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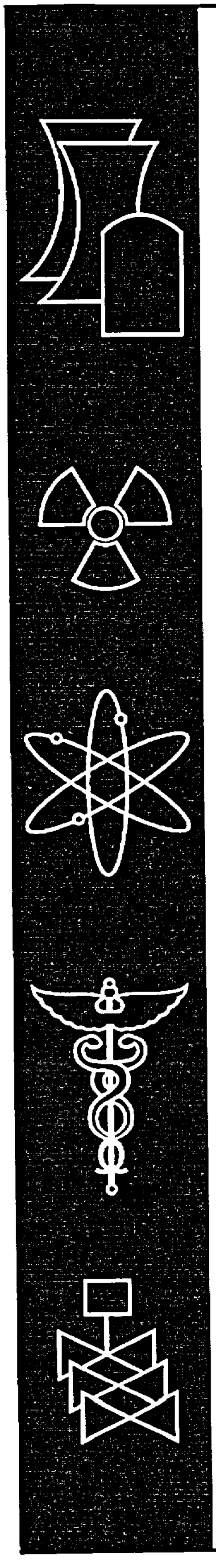

Evaluation of Aging and Qualification Practices for Cable Splices Used in Nuclear Power Plants

Brookhaven National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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ABSTRACT

An evaluation of aging and environmental qualification practices for safety-related cable splices 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 cable splices have been reviewed. Based on the results of the aforementioned reviews, predominant aging characteristics are identified and potential condition monitoring techniques are evaluated. As part of this study, a review of environmental qualification test reports and analyses related to electric cable splices was conducted. In addition, cable splices that were pre-aged and exposed to simulated accident conditions in a previous NRC/RES Program were disassembled and inspected to gain insights into splice performance and potential failure mechanisms under harsh environments.

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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 could be susceptible to aging degradation and should be studied to address issues related to their current qualification practices. Cable splices are among the equipment identified for additional study.

Cable splices are used to provide electrical connections between two conductors in different cables of the same circuit. There are two splice designs that are commonly used; 1) heat-shrink tubing or 2) tape splices. For safety-related applications, the splices must provide an environmental seal capable of preventing the intrusion of moisture or contaminants during accident conditions. The insulating materials for the splices are typically constructed of polymers, therefore, they are subject to the same aging stressors and mechanisms as the cable insulation and jacket materials.

Safety-related cable splices are used in numerous applications in a nuclear power plant, including instrumentation and control circuits, as well as power circuits. They are susceptible to aging degradation that can compromise the operation of this equipment, therefore, it is important to understand the various aging mechanisms and potential degradation to which splices are susceptible, as well as what impact this degradation may have on their performance. In light of this, the NRC Office of Nuclear Regulatory Research is sponsoring this research program to perform an assessment of the aging effects and qualification practices for cable splices.

The objectives of this research program are: (1) to characterize the effects of aging on cable splices 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 cable splices in terms of how well they address the aging effects identified, and (3) to evaluate the feasibility of in situ condition monitoring of cable splices in terms of what techniques are currently available and how effective they might be at determining the current condition of the cable splice and predicting future performance under accident conditions.

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

- Cable splice 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 splice failure, although these failures have been infrequent.

- Cable splices 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, including the loss of function of safety-related equipment, loss of safety system redundancy, reactor scrams, and unscheduled reductions in power.

- The predominant aging mechanism for cable splice failure is loosening of the connectors, which can result in intermittent operation of the equipment or complete failure. Other important aging mechanisms are corrosion of the connectors, short circuit to ground or another conductor, and arcing at loose connections.

- The failure mode most commonly found is "open circuit," in which the conductive pathway of the splice is broken. Almost equally important failure modes are degraded electrical connection, in which the degradation of electrical contact surfaces causes either high resistance or intermittent output, and electrical short circuits to ground or to other conductors.

- The number of cable splice events reported in the various databases is relatively small, suggesting that splice failures are infrequent. However, there may be a number of splice events that were judged to be of insufficient importance to report by the utility.

While the number of failures is relatively low, the data indicate that cable splices are susceptible to aging degradation that can lead to failure. Cable splices are not typically replaced on a periodic basis, unless there is a problem with the cable. As nuclear power plants age and the splices 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 splice insulation and connectors will increase. This could lead to an increase in the number of splice failures in later years of plant life. An aging management program to monitor and mitigate the effects of cable splice aging would be beneficial in anticipating these potential problems.

Aging management of cable splices 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 splices appears to be feasible. The following recommendations are made with respect to the establishment of a monitoring program:

- Visual inspection should be considered as a first step for all cable splices, connectors, and terminations that are physically accessible. This is an inexpensive, simple technique that can provide valuable information on the overall condition of a cable joint. The qualitative information obtained from visual inspection by experienced personnel can be enhanced by grading important specified parameters and attributes of a splice in the context of a well-structured inspection procedure.

- Imaging infrared thermography and time domain reflectometry are two techniques that appear to be very well suited to identifying, locating, and monitoring problems in cable splices, connectors, and terminations.

- It is recommended that any situ monitoring program include the use of several different CM methods. The method chosen for a particular application should be based on the location, configuration, accessibility, materials, and voltage class of the cable splice, connection, or termination.

- Insulation that is in good condition can, without damage, sustain the application of a dc potential equal to the system basic impulse level for very long periods. In contrast, most insulating materials will sustain degradation from ac overpotential. Consequently, high dc potential should normally be used for periodic field testing of cable and splice insulation, and care should be exercised in the selection of the test voltage levels and the frequency of testing.

As a result of the review of past environmental qualification test reports on splices, and the disassembly and inspection of splices that were preaged and exposed to simulated accident conditions, the following observations were made regarding current qualification practices:

- Since IEEE Standards 323-1974 and 383-1974 were adopted and endorsed by the NRC, the requirements, procedures, and acceptance criteria for the qualification testing of cable splices have become very consistent. Cable splices are treated as an integral part of cable systems in a nuclear power plant, and current qualification practices are consistent with that philosophy.

- From the qualification tests reviewed, cable splices are sometimes subjected to more severe environments during qualification than the electric cables to which they will be applied.

