 [23] and IEEE Std. 383-1974 [25]. All of the specimens were simultaneously thermally aged for either168 hours at 248°F (121°C) or 941 hours at 302°F (150°C) to simulate 45 years of service at 90°C (greater than 10% above the postulated 40-year service life). They were then irradiated to a total dose of 200Mrads (50Mrads of service aging plus 150Mrads of accident exposure). All of the specimens were then exposed to a LOCA profile, with chemistry and spray rate of the accident spray solution, similar to that suggested in Appendix A to IEEE Std 323-1974 [23].

The third category of qualification tests encountered in the review generally involved the earliest tests that preceded the establishment of environmental qualification standards and guidelines in the 1970's and early 1980's. In many of these earlier tests, specific aspects of the power cable's performance criteria are addressed separately. For example, Raychem test report EM #1074 [47] described electrical characteristics and performance tests for Flamtrol™ insulated power cables that were submerged in water at 75°C for 1000 days (2¾ years) while energized at -600Vdc. Franklin Institute Research Laboratories test report F-C2525 [59] studied the performance of irradiated (up to 24Mrad) power and control cables in a steam (up to 50psig and 296°F) and chemical spray environment for two hours with one additional hour of cooldown to ambient conditions. Raychem test reports EM #1222 [48] and EM #1224 [49] described flame resistance tests for Flamtrol™ insulated power, instrumentation and control cables in vertical and horizontal cable trays, respectively, with no preconditioning; Raychem test report EM #1075B [52] described a similar flame resistance test for Flamtrol™ insulated power, instrumentation, and control cables in vertical cable trays, after 7 days of thermal preaging at 302°F (150°C). Anaconda test report #P-1625-Q "Qualification Data (Type Test Results) of 5-15kV Power Cable" [38], described above, included an electrical moisture absorption test of #4/0 AWG power cable, with one specimen at 0V and the other energized continuously at 15kV, while immersed in water at 90°C for 12 months. Several other qualification test reports of this type are summarized in Table 7.

7.3 Evaluation and Summary

The review of power cable qualification test reports showed that once the general qualification standard IEEE Std. 323-1974 [23] was adopted and endorsed by the NRC in the early 1970's, along with IEEE Std 383-1974 [25], with its more specific requirements and procedures for electric cable qualification type testing, the requirements, procedures, and acceptance criteria for the qualification testing of power cables have become very consistent. The general format of these tests incorporates a preconditioning sequence for cable test specimens involving accelerated thermal aging followed by irradiation to simulate in service and accident irradiation doses. Then the test specimens are subjected to a design basis accident (often referred to as a loss-of-coolant accident, or LOCA) exposure simulation, while energized at rated voltage and current. This consists of a high temperature and pressure steam exposure, including the application of a chemical spray, as suggested by the accident profile given in Appendix A to IEEE Std. 323-1974. The duration of the accident simulation may be anywhere from one week to several months, depending on the application. Finally, the electric cable specimens are subjected to a submerged voltage withstand test at 80V/mil of insulation thickness and a mandrel bend test.

Most low- and medium-voltage power cables operating in nuclear power plants utilize the same solid polymeric insulating materials as low-voltage instrumentation and control (I&C) cables, and they are located in, and routed through, similar operating environments. Thus, for purposes of qualification type testing they are all frequently treated in the same way using the same general requirements, environmental and accident simulation exposures, and other details of their qualification testing procedures. This is clearly the case in the sampling of test procedures reviewed for this evaluation, where the power cable specimens were often included in cable qualification tests together with a number of other power, control, and instrumentation cable specimens.

This approach to qualification is justified for most low-voltage power cable applications. However, there are a number of differences which should be considered, particularly in higher voltage cables with higher loadings. Power cables have larger conductors to accommodate the higher current, on a continuous basis, typically found in power applications. The continuous current flow in power cables is accompanied by ohmic heating in contrast to the low current, intermittent duty of I&C cables, which experience negligible internal heating. Power cables used to energize medium- and high-voltage equipment, such as pump motors and switchgear, must operate at voltages and currents that are significantly higher than I&C cables. This results in an increased stress on the cables, which could accelerate thermal aging degradation. In addition, the higher voltages these cables experience make them susceptible to unique aging mechanisms, such as treeing, that low-voltage cables would not experience.

Furthermore, placement in conduit, raceways, underground ducts, and cable trays will affect the service conditions under which the cables must operate. Routing in densely filled cable trays, enclosed ducts, or fire-wrapped cable trays, together with other continuous duty power cables, will result in elevated operating temperatures. Cable ducts that run below grade or beneath floor level will frequently be susceptible to seepage and water intrusion that can lead to the failure of power cables.

The operating experience review for power cables (Section 5) showed that the number of age-related failures is relatively small. However, the insulating and jacket materials used in power cables are polymers that are susceptible to aging degradation. Operating experience has shown that elevated temperature, wetting or long-term immersion while energized, and vibration/cyclic movement were the predominant stressors that contributed to cable failures.

The present methods for qualification of electric cables adequately anticipate the effects of thermal and radiation-related aging degradation on the polymeric materials. However, for power cables operating at high current loads, generating significant internal heating, and in densely-filled trays, ducts, conduits, or raceways with other power cables, the effects of the total thermal loading of the cable may not be fully accounted for in those instances where power cables are tested together with low-voltage I&C cables. Conservatism built in to the environmental qualification process should cover the difference in aging that results from additional thermal loading in power cables, however, the margin is reduced compared to the low-voltage I&C cables that the power cables are tested with.

Two of the power cable qualification tests [38 and 47] reviewed specifically addressed the effects of long-term immersion, while energized, on cable insulation performance. This indicates that the industry acknowledges the importance of this stressor on power cable aging and performance, however, most of the tests reviewed for this study did not include these stressors. None of the power cable qualification tests included in the review specifically addressed the effects of vibration/cyclic movement either as a factor in preconditioning or as a separate performance test. Since vibration and water immersion are application-specific variables, they may not normally have been included in general qualification testing for cables. Vibration/cyclic movement for power cables may be addressed as part of the qualification for another piece of equipment, e.g., motor leads feeding a large electric motor. Given the low number of power cable failures, the best way to manage application specific stressors may be through maintenance, inspection, and condition monitoring. An overview and evaluation of many of the inspection and condition monitoring techniques for power cables is provided in Section 6.

To ensure that all applicable aging stressors are addressed during qualification testing, it may be beneficial to reference an appropriate aging management guidance document, such as IEEE Std. 1205-2000 [60], in the governing IEEE qualification standards. The guidance document could then be reviewed, based on the specific intended application of the qualified equipment, and all applicable stressors could be identified for inclusion in the qualification test.

One other factor related to the qualification of power cables that was noted in NUREG/CR-6704 [10], Volume 1, is the effect of configuration on the performance of a cable. Currently accepted standards permit the qualification of various configurations of electric cables based on simple analysis or their similarity to other cables of the same materials or construction that have already passed environmental qualification type tests. It was found that factors such as cables with insulated conductors of different diameters and thicknesses, single versus multiconductor cable configurations, and bonded versus unbonded jackets performed differently during qualification testing even though they incorporated the same materials. In these cases, qualification by simple analysis and similarity of materials may not be appropriate.

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Cable Typel	Remarks
18056-1 [27]	Wyle	1988	Anaconda-Continental	CC-2193 Nuclesil	600	Nuclesil SR	Asbestos	1/C #12 AWG 7 Strand Cu	Power or Control	Aging irradiation, thermal aging, accident irradiation, steam and chem spray with electrical tests and inspections
NQRN-1A [28]	Okonite	1988	Okonite	Okonite	600	EPR	None	1/C #12 AWG 7 Strand tinned Cu	Power or Control	Tested with, and using same techniques as, medium voltage power cable
					2000	EPR	None	1/C #6 AWG 7 Strand tinned Cu	Power	Tested with, and using same techniques as, LV power & control cable
NQRN-2 [29]	Okonite	1987	Okonite	Okonite-FMR	600	EPR	None	1/C #12 AWG 7 Strand Cu	Power or Control	Tested alone using similar techniques as, LV and I&C cables
NQRN-3 [30]	Okonite	1988	Okonite	Okoguard	5000	EPR	None	1/C #6 AWG 7 Strand Cu	Power	Tested using same techniques as LV and I&C cables
				T-95 & No 35 Splice Tapes	5000	Unknown & EPR	EPR	Hand-wrapped, filled splice	Power Cable with Splice	Splice tested on medium voltage power cable
#QR-5804 [31]	Rockbestos	1987	Rockbestos	Firewall III	600	FR-XLPE	None	1/C #6 AWG 7 Strand x 0 0612" tinned Cu	Power	Chem X-linked; tested with, and using same techniques as, LV and I&C cables
#QR-5805 [32]	Rockbestos	1987	Rockbestos	Firewall III	600	FR-XLPE	None	1/C #6 AWG 7 Strand x 0.0612" tinned Cu	Power	Rad X-linked; tested with, and using same techniques as, LV and I&C cables
NQRN-6 [33]	Okonite	1987	Okonite	X-Olene-FMR	600	XLPE-FMR	None	1/C #12 AWG 7 Strand Cu	Power or Control	Tested alone using similar techniques as LV and I&C cables

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Application	Remarks
F-A5550-7 [34]	Franklin Institute Research Labs	1982	ITT Surprenant Division	SIS-Type	600	XLN	None	1/C #12 AWG Cu	Power or Control	Electron beam irradiation aging, thermal aging, accident gamma irradiation, and steam line break/LOCA simulation with steam/chemical spray/ high humidity with electrical tests
F-C5285-1 [35]	Franklin Institute Research Labs	1980	General Electric Company - Wire & Cable Business Department	Vulkene Supreme	600	XLPE	None	1/C #12 AWG insulation & conductor factory reworked	Power or Control	Thermal aging, irradiation, and LOCA/MSLB/DBE simulation with electrical tests
				Gexene	600	Unknown	Coated Cu tape shield, Asbestos tape shield, CSPE	1/C #12 AWG insulation & conductor factory reworked	Power or Control	
				Burndy-RayChem field splice on Vulkene Supreme Cable	600	XLPE	Coated Cu tape shield, Asbestos tape shield, CSPE	1/C #12 AWG Vulkene Supreme insulation, Burndy-RayChem field splice	Power or Control	
Report No. PE-53 [36]	Essex Grp (Essex, Isomedix, Franklin Institute, GE, Westinghouse	1980	Essex	Unnamed power or control cable	600	EP	None	1/C #12 AWG, 0.030" EP, unknown configuration Cu	Power	Thermal aging, irradiation, and LOCA/MSLB/DBE simulation with electrical tests