- The currently accepted IEEE standards for qualification of cable splices adequately address the effects of aging related degradation on the design and materials used in the construction and sealing of cable splices. However, qualification testing used for the purpose of generically qualifying a specific splice design or construction may not address all of the stressors that may be important for the degradation of a splice in all applications. Loosening of the connectors in splices, caused by vibration, thermal or mechanical cycling, electrical transients, or mechanical stress, was identified as the predominant aging mechanism for splices in the operating experience review. However, none of these stressors was specifically addressed in the qualification tests that were reviewed for this study. These stressors are application specific, and would only be a potential problem in applications where such stressors are actively involved. In many cases, the best way to manage application specific stressors is by maintenance, inspection, and condition monitoring.

- Qualification testing has demonstrated that the materials used in heat-shrinkable and taped splices perform exceptionally well when used in a properly engineered and installed cable splice. However, splice performance will be adversely affected if these materials are misapplied, improperly installed, or damaged during installation or subsequent service. Common installation problems include:

    - Inadequate heat-shrink tubing seal length
    - Improper shim size/installation
    - Improper use of padding on sharp corners or surfaces, or on bolted connections
    - Exceeding the recommended bend radius limitations for the splice
    - Improper/inadequate application of sealant under heat-shrink tubing
    - Misapplication of the splice in the intended use range

- Installation of splices onto cables that had been exposed to accelerated thermal and radiation preaging can be problematic. Hardening and cracking of the cable jackets can make it difficult to obtain a good seal when heat-shrinkable material is applied over it. Cracked and damaged cable jackets can provide a leakage pathway for high pressure steam, moisture-borne deposits, chemical spray, and other contaminants to enter into the interior of cable splices and adversely affect performance.

- In multi-conductor splice geometries sheathed by an overall covering of heat-shrinkable sleeving, high pressure steam, moisture-borne deposits, chemical spray, and other contaminants can enter into the interior of cable splices via the spaces between the multiple conductors if these areas of the splice have not been properly sealed. A sufficient quantity of nuclear sealant must be applied to assure that these areas are properly blocked and sealed against the environment.

The observations made during the evaluation of current qualification practices for splices have resulted in the following conclusions:

- In addition to the thermal and radiation preaging, vibration, temperature cycling, high humidity or other location-specific conditions should also be considered as preaging stressors in the qualification testing of cable splices for generic applications.

- Prior to applying a splice to an aged cable, the condition of the cable insulation and jacket should be evaluated to determine if a good seal can be made. Evidence of hardening or cracking should be considered an indicator that proper sealing will be difficult or impossible.

- The importance of training, proper engineering, and proper specification of splices for specific applications, and the proper installation of splice kits in accordance with manufacturer's instructions should be emphasized. A deficiency in any one of these areas can lead to poor splice performance.

ACKNOWLEDGMENTS

The research program described in this report was sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission. The authors would like to express their gratitude to Satish Aggarwal, NRC Project Manager, for the technical and administrative support he has provided in performing this study.

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1.0 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 could be susceptible to aging degradation and should be studied to address issues related to their current qualification practices. Cable splices are among the equipment identified for additional study.

Cable splices are connections used to join two ends of a cable both electrically and physically. There are two splice designs that are commonly used; 1) heat-shrink tubing or 2) tape splices. For safety-related applications, the splices must provide an environmental seal capable of preventing the intrusion of moisture or contaminants during accident conditions. The materials of construction for the splices are typically polymers, therefore, they are subject to the same aging stressors and mechanisms as the cable insulation and jacket materials.

Safety-related cable splices are used in numerous applications in a nuclear power plant, including instrumentation and control circuits, as well as power circuits. They are susceptible to aging degradation that can compromise the operation of this equipment, therefore, it is important to understand the various aging mechanisms and potential degradation to which splices are susceptible, as well as 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 cable splices.

In past studies performed on electrical equipment aging [1,2], the typical aging stressors and failure mechanisms to which cable splices are susceptible have been assessed based on available operating data. The current study will build upon these past results using more recent operating experience to determine whether the predominant aging mechanisms previously identified are still the most important, or if any previously unidentified aging characteristics that could affect performance are now becoming 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 is expected to be the most insightful. These results will then be used to evaluate current qualification practices for cable splices to determine if aging is adequately addressed and if improvements are warranted.

1.2 Objectives

The objectives of this research program are: (1) to characterize the effects of aging on cable splices 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 cable splices in terms of how well they address the aging effects identified, and (3) to evaluate the feasibility of in situ condition monitoring of cable splices in terms of what techniques are currently available and how effective they might be at determining the current condition of the cable splice and predicting future performance under accident conditions.

1.3 Scope

This study will examine cable splices used for low-voltage (<1kV) and medium-voltage (2kV to 15 kV) safety-related applications in nuclear power plants. The boundaries of the study will encompass the cable splice components, including the conductor connectors, the insulating material, and any sealing compounds used in the splice.

2.0 DESCRIPTION OF CABLE SPLICES

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

2.1 Subcomponents and Materials of Construction

Cable splices, also referred to as joints, are connections used to join two ends of a cable both electrically and physically. They must provide electrical continuity between the connected conductors while also providing electrical separation between the conductors being joined and other conductors in the same cable, adjacent cables, or electrical ground. Ideally, the splice will also provide the same, or better, level of mechanical strength, along with thermal and chemical resistance characteristics that are similar to the original cable.

Splices are commonly used in nuclear power applications to connect equipment extension leads to field cable, or to connect separate runs of field cable together. The splices are designed for low-, medium- and high-voltage applications, although the majority of environmentally qualified splices for application in harsh environments in nuclear power plants are low-voltage (<1,000 volts) [2]. This study will focus on low- and medium-voltage cable splice designs since they are the predominant types of splices used in safety-related applications.

For most low-voltage applications, such as instrumentation and control cables, the splice designs are relatively simple. Nevertheless, it is important to follow the proper installation procedures, particularly for environmentally qualified electrical splices, to assure that the dimensions, connections, cleanliness, insulating materials, and other details of the splice will be as specified in the original design. A mechanical device, such as a butt-type crimp or compression connector, or bolted ring lugs are used to connect the uninsulated conductors from the two cable ends being joined. If the outer diameters of the insulation on the cable ends are different, shims are used to build up the smaller diameter to match the larger diameter end. The connection is then covered with a potting compound to provide an environmental seal (if necessary) and an insulating material is then used to cover the entire joint. The insulating material is typically a polymer tape, which is wrapped over the spliced section of the cable in an overlapped configuration, or a heat-shrinkable tubing, which is placed over the cable joint and heated to shrink it in place. The potting compound and insulating material are typically applied so that they extend several inches past each end of the mechanical connector. Figure 1 shows a typical cable splice design for low-voltage applications.

For medium-voltage applications, such as power cables, the splice design is similar to that used for low-voltage applications, however, there are design differences that must be incorporated to handle the higher electrical stresses imposed at the cut cable ends from the conductor to the insulation shield. When a medium voltage cable must be spliced, the details of the joining process, i.e., physical dimensions, cleanliness, geometry, dryness, materials compatibility, and installation technique, all become much more critical. Consequently, when a medium-voltage cable is cut, special termination procedures must be followed to minimize the resulting stress concentration due to the disruption of the cable geometry at the cable end. Typically, stress cones are used to minimize this stress concentration by increasing the spacing from the

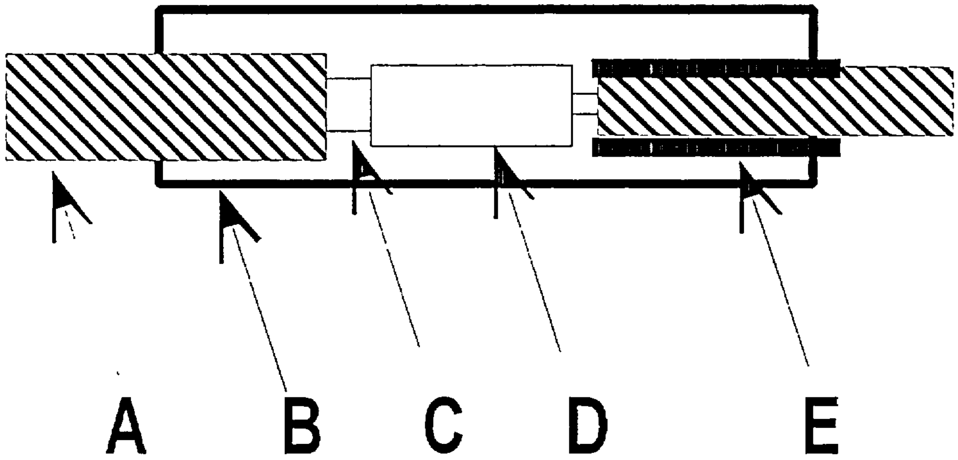


Figure 1: Typical cable splice design for low-voltage applications
A = Cable conductor insulation
B = Splice outer insulating jacket
C = Cable conductor
D = Mechanical conductor connector
E = Insulation shim

conductor to the end of the insulation shield. The stress cones can be fabricated by hand taping, or pre-molded designs can be used [4]. Figure 2 shows a typical configuration using stress relief cones in a cable splice. Other forms of stress relief are the application of high permittivity materials, or materials with non-linear current-voltage characteristics to the cable ends [5]. These also act to spread out the equipotential lines and minimize the stress concentration on the cable insulation ends. The mechanical connectors used to join the cable conductors in a splice are normally constructed of either the same metal as the cable conductor or an electrolytically compatible alloy. Cable conductors are typically copper, although aluminum conductors are not uncommon, particularly in the larger diameter cables. The connectors for copper conductors are varied and can be of the crimp, compression, solder or welded type. Aluminum connectors require greater care due to the increased thermal instability of this material compared to copper. To minimize electrical stress in medium-voltage applications, the connector designs incorporate tapered shoulders and filled indents.

The insulating materials used in splices are generally polymers. The material chosen must be compatible with the cable materials, and its thickness must be sufficient to withstand the design stress of the cable operating voltage. The tape-wrap type insulations are self-amalgamating tapes that form an environmental

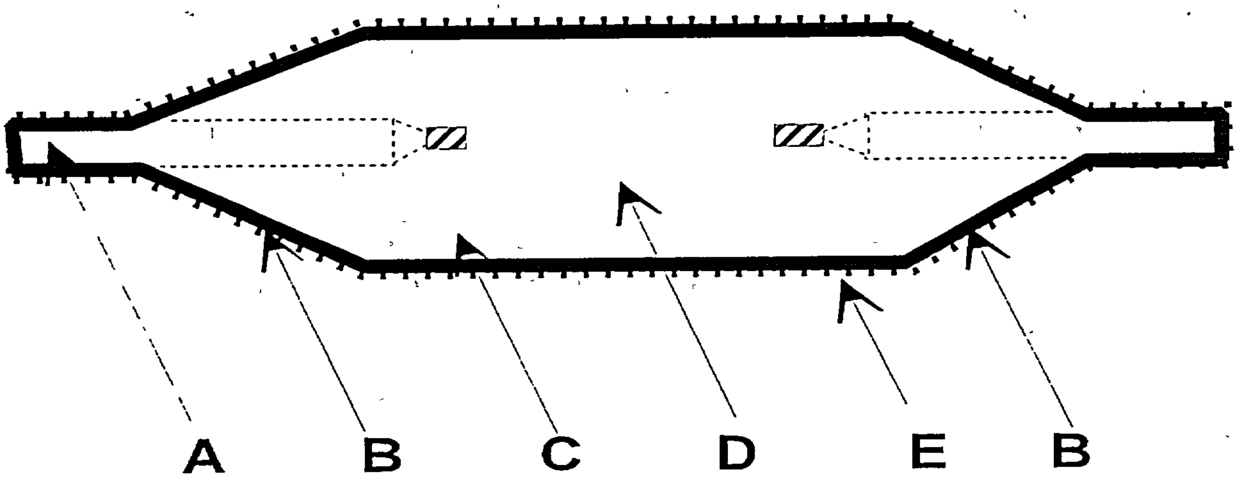


Figure 2: Cable splice with stress cones for medium-voltage applications
A = Cable insulation
B = Stress cone
C = Joint insulating material
D = Conductor connector
E = Shield

seal once they are applied. These tapes are typically made of ethylene propylene rubber (EPR), ethylene propylene diene monomer (EPDM), silicone, or polyvinylchloride (PVC) material [2]. The heat-shrink tubing type insulations are made of polyolefin compounds that expand after being cross-linked using irradiation [4].