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Appli-cation	Remarks
Report No. 26333-1 [37]	Wyle	1980	Rockbestos	Firewall III	600	XLPE	Neoprene	2/C #12 AWG, 0.030" XLPE, 0.045" Neoprene Jacket, 7 Strand Cu	Power or Control	Qualification by analysis for three power cables and one power or control cable to DOR guidelines and I&E Bulletin 79-01B with respect to beta radiation dose compared to the previously determined gamma radiation dose qualified level for those cables
					600	XLPE	Neoprene	3/C #10 AWG, 0.030" XLPE, 0.060" Neoprene Jacket, 7 Strand Cu	Power	
					600	XLPE	Neoprene	1/C #6 AWG, 0.035" XLPE, 0.030" Neoprene Jacket, 7 Strand Cu	Power	
					600	XLPE	Neoprene	0.090" 300 MCM Triplex, 0.065 XLPE, 0.065" Neoprene Jacket, 7 Strand Cu	Power	
P-1625-Q [38]	Anaconda	1979	Anaconda	Unnamed power cable	15kV	EPR	None	1/C #4/0 AWG 19 Strand tinned Cu	Power	Submerged electrical moisture absorption test at 0V and 15kV, thermal aging & EAB for insulation specimens only
Anaconda-Continental Rpt 79117 [39]	Anaconda Continental	1979	Anaconda	Unnamed LV power cable	600	Nuclesil SR	Glass braid	1/C #12 AWG 7 Strand x 0.0305" tinned Cu	Power or Control	Irradiation, steam, and chem spray followed by electrical tests
#QR-1806 Rev 3 [40]	Rockbestos	1981	Rockbestos	Firewall III	600	FR-XLPO	None	1/C #12 AWG 7 Strand x 0.0305" tinned Cu	Power or Control	Thermal aging, irradiation, mandrel bend, accident irradiation, accident steam/chem spray, and electrical tests
L.O.C.A. XLPO/ EPDM [41]	Isomedix, Inc	1978	Samuel Moore	FR-EPDM	600	FR-EPDM	CSPE/ CSPE	2/C #10 AWG, 7Strand tinned Cu, w/ individual & overall CSPE jackets	Power or Control	Tested with, and using same techniques as, LV and I&C cables
None (7/7/77) [42]	Rockbestos	1977	Rockbestos	Firewall III	600	FR-XLPE	None	1/C #12 AWG Cu	Power or Control	Thermal aging, irradiation, mandrel bend, accident irradiation, accident steam/chem spray, and electrical tests

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Application	Remarks
					600	FR-XLPE	None	1/C #6 AWG Cu	Power	
None (2/1/77) [43]	Rockbestos	1977	Rockbestos	Firewall III	600	FR-XLPE	None	1/C #12 AWG Cu	Power or Control	Thermal aging, irradiation, mandrel bend, accident irradiation, accident steam/chem spray, and electrical tests
					600	FR-XLPE	None	1/C #6 AWG Cu	Power	
F-C4350-2 [44]	Franklin Institute Research Labs	1976	Anaconda	Unnamed LV power cable	600	FR-EPR	None	1/C #12 AWG 7 Strand x tinned Cu	Power or Control	Tested with, and using same techniques as, LV I&C cable
F-C4197-1 [45]	Franklin Institute Research Labs	1975	AIW	EPR with Neoprene Jacket	600	EPR	Neoprene	1/C #12 AWG, 0 030" EPR, Cu	Power	Tested with, and using same techniques as, I&C cable
F-C4033-1 [46]	Franklin Institute Research Labs	1975	Raychem	Flamtrol Power Cable	1000	XLPE	None	1/C #12 AWG, 0 045" XLPE, Cu (Part No W1TC12C10)	Power	Qualification test in accordance with IEEE Stds 323-1974 and 383-1974 using thermal and radiation preaging followed by simultaneous exposure to steam, chemical spray, and radiation to simulate LOCA conditions
					1000	XLPE	None	1/C #6 AWG, 0 045" XLPE, Cu	Power	
					1000	XLPE	None	1/C #12 AWG, 0.045" XLPE, Cu (Part No. W1TC12B10)	Power	
Test Rpt #1074 [47]	Raychem	1975	Raychem	Flamtrol	600	XLPE	None	1/C #12 AWG Cu	Power or Control	Verification, via electrical tests, of the cable's 1000-day elevated temperature water immersion capability ,no preaging