When splicing medium-voltage cables that include a shield, the splice must also connect the shields on the cable. These splice shields must be compatible with the cable materials, and are typically made of polymers to which carbon black has been added. This makes the material conductive and allows it to drain off electrostatically induced voltages, charging currents, and leakage currents.

Metallic neutral conductors may also be required as part of the splice to connect the cable ground wires. These may be made of stranded copper wire or copper tape.

2.2 Operating Environments and Aging Stressors

Cable splices can be installed in various locations in the plant, including underground ducts and conduits, above ground raceways and cable trays, electrical equipment termination enclosures, and in cable junction boxes. The installation location will affect the service conditions under which the splices must operate and could have an impact on their aging degradation rate. Installation 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 would increase their degradation rate. Also, installation in cramped junction boxes can impose mechanical stresses on the splices that can result in cracking or other degradation. Cable splices at or near operating electric motors, pumps, fans, engines, pipelines, generators, or other equipment will be subjected to various combinations of mechanical and thermal cycling or vibration for extended periods. This may lead to mechanical wear, fatigue, and loosening of crimped and bolted connectors, as well as contributing to the degradation of electrical connections. Cable ducts that run below grade or beneath floor level may be susceptible to seepage and water intrusion that can compromise the integrity of splices installed on cables in those locations.

Similar to electric cables, aging degradation of the insulating material is a concern for splices. In addition, the other subcomponents that make up an electrical splice are also susceptible to aging degradation due to the various stressors to which they are exposed, particularly the connectors, which are susceptible to loosening and corrosion. Table 1 summarizes the potential environmental stressors, degradation mechanisms, and aging effects for cable splices.

Table 1: Summary of potential aging mechanisms and aging effects for cable splices

Subcomponent	Material	Stressors	Potential Aging Mechanisms	Potential Aging Effects	Comment
Insulation; Shield	• Various polymer materials (e.g., XLPE, EPR)	• Elevated temperature • Elevated radiation fields • Mechanical cycling • Vibration • Electrical transients • Overvoltage	• Embrittlement • Cracking • Mechanical wear • Treeing	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	Elevated temperature can be due to external environment or high resistance from a poor or degraded electrical connection.
	• Various polymer materials that are permeable to moisture	• Wetting	• Moisture intrusion	• Decrease in dielectric strength • Increase in leakage currents • Eventual failure	Cracking of splice outer jacket or underlying cable jacket can lead to moisture intrusion into splice.
Connnector	• Copper • Aluminum	• Wetting due to moisture intrusion	• Corrosion • Oxide formation	• Increased electrical resistance to current flow • Increased ohmic heating	
	• Copper • Aluminum	• Vibration • Mechanical Stress • Thermal & mechanical cycling • Electrical transients	• Metal fatigue • Loosening of connectors	• Loss of structural integrity • Degraded connector contact	Applicable to portion of splice connecting conductors on two separate cables.

3.0 SUMMARY OF PAST RESEARCH ON CABLE SPLICES

As part of the current study, a literature search and review was performed to identify past work on aging of cable splices. 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 can be avoided and insights gained from past research can be incorporated into the current study.

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

3.1 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 limitation of this study as it relates to splices is that all connectors (terminal blocks, coaxial connectors, and cable splices) are combined and treated as one in the data review and analysis. Therefore, no results specific to cable splices are presented.

A review of operating experience from LERs was found to provide relatively few events, thus, little information on failure causes or mechanisms was obtained. The following insights are presented related to connectors:

- failures are predominated by loose connections (32%) and bad connections (28%). The remaining failures are moisture/corrosion related failures (10%), design problems (22%), and shorted connections (8%),
- the loose connection type failures are typically found on crimped connectors rather than screwed or bolted connections in splices, and this is usually due to inadequate crimping,
- electrical leakage or shorting is expected to be the most likely failure cause under accident conditions,
- electrical insulating heat shrink tubing and tape materials are similar to cable insulation materials, and are susceptible to the same aging mechanisms, and
- correct installation and adhesion of the tape or splice is important to prevent failure of the splice

The study concludes that cable splices are highly reliable devices under normal plant operating conditions, with no evidence of significant failure rate increases with age. In regard to condition monitoring, cable splices 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.

3.2 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.

The study found that there are relatively few failures of electric cable splices. It is noted that the data are limited in that there are no accident performance data, and operating experience is limited to plants that are typically less than 20 years old.

The review of operating experience for low-voltage splices found that most events did not identify the failed component, however, for those that did the insulation (18%) and conductor (18%) were the predominant component failed. The predominant failure mode was grounding or short circuit (29%) and high resistance (29%). Most (47%) of the reported failures were detected during operation, and 35% were detected during surveillance testing. Similar results were found for medium-voltage splices.

3.3 NUREG/CR-6412, "Aging and Loss-of-Coolant Accident (LOCA) Testing of Electrical Connections," prepared by Sandia National Laboratories, January 1998 [3].

This study performed for the NRC presents information on the aging and accident performance of various electric cable connectors, including splices. In this study, the components were exposed to accelerated aging conditions to simulate 60 years of service, then exposed to simulated LOCA conditions. During the aging and accident testing, electrical testing was performed to monitor the performance of the components.

The results of the testing showed that the Okonite and Raychem splices performed acceptably, even after accelerated aging to 60 years of service. No information on predominant aging stressors or mechanisms, or on typical failure modes is presented in this report.

3.4 NUREG/CR-6704, "Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-voltage Electric Cables," Brookhaven National Laboratory, February 2001 [6]

This report documents the results of a cable research program performed by Brookhaven National Laboratory for the NRC. In this program, several different low-voltage cables were preaged and exposed to simulated accident steam test conditions to obtain performance data. The test configuration included ten-foot test specimens that were energized during the accident simulation tests. This required connection of the test specimens to leads connected to data acquisition equipment. The connections were protected with qualified Raychem splices, which were applied after the cables were preaged. For several of the test specimens, the outer cable jacket was embrittled and cracked due to the preaging performed. During subsequent testing under simulated accident steam conditions, these cables exhibited high leakage currents and failed a post-accident submerged dielectric withstand test. The failures were attributed to moisture intrusion into the splices through the cracked cable outer jackets.

While the Raychem splices were not meant to be tested in this study, the cable performance data provided insights into splice performance when applied to degraded cables. These data identified the potential problems of applying splices to degraded cables, particularly when embrittlement and cracking of the cable outer jacket is present, or if such a condition might subsequently develop.

4.0 PAST EVENTS RELATED TO CABLE SPLICE 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 cable splices. Since past studies reviewed documents up to 1994, this search covered the period January 1994 to July 2001.

4.1 Summary of Past Cable Splice Events

Two 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 NRC Information Notice 98-21

This information notice discusses results of testing performed by Sandia National Laboratories on various cable connectors, including Raychem and Okonite cable splices [3]. The test specimens were preaged to simulate 60 years of service, then exposed to simulated accident conditions. A number of the connectors failed to pass a post-accident dielectric withstand test. While the Raychem and Okonite splices performed acceptably, this notice points out that the integrity of the cable jacket to which the connector is attached is important in preventing moisture intrusion into the connector. This scenario was observed during cable testing in a program performed by Brookhaven National Laboratory in which cable performance anomalies were observed due to jacket cracking, which allowed moisture intrusion into the Raychem splices used to connect the test cables to the facility lead wires [6].

4.1.2 Headquarters Daily Report, May 26, 2000

This report discusses an event at the Cooper Nuclear Plant on April 3, 2000 in which plant management informed the resident inspectors that drywell temperature profiles during design basis accidents may exceed their equipment qualification test temperatures. Subsequent review determined that the overall concern with the environmental qualification of drywell equipment was bounded by existing test results, as long as all electrical splices were in the configuration bounded by the test. To confirm the actual configuration of the installed splices, an inspection was performed. The inspection found that, for most of the Okonite tape splices, the outer tape was unraveling.

A special inspection was subsequently performed to review the circumstances of these non-conforming splices. It was determined that the splices had not been wrapped properly and were coming undone when the problem was spotted. This was identified as a significant safety concern since there was a high potential for moisture exposure in the areas in which the splices were located. Some of the electrical wiring involved was for safety-related equipment. All 2000 splices in the plant were subsequently replaced.

4.2 Evaluation of Past Events

The events identified from a review of NRC documents are relatively few, however, they demonstrate that cable splices are susceptible to age degradation that can compromise their performance. Splices are used throughout the plant for many safety-related applications and their failure can have a significant impact on plant operation, including the loss of function of safety-related equipment, reactor scrams, and unscheduled reductions in power. Since their primary insulating materials are polymers, similar to that used in electrical cables, they are susceptible to the same aging stressors and mechanisms. It is noteworthy that the number of reported cable splice events is relatively small, suggesting that splice 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 cable splices. 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 unless they have an impact on plant safety, as described in the reporting requirements specified in 10 CFR 50.73. The events reported cover any and all equipment and systems in the plant that have an impact on plant safety, but, they 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 individually 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 criterion was purposely made broad to ensure that no relevant events were omitted. The search generated 69 events, which were reviewed to identify age-related cable splice incidents. A total of three events out of the 69 were identified that were relevant for this study. This low number of events suggests that cable splice failures that significantly affect plant safety are infrequent, which is consistent with results from previous studies. The relevant LERs are discussed in the following paragraphs.

5.1.1 LER 45494007, "1B Wide Range Hot Leg RTD Indication Spiked Low and Could Not be Restored Within LCO Time Limit"

On July 25, 1994, at the Byron Nuclear Power Station, during the Reactor Containment Fan Cooler (RCFC) monthly surveillance a Wide Range Hot Leg resistance temperature detector (RTD) spiked low. An amplifier card was replaced and the circuit calibrated, but oscillations still occurred when the RCFC's were started in low speed. The Wide Range Hot Leg RTD was declared inoperable and relief was requested from the Technical Specification related to remote shutdown instrumentation.

The root cause of this instrument failure was a bolted lug type splice at the RTD pigtail and the field cable which goes to the containment penetration. The RTD pigtail is a solid copper conductor and when the lug is crimped to it, it is difficult to get a good electrical connection. It was reported that a butt splice would be installed during the next refueling outage. A similar problem had occurred previously on the narrow range RTD's and was corrected for all the narrow range RTD's with a butt splice technique. It is believed that when the RCFC's speed is changed, a flow induced vibration or a temperature transient affects the RTD connection which gives the erratic indication. It was indicated that all Unit 1 Wide Range RTD's splices would be replaced during the next outage. Unit 2 Wide Range RTD's splices were to be replaced during the next Unit 2 outage starting in February 1995.

The LER identified six previous events involving failure of a Wide Range RTD and replacement of the RTD. These failures were believed to be caused by a poor connection in the splice at the pigtail of the RTD and not the RTD itself. Byron conservatively replaced the splice and RTD. A new splice has been qualified and was to be installed in the outage beginning September 8, 1994.

5.1.2 LER 34697014, "Pressurizer Pilot-Operated Relief Valve Setpoint Less than Allowable Value Due to Degraded Wire Splice"

On August 1, 1997, at the Davis-Besse Nuclear Plant, with the plant operating at full power, a problem was discovered involving the Nuclear Instrumentation output from the Reactor Protection System to the Non-Nuclear Instrumentation System. Troubleshooting revealed a faulty wire splice connecting the RPS signal common and power common bus bars to the instrument ground bus had caused a voltage difference between the bus bars. The wire splice was repaired on August 7, 1997. It was determined on August 11, 1997 that this problem affected the Pressurizer Pilot-Operated Relief Valve (PORV) setpoint, but that the PORV setpoint was within Technical Specifications. Further detailed examination of the incident in October 1997 showed that the PORV setpoint was outside the Technical Specification allowable value.