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Appli-cation	Remarks
Test Rpt. #1222 [48]	Raychem	12/15 1975	Raychem	Flamtrol	600+	XLPE	None	1/C 350 MCM Primary Cu	Power	Flame resistance test only on a 30% filled vertical cable tray in accordance with IEEE Standard 383-1974, no preaging, no voltage rating specified
				Flamtrol	600+	XLPE	None	4/C #4 AWG, Cu		
				Flamtrol	600+	XLPE	None	4/C #6 AWG, Cu		
				Flamtrol	600+	XLPE	None	2/C #6 AWG, Cu		
				Flamtrol	600+	XLPE	None	2/C #8 AWG, Cu		
				Flamtrol	600+	XLPE	None	4/C #10 AWG, Cu		
				Flamtrol	600+	XLPE	None	2/C #10 AWG, Cu		
				Flamtrol	600+	XLPE	None	2/C #2 AWG, Cu		
				Flamtrol	600+	XLPE	None	4/C #2 AWG, Cu		
Test Rpt #1224 [49]	Raychem	12/17 1975	Raychem	Flamtrol	600+	XLPE	None	1/C 350 MCM Primary Cu	Power	Flame resistance test only on 30% filled double horizontal cable tray in accordance with IEEE Standard 383-1974; no preaging; no voltage rating specified
				Flamtrol	600+	XLPE	None	4/C #2 AWG, Cu		
				Flamtrol	600+	XLPE	None	2/C #2 AWG, Cu		
				Flamtrol	600+	XLPE	None	4/C #6 AWG, Cu		
				Flamtrol	600+	XLPE	None	2/C #8 AWG, Cu		
				Flamtrol	600+	XLPE	None	4/C #10 AWG, Cu		
				Flamtrol	600+	XLPE	None	4/C #4 AWG, Cu		
F-C3694 [50]	Franklin Institute Research Labs	1974	Okonite	Okonite	600	EPR	None	1/C #12 AWG 7 Strand tinned Cu	Power or Control	Tested with, and using same techniques as, medium voltage power cable

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Application	Remarks
				Okoguard	5000	EPR	Semicon Tape	1/C #6 AWG 7 Strand bare Cu	Power	Tested with, and using same techniques as, LV power & control cable
Test Rpt #1030 [51]	Raychem	1974	Raychem	Flamtrol	600	XLPE	None	1/C #12 AWG Cu	Power or Control	Verification of high temperature voltage withstand capability with no preaging
Test Rpt #1075B [52]	Raychem	1974	Raychem	Flamtrol	600	XLPE	None	1/C #12 AWG Cu	Power or Control	Vertical flame resistance test only in accordance with IPCEA S-19-81, Paragraph 6 19, thermal preaging for 1 week at 150°C
F-C3341 [53]	Franklin Institute Research Labs	1973	Anaconda	Durasheath EP	600	EPR	CSPE	1/C #2 AWG 7 Strand tinned Cu	Power	Tested with, and using same techniques as, medium voltage power cable
				Durasheath EP	600	EPR	CSPE	1/C #12 AWG 7 Strand tinned Cu	Power or Control	Tested with, and using same techniques as, medium voltage power cable
				Okoguard	5000	EPR	Semicon Tape	1/C #6 AWG 7 Strand bare Cu	Power	Tested with, and using same techniques as, LV power & control cable

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Appli-cation	Remarks
Engrng Report No 141 [54]	Okonite	1972	Okonite	Okonite/ Okoprene	600	EPR	Neoprene	1/C #4/0 AWG, 0 055" Okonite, 0 045" Okoprene	Power	Presents the results of the qualification testing described in Franklin Reports F-C 3094, July 1971, and F-C 3171, September 1971; thermal aging, aging and accident irradiation, 7½-day steam and chemical spray accident simulation exposure with electrical testing
				Okoguard/ Okolon with T-95 Splice & T-35 Jacketing Tapes	5kV	EPR	CSPE	1/C #4/0 AWG, 0 140" Okoguard, 0 065" Okolon with a hand-wrapped, filled splice	Power Cable with Splice	
Test Rpt. #517 [55]	Raychem	1972	Raychem	Flamtrol	600?	XLPE	None	1/C #12 AWG Cu	Power or Control	Thermal and radiation aging, LOCA simulation, with insulation resistance tests
Test Rpt. #1070 [56]	Raychem	1972	Raychem	Flamtrol	Unknown	XLPE	None	1/C Unknown AWG Cu	Power or Control	Verification of the elevated temperature and pressure steam exposure performance capability of irradiated electric cable in accordance with Raychem Spec 1260, as measured by insulation resistance measurements; both with and without thermal preaging
					Unknown	XLPE	None	1/C Unknown AWG Cu	Power or Control	
					Unknown	XLPE	None	1/C Unknown AWG Cu	Power or Control	
					Unknown	XLPE	None	1/C Unknown AWG Cu	Power or Control	
F-C3033 [57]	Franklin Institute Research Labs	1971	Anaconda	#2 Triplexed 5kV UNGRD Type E	5000	EP, SCT	Coated Cu tape shield, Asbestos tape shield, CSPE	3/C #2 AWG 7 Strand x coated Cu	Power	Irradiation, steam, and chem spray followed by electrical tests

Table 7: Summary of Review of Qualification Test Reports for Electric Power Cables (continued)