The wire connecting the RPS Channel 2 common bus bars to the instrument ground bus contained a butt splice that caused a voltage difference of between approximately 120 and 170 millivolts. This resulted in the RPS Channel 2 bus bar being at a higher potential than the instrument ground bus. This splice appears to have existed since the original plant startup. The electrical resistance of the splice apparently increased due to a gradual breakdown of the conductor and contact surfaces over time. The data recorded by the Integrated Control System data acquisition and analysis system was reviewed after the degraded splice was repaired. This review showed the electrical resistance of this splice was not of significant magnitude for detection until approximately one month prior to identification of the problem. The same condition was checked for in all other channels of the RPS, and no problems were noted.

The wire containing the faulty splice was replaced on August 7, 1997. This restored the RPS Channel 2 signal common and power common bus bars to within several millivolts of the instrument ground bus bar.

There have been no LERs within the past three years of this event associated with grounds in essential instrumentation systems, or associated with the operability of the PORV.

5.1.3 LER 24498005, "Loss of 34.5 kV Offsite Power Circuit 751, due to Faulted Cable Splice, Results in Automatic Start of "B" Emergency Diesel Generator"

On November 20, 1998, at the Ginna Nuclear Plant, power from the 34.5 KV offsite power source was lost resulting in de-energization of a 4,160 volt bus and 480 volt safeguard buses. An emergency diesel generator automatically started and re-energized the safeguard buses. There was no change in reactor power or turbine load.

The underlying cause of the loss of power from the 4,160 volt bus was a faulted cable splice in an underground cable at a manhole. The faulted splice was an original splice in the cable, installed approximately 30 years ago, and is the only operational fault of a splice on this circuit. This event was categorized as NUREG-1022 Cause Code (B), "Design, Manufacturing, Construction/Installation."

The faulted splice was reconstructed by plant personnel and the circuit was cleared for use and reenergized. The cable for the circuit tested satisfactorily, however, it was indicated that the cable will be replaced as part of the plant's cable replacement program. The failed component was a splice in a 34.5kV 250 MCM electrical cable, with XLP insulation.

An historical search of LERs identified six (6) similar events with similar root causes (start of an emergency diesel generator due to loss of offsite power from external causes). However, none of the external causes for these LERs were due to faulted underground cables or faulted splices in the cable.

5.1.4 Non age-related LERs Pertaining to Cable Splice Issues

Ten LERS involving non-aging cable splice issues were identified, and are summarized below for information. These events involved various installation problems related to the lack of conformance to environmental qualification requirements, inadequate installation requirements or inadequate repair procedures.

On July 20, 1995, at the Palisades Nuclear Plant, during cold shutdown, a review of qualified splices was initiated as a result of a problem with a splice completed during a transmitter replacement. It was discovered that 12 instrument loops had V-bolted type qualified cable splices connecting Rosemount conduit seal pigtail wires to instrument field cable. The design of the splice was such that it left several inches of Kapton insulation on the wire exposed. This insulation has been shown to degrade over time when exposed to the steam and water chemistry of a LOCA. It was determined that this splice design was a potential safety concern since the Kapton insulation could degrade during a LOCA causing failure of the splice and the equipment to which it was connected. The splices were replaced with qualified in-line splices which cover the Kapton insulation.

On April 21, 1994, at Palo Verde Units 1, 2 & 3, it was determined that the Raychem heat shrinkable high voltage (i.e., 5kV) motor splice kit installation instructions do not ensure that the ribbon adhesive will thoroughly melt with each application, potentially impacting a uniform moisture seal required to meet harsh environmental equipment qualification requirements. An investigation determined that the Raychem splice kit installation documentation was inadequate in that the method prescribed did not ensure a proper seal in order to prevent moisture intrusion.

On May 15, 1996, at Vogtle Unit 1, containment sump level transmitters were found to be wired with cabling that was not environmentally qualified because the outside jacketing had been removed on a cable on one side of a splice. Further investigations determined that on Unit 2 an unjacketed splice was left in a junction box that was not environmentally qualified. A splice was also found that did not fully jacket the conductors. A similar event was reported at Vogtle Unit 1 on March 22, 1997. In this event, two atmospheric relief valves were found to have cable splices that were not fully jacketed.

On November 24, 1996, at Palisades, during a routine refueling outage maintenance activity, a Class 1E electrical cable splice was discovered to have been installed incorrectly due to an inadequate procedure. Thus, the installation could not be considered qualified for Class 1E service. The splice was made in a manner that included the PVC jacket on a Rome cable conductor within the Raychem splice. This resulted in a configuration which had not been qualified by test. Of the 381 splices inside containment that could have been affected, a total of 270 splices were replaced.

On December 16, 1996, at Monticello, an unqualified electrical splice was found by a system engineer performing an as-built inspection. An electrical connection in a box was bolted and then taped which was not in accordance with environmental qualification requirements.

On March 6, 1998, at D.C. Cook Units 1 and 2, it was determined that the splices for the limit switches on the Unit 1 pilot operated relief valves (PORVs) were installed without the breakout boot required for environmental qualification requirements. For Unit 2, inspection of the PORV limit switches confirmed that the breakout boot was installed, however, it was identified that a problem with the length of the splice overlap existed at a different splice location. The root cause of the lack of breakout boots was determined to be inadequate guidance in the installation documents. The root cause for the improper splice overlap length could not be determined. These splices are not normally accessed during routine work and no record could be found that indicated when these splices were last worked or when they were originally installed. A review of documents that provide the splice installation details clearly indicate a requirement for a 6 inch sleeve length with a 2 inch overlap.

On April 5, 1998, at Salem Units 1 and 2, the epoxy covering was determined to be missing from terminals in the RTD enclosures for the hydrogen analyzers. Following the initial installation of the hydrogen analyzers the requirement for coating the terminals inside the RTD enclosure with epoxy following the replacement of the hydrogen sensors was not included in the appropriate procedures. The uncovered terminals within the RTD enclosures of the hydrogen analyzers were repaired by butt splicing the wires and covering the splices with an environmentally qualified Raychem sleeve.