Report No.	Test Lab	Year	Cable Mfgr.	Cable Type	Voltage Rating	Insulation Material	Jacket Material	Configuration	Application	Remarks
				1/C 750mcm 5kV UNGRD Type E	5000	EP, SCT	Coated Cu tape shield, Asbestos tape shield, CSPE	1/C 750 mcm 61Strand coated Cu	Power	Irradiation, steam, and chem spray followed by electrical tests
Engrng Report No 110E [58]	Okonite	1970	Okonite	Okonite/ Okoprene	1000	EPR	Neoprene	1/C #6 AWG, 0.062" Okonite, 0.030" Okoprene	Power	Thermal and radiation aging, LOCA simulation with electrical tests
				T-95 Splice Tape	600	Unknown	None	Two (2) unknown cable configurations with hand-wrapped, filled splice	Power Cable with Splice	No preaging, LOCA simulation with electrical tests only
F-C2525 [59]	Franklin Institute Research Labs	1969	Anaconda	Unnamed power cable	600	ME 299	MH 8100	1/C #6 AWG 7 Strand x Cu	Power	Tested with, and using same techniques as, I&C cable

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Effects of Aging on Power Cables

A review and evaluation of past work and events related to power cables has been performed to characterize the effects of aging on power cable performance and reliability. The following observations are made from this review and evaluation:

- Power cable insulation and jackets are constructed of polymeric materials that are susceptible to age-related degradation. If it becomes severe, this degradation can and has resulted in cable failures. In all cases reviewed in this study, the cable insulation was the subcomponent that failed as a result of aging degradation.

- Power cables are used in both safety-related and non safety-related applications in nuclear power plants and their failure can have a significant impact on plant operation. Examples include the loss of function of safety-related equipment or reactor trip. Less severe consequences are challenges to safety systems and a loss of redundancy of one or more safety system trains.

- The predominant aging mechanism for power cable failure is moisture intrusion, which can degrade the dielectric properties of the insulation and result in water treeing. Other important aging mechanisms are embrittlement of the insulation due to elevated temperatures, and chafing or cutting of the insulation due to vibration or cyclic movement of the cable.

- The number of power cable events reported in the various databases is relatively small, suggesting that power cable failures are infrequent. However, there may be a number of power cable events that were judged to be of insufficient importance to report by the utility. As the age of the installed base of power cables in nuclear power plants increases, there is the potential of seeing more power cable failures resulting from age-related degradation.

- The failure mode most commonly found is an electrical "ground fault," in which the cable faulted to ground from one or more of its conductors. Other less frequent failure modes are phase-to-phase fault, in which the cable faulted from one conductor to another conductor, or "low resistance," which indicates that the dielectric properties of the insulation had degraded to an unacceptable level.

While the number of failures is relatively low, the data indicate that power cables are susceptible to aging degradation that can lead to failure. Power cables are not typically replaced on a periodic basis, unless there is a problem with the cable. As nuclear power plants age and the cables are subjected to the cumulative effects of exposure to aging stressors over a period of many years, the amount of aging degradation experienced by the cable insulation and jacket materials will increase. This could lead to an increase in the number of power cable failures in later years of plant life. An aging management program to monitor and mitigate the effects of cable aging may be beneficial in anticipating these potential problems.

8.2 Managing Aging

Aging management of power cables should be based on the implementation of one or more condition monitoring techniques to closely monitor their condition. Based on the review and evaluation of condition monitoring methods, in situ monitoring of medium-voltage power cables appears to be feasible. The following recommendations are made with respect to the establishment of a monitoring program:

- An in situ monitoring program should include the use of several different CM methods. The cables selected for monitoring and the method chosen for a particular cable should be based on the construction of the cable, as well as its application, accessibility, and installation.

- Visual inspection should be considered as a first step for all cables that are accessible. This is an inexpensive, easy-to-perform technique that can provide valuable information on the condition of a cable, as well as the location of any potential problem areas along the length of a cable run. While qualitative information only is provided, it can be used to make an informed decision as to whether additional, more intrusive testing is required, or the frequency of condition monitoring needs to be modified.

- Care should be exercised in the use of dc high voltage electrical tests since past work has shown the potential for this type of test to contribute to or cause premature failure of cables

8.3 Qualification Practices

The evaluation of current qualification practices for power cables have resulted in the following observations:

- The present methods for qualification of electric cables adequately anticipate the effects of thermal and radiation-related aging degradation on the polymeric materials. However, for power cables operating at high current loads, generating significant internal heating, and in densely-filled trays, ducts, conduits, or raceways with other power cables, the effects of the total thermal loading of the cable may not be fully accounted for in those instances where power cables are tested together with low-voltage I&C cables.

- To ensure that all applicable aging stressors are identified and addressed in qualification tests, it may be beneficial to reference an appropriate aging management guidance document, such as IEEE Standard 1205-2000, in the governing IEEE qualification standards (323 and 383).

- Two of the power cable qualification tests [38 and 47] reviewed specifically addressed the effects of long-term immersion, while energized, on cable insulation performance. This indicates that the industry acknowledges the importance of this stressor on power cable aging and performance, however, most of the tests reviewed for this study did not include these stressors. None of the power cable qualification tests included in the review specifically addressed the effects of vibration/cyclic movement either as a factor in preconditioning or as a separate performance test. Since vibration and water immersion are application-specific variables, they may not normally have been included in general qualification testing for cables. Vibration/cyclic movement for power cables may be addressed as part of the qualification for another piece of equipment, e.g., motor leads feeding a large electric motor.

- Currently accepted standards permit the qualification of various configurations of electric cables based on simple analysis or their similarity to other cables of the same materials or construction that have already passed environmental qualification type tests. During previous research [10] it was found that factors such as cables with insulated conductors of different diameters and thicknesses, single versus multiconductor cable configurations, and bonded versus unbonded jackets performed differently during qualification testing even though they incorporated the same insulation and jacket materials. Consequently, qualification by simple analysis and similarity of materials may not be appropriate in every case.

9. REFERENCES

1. NUREG/CR-5461, "Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants," Sandia National Laboratories, July 1990.

2. SAND96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cable and Terminations," Sandia National Laboratories, September 1996.

3. EPRI Report NP-7485, "Power Plant Practices to Ensure Cable Operability," prepared by Ogden Environmental and Energy Services Co., July 1992.

4. EPRI Report TR-103834, "Effects of Moisture on the Life of Power Plant Cables," August 1994.

5. IEEE Standard 141-1986 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Institute of Electrical and Electronics Engineers, New York, NY, 1986.

6. Moore, G. F., "Electric Cables Handbook," Third Edition, Blackwell Science, Inc. 1999.

7. IEEE Standard 835-1994 (R2000), "IEEE Standard Power Cable Ampacity Tables," Institute of Electrical and Electronics Engineers, New York, NY, 1994.

8. NEMA WC51-1986/ICEA P-54-440, "Ampacities of Cables in Open-Top Trays," (Rev. 1, 1994).

9. Romanoff, M., "Underground Corrosion," National Bureau of Standards Circular 579, April 1957.

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

11. Teich, Andrew, "Infrared Imaging Expands Its Markets," *Lasers & Optronics*, pages 29-31. April 1998.

12. Srinivas, N.H., et al., "Effect of dc Testing on Aged XLPE Insulated Cables with Splices," JICABLE91, Paris, France, June 1991.

13. Eager, G.S. et al., "Effect of dc Testing on Water Tree Deteriorated Cable and a Preliminary Evaluation of VLF as an Alternative," IEEE Transactions on Power Delivery, Vol. 7, No. 3, July 1992.

14. IEEE Standard 400-1991, "IEEE Guide for Making High-Direct Voltage Tests on Power Cable Systems in the Field," Institute of Electrical and Electronics Engineers, New York, NY, 1991.

15. IEEE Standard 4-1978, "IEEE Standard Techniques for High Voltage Testing," Institute of Electrical and Electronics Engineers, New York, NY, 1978.

16. IEEE Standard 62-1978, "IEEE Guide for Field Testing Power Apparatus Insulation," Institute of Electrical and Electronics Engineers, New York, NY, 1978.

17. IEEE Standard 141-1986 (Red Book), "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants," Institute of Electrical and Electronics Engineers, New York, NY, 1986.

18. Thue, W. A., "Electrical Power Cable Engineering," Marcel Dekker, Inc. 1999.

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

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

21. Steiner, J.P. and Martzloff, F.D., "Partial Discharges in Low-voltage Cables," paper presented at IEEE International Symposium on Electrical Insulation, Toronto, Canada, June 3-6, 1990.

22. Seffrin, James R., "Thermography Advances Aid Proactive Maintenance," *Energy User News*, page 30. June 1996.

23. IEEE Std. 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, " Institute of Electrical and Electronics Engineers, New York, NY, 1974.

24. US NRC Regulatory Guide 1.89, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants," Revision 1, US Nuclear Regulatory Commission, June 1984.

25. IEEE Std. 383-1974, "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations, " Institute of Electrical and Electronics Engineers, New York, NY, 1974.

26. NUREG/CR-6788, BNL-NUREG-52667, "Evaluation of Aging and Qualification Practices for Cable Splices Used in Nuclear Power Plants," Brookhaven National Laboratory, Upton, NY, July 2002.

27. 18056-1 "Qualification Test Program for Silicon Rubber Insulated Cables for Use in Tennessee Valley Authority's Sequoyah and Watts Bar Nuclear Plants," prepared by Wyle Laboratories for Tennessee Valley Authority, December 1988.

28. NQRN-1A "Nuclear Environmental Qualification Report for Okonite Insulated Cables," Revision 5, The Okonite Company, October 24, 1988.

29. NQRN-2 "Qualification of Okonite-FMR Insulated Cables for Nuclear Plant Service," Revision 6, The Okonite Company, February 27, 1987.

30. NQRN-3 "Nuclear Environmental Qualification Report for Okoguard Insulated Cables and T-95 & No. 35 Splicing Tapes," Revision 4, The Okonite Company, February 27, 1987.

31. QR#-5804 "Report on Qualification Tests for Rockbestos Firewall® III Chemically Cross-Linked Polyethylene Construction for Class 1E Service in Nuclear Generating Stations," Revision 3, The Rockbestos Company, July 2, 1987.

32. QR#-5805 "Report on Qualification Tests for Rockbestos Firewall® III Irradiation Cross-Linked Polyethylene Constructions for Class 1E Service in Nuclear Generating Stations," Revision 2, The Rockbestos Company, July 2, 1987.