An event similar to the previous event occurred on June 15, 1998 at Point Beach Unit 1. The component instruction manual for system maintenance of the hydrogen monitors, including sensor replacement, did not identify the need for replacement of the protective coating applied to the monitors' electrical terminal strips if the connections were ever disturbed.

On October 9, 1999 at Surry Unit 1, a bus bar-to-cable connection experienced electrical arcing due to moisture intrusion into the protective sleeve of the cable connection. It was concluded that the vertical orientation of the failed cable connection to the 4160 V bus permitted moisture to enter the protective sleeve of the connection. The moisture within the connection provided a conductive path from the cable conductor to the cable shielding. This path allowed electrical arcing to occur within the connection, which caused the overvoltage annunciator to alarm.

In addition to the ten non aging-related LER's described above, one other LER that occurred prior to 1994 is mentioned here because it resulted in a reactor scram. It is also notable because the splice failure occurred on a non nuclear-safety system. On December 22, 1991, while reducing power from 95% at Clinton 1, the reactor had to be manually scrammed when the 'B' reactor recirculation loop suddenly indicated a decrease in flow concurrent with changes in flow control valve position. The valve position control circuitry failed due to an incorrectly installed butt splice at the valve position transducer. Electrical contact at the splice had degraded and caused a high resistance at the splice which was interpreted by the control circuitry as a valve position error.

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.

5.2.1 NPRDS Reports Pertaining to Age-related Failures of Cable Splices

A keyword search of the NPRDS database was performed covering the period from January 1994 through December 1996 to identify events related to "splice(s)." This was further supplemented by additional keyword combination searches such as "tape" near "cable, wire, wiring, lead, and insulation," and "cable" near "Raychem, wire and sleeve, RTV, and heat shrink." As with the LER database, broad search criteria were used to ensure that no relevant events would be omitted. The search generated 42 events, which were reviewed to identify age-related cable splice incidents. A total of 24 out of the 42 were identified as being relevant for this study. The low total number of events is consistent with the LER search results, suggesting that splice failures occur infrequently.

Since the NPRDS contained the greatest number of splice-related failure events, these data were analyzed more closely to gain insights into the details of cable splice failures. Figure 3 shows the distribution of the failed subcomponent of the splices in the failure reports. The majority of the failures (75%) involved degradation or failure of the electrical connection portion of the splice. In nearly half of these cases, this involved a problem with a compression connection or crimp-type butt splice connector. In the other half of the electrical connection problems, insufficient information was available to classify the specific type of electrical connection used. Degradation or failure of insulating tape or heat shrink insulating material was identified in 17% of the events reported. One event resulted from the failure of the electrical conductor in a splice and one event was caused by a degraded bolted electrical connection.

Figure 4 shows the distribution of the applications in which the reported NPRDS splice failures were utilized. Slightly more than half of the failed splices were being used in instrumentation and control (I&C) circuits. These included spliced connections at instruments, recorders, and switches (25%), I&C field splices (17%), and I&C penetration connections (4%). About 42% of the splice failures reported were found in motor applications, including pump drivers, motor operated valves, and fans/blowers. Only one aging-related power cable splice was reported to NPRDS in the period 1994 through 1996. These results are consistent with the operating voltage levels reported for the failed splices: 58% were 120 volts or less (corresponding to most instrumentation and control applications), 37.5% were operating at 480Vac (corresponding to most 3-phase ac motor applications), and one was operating at 2400Vac (a power cable application).