33. NQRN-6 "Qualification of X-Olene-FMR Insulation for Nuclear Plant Service," Revision 3, The Okonite Company, March 31, 1987.

34. F-A5550-7 "Qualification Tests of Electrical Cables in a Simulated Steam-Line-Break and Loss-of-Coolant Accident Environment: 100-Day Duration 1/C #12 AWG SIS-Type Wire," prepared by The Franklin Institute Research Laboratories for ITT Surprenant Division, November 16, 1982.

35. F-C5285-1 "Qualification Tests of Electrical Cables in a Simulated Loss-of-Coolant Accident (LOCA) Environment," prepared by The Franklin Institute Research Laboratories for General Electric Company, Wire and Cable Business Department, May 2, 1980.

36. Report No. PE-53 "Main Steam Line Break (MSLB) Test on Aged and Irradiated Cable," Essex Group, Inc., Power Conductor Division, May 7, 1980.

37. Report No. 26333-01 "Assessment of Beta Radiation on Safety-Related Electrical Cable for Fort Calhoun Station, Unit 1," prepared by Wyle Laboratories for Omaha Public Power District, October 23, 1980.

38. #P-1625-Q "Qualification Data (Type Test Results) of 5-15kV Power Cable," performed for Gilbert Associates, Inc. by The Anaconda Company, January 31, 1979.

39. Anaconda-Continental Report No. 79117 "L.O.C.A. - 5 IPEC" prepared by Anaconda-Continental for Tennessee Valley Authority, April 1979.

40. QR #1806 "Qualification of Firewall III Class 1E Electric Cables (Irradiation Cross-Linked Insulation)," Revision 3, The Rockbestos Company, May 1, 1981.

41. L.O.C.A. XLPO/EPDM "Qualification Test of Electric Cables Under a Simulated LOCA/DBE by Sequential Exposure to Environments of Radiation, Thermal Aging, Steam and Chemical-Spray," performed by the Component Testing Division of Isomedix, Inc. for Samuel Moore and Company, Dekoron Division, June 1978.

42. "Qualification of Firewall III Class 1E Electric Cables," The Rockbestos Company, July 7, 1977.

43. "Qualification of Firewall III Class 1E Electric Cables," The Rockbestos Company, February 1, 1977.

44. F-C4350-2 "Tests of Electrical Cables Subjected to Thermal aging, Gamma Radiation and a Loss-Of-Coolant Accident Simulation," prepared by The Franklin Institute Research Laboratories for The Anaconda Company, July 1976.

45. F-C4197-1 "Qualification of Cables for a Loss-of-Coolant Accident," prepared by The Franklin Institute Research Laboratories for American Insulated Wire Corporation, October 1975.

46. F-C4033-1 “Tests of Raychem Flamtrol Insulated and Jacketed Electrical Cables Under Simultaneous Exposure to Heat, Gamma Radiation, Steam and Chemical Spray While Electrically Energized,” prepared by The Franklin Institute Research Laboratories for Raychem Corporation, January 1975.

47. Test Report EM #1074 "Raychem Flamtrol - Elevated Temperature Water Immersion - 2-3/4 Years (1000 Days)," prepared by the Raychem Corp. in accordance with ICEA Method T-22-294 except for the 16 week duration which was extended to 1000 days, October 2, 1975.

48. Test Report EM #1222 "Flamtrol - Vertical Tray Tests - 30% Cable Fill," prepared by the Raychem Corp. in accordance with IEEE Standard 383-1974; no preaging, December 15, 1975.

49. Test Report EM #1224 "Flamtrol - Horizontal Double Tray Tests - 30% Cable Fill," prepared by the Raychem Corp. in accordance with IEEE Standard 383-1974; no preaging, December 17, 1975.

50. F-C3694 “Type Test Cable Qualification Program and Data for Nuclear Plant Designed Life Simulation Through Simultaneous Exposure,” prepared by The Franklin Institute Research Laboratories for The Okonite Company, January 1974.

51. Test Report EM #1030 "Flamtrol - High Temperature Voltage Withstand Tests," prepared by the Raychem Corp. for Pacific Gas & Electric Co., September 24, 1974.

52. Test Report EM #1075B "Vertical Flame Resistance Tests on Raychem-Flamtrol," prepared by the Raychem Corp. in accordance with ICEA S-19-81, Paragraph 6.19, December 3, 1974.

53. F-C3341 “Long Term Testing of Electrical Cables Under Simultaneous Exposure to Gamma Radiation, Steam and Chemical Spray,” prepared by The Franklin Institute Research Laboratories for Anaconda Wire and Cable Company, January 1973.

54. Engineering Report No. 141 "Qualification Tests of Electrical Cables Through Sequential Exposure to Heat, Gamma Radiation, LOCA, and Post-LOCA Simulations," The Okonite Company, February 29, 1972.

55. Test Report EM #517 "The Effects of Radiation and Aging on Flamtrol Insulated Wire," prepared by the Raychem Corp. in accordance with Raychem Specification1260, April 8, 1972.

56. Test Report EM #1070 "The Effects of Radiation on Flamtrol at Elevated Temperatures," prepared by the Raychem Corp. in accordance with Raychem Specification 1260, April 8, 1972.

57. F-C3033 “Tests of Electrical Cables Under Simulated Reactor Containment Service Conditions,” prepared by The Franklin Institute Research Laboratories for the Anaconda wire and Cable Company, April 1971.

58. Engineering Report No. 110E "Nuclear Qualification Tests on Insulating Compounds," The Okonite Company, November 12, 1970.

59. F-C2525 “Qualification Tests of Electrical Cables Under Simulated Post-Accident Reactor Containment Service Conditions,” prepared by The Franklin Institute Research Laboratories for Anaconda Wire and Cable Company, October 1969.

60. IEEE Std. 1205-2000, "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, New York, NY, 2000.

APPENDIX A: DEFINITIONS

A.1 Introduction

To ensure a consistent usage and meaning of the various terms used in this aging assessment, the following definitions have been used in this study. These definitions are adopted from EPRI Report TR-100844, "Nuclear Power Plant Common Aging Terminology," November 1992. They are defined as they relate to a specific system, structure, or component (SSC) under evaluation.

A.2 Definitions

age	Time from fabrication of an SSC to the stated time.
aging	General process in which characteristics of an SSC gradually change with time or use.
aging degradation	Aging effects that could impair the ability of an SSC to function within acceptance criteria. Examples: reduction in diameter from wear of a rotating shaft, loss in material strength from fatigue or thermal aging, swell of potting compounds, and loss of dielectric strength or cracking of insulation.
aging effects	Net changes in characteristics of an SSC that occur with time or use and are due to aging mechanisms. Examples: negative effects - see aging degradation, positive effects - increase in concrete strength from curing, reduced vibration from wear-in of rotating machinery.
aging management	Engineering, operations, and maintenance actions to control within acceptable limits aging degradation and wearout of SSCs. Examples of engineering actions: design, qualification, and failure analysis. Examples of operations actions: surveillance, carrying out operational procedures within specified limits, and performing environmental measurements.
aging mechanism	Specific process that gradually changes characteristics of an SSC with time or use. Examples: curing, wear, fatigue, creep, erosion, microbiological fouling, corrosion, embrittlement, and chemical or biological reactions.
characteristic	Property or attribute of an SSC (such as shape, dimension, weight, condition indicator, functional indicator, performance, or mechanical, chemical, or electrical property).
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 and future ability of an SSC to function within acceptance criteria.
failure	Inability or interruption of ability of an SSC to function within acceptance criteria.
failure cause	Circumstances during design, manufacture, test, or use that have led to failure.
failure mechanism	Physical process that results in failure. Examples: cracking of an embrittled cable insulation (aging-related), an object obstruction flow (non-aging-related).

failure mode	The manner or state in which an SSC fails. Examples: stuck open (valve), short to ground (cable), bearing seizure (motor), leakage (valve, vessel, or containment), flow stoppage (pipe or valve), failure to produce a signal that drops control rods (reactor protection system), and crack or break (structure).
normal stressor	Stressor that stems from normal conditions and can produce aging mechanisms and effects in and SSC.
operating conditions	Service conditions, including normal and error-induced conditions, prior to the start of a design basis accident or earthquake.
qualified life	Period for which an SSC has been demonstrated, through testing, analysis, or experience, to be capable of functioning within acceptance criteria during specified operating conditions while retaining the ability to perform its safety functions in a design basis accident or earthquake.
stressor	Agent or stimulus that stems from pre-service and service condition and can produce immediate or aging degradation of an SSC. Examples: heat, radiation, humidity, steam, chemicals, pressure, vibration, seismic motion, electrical cycling, and mechanical cycling.
wearout	Failure produced by an aging mechanism.

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202 U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any) NUREG/CR-6794 BNL-NUREG-52673
2. TITLE AND SUBTITLE Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants	3. DATE REPORT PUBLISHED MONTH: January YEAR: 2003 4 FIN OR GRANT NUMBER W6822
5 AUTHOR(S) M. Villaran and R. Lofaro	6. TYPE OF REPORT 7. PERIOD COVERED *(Inclusive Dates)*

8 PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address, if contractor, provide name and mailing address)*

Brookhaven National Laboratory
Energy Sciences & Technology Dept.
Building 130, P.O. Box 5000
Upton, NY 11973-5000

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address.)*

Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

S. K. Aggarwal, NRC Program Manager

11. ABSTRACT *(200 words or less)*

An aging assessment of safety-related power cables used in commercial nuclear power plants has been performed to determine the effects of aging degradation. This study is based on the review and analysis of past operating experience, as reported in the Licensee Event Report, Nuclear Plant Reliability Data System, and Equipment Information and Performance Exchange databases. In addition, documents prepared by the Nuclear Regulatory Commission that identify significant issues or concerns related to power cables have been reviewed. Based on the results of the aforementioned reviews, predominant aging characteristics are identified and potential condition monitoring techniques are evaluated. The results of the aging assessment were then used to evaluate environmental qualification practices for power cables to determine if all significant aging mechanisms are appropriately addressed.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	13. AVAILABILITY STATEMENT: unlimited
Nuclear plant aging, power cables, condition monitoring, environmental qualification	14 SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified
	15. NUMBER OF PAGES
	16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300