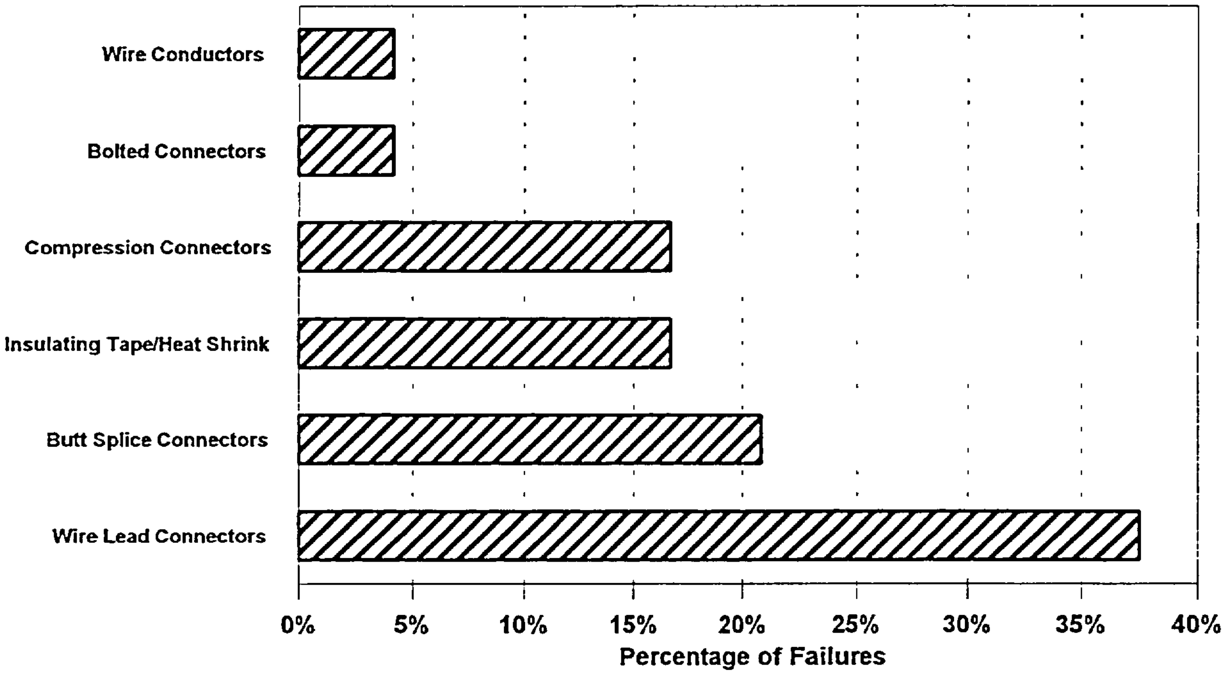


Figure 3: Subcomponents failed in cable splices - from NPRDS

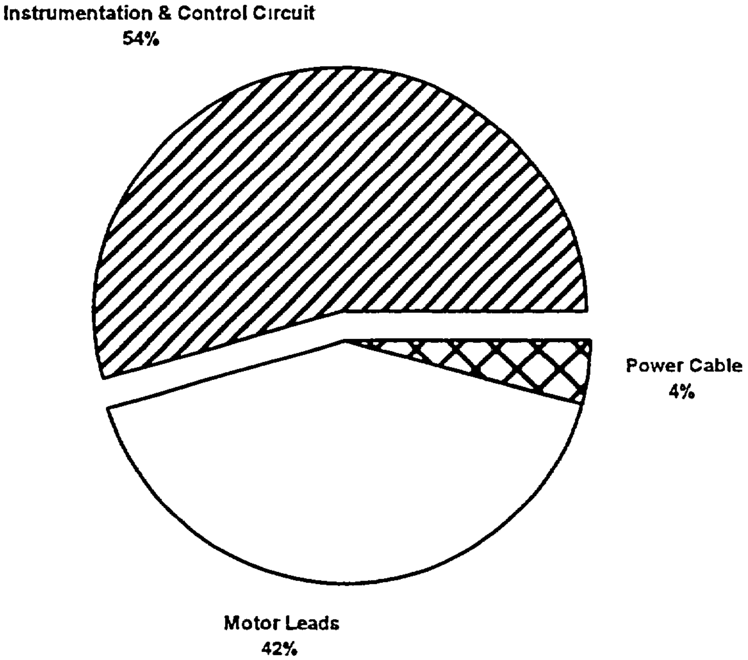


Figure 4: Applications of failed cable splices - from NPRDS

The failure mechanisms determined for the NPRDS splice failures are presented in Figure 5. Most of the failure mechanisms in these events affected the electrical connection pathway of the splice, which is consistent with the splice subcomponent failure information presented in Figure 3 above. Failure mechanisms affecting the conductive pathways of the splice included thermal and mechanical cycling (42%) (which tend to loosen bolted and compression connections), corrosion/degradation of the electrical contact surfaces (29%), mechanical wear and stress (12.5%), and vibration (8%).

The resulting failure modes for cable splice failures are summarized in Figure 6. In 38% of the events, the splice failed as an open circuit. In one third of the cases, the splice failure was manifested as a degraded electrical contact; this consisted of either a high resistance electrical connection (12%), causing excessive heating in and around the degraded connector, or an intermittent electrical connection (21%). In the remainder of the events reported to NPRDS, the failure mode was either an electrical short circuit to ground (25%) or a line-to-line electrical fault (4%).

The effect of the splice failures on the system in which they are operating was most frequently (63%) a loss or degradation of a function of one or more channels, trains, or systems. In 13% of the cases, the plants reported that the splice failure event resulted in the degradation of a train or channel. There was no effect reported on the function or operation of the system in the remaining 25% of the events. These results are shown in Figure 7.

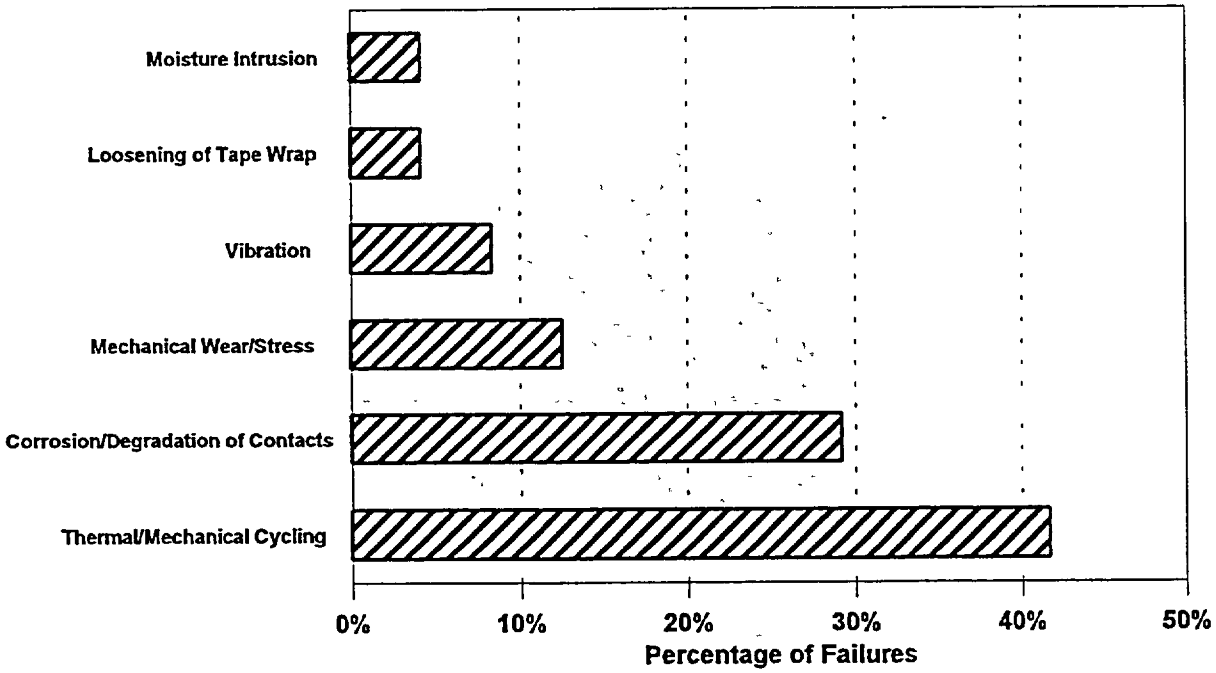


Figure 5: Distribution of failure mechanisms for cable splices - from NPRDS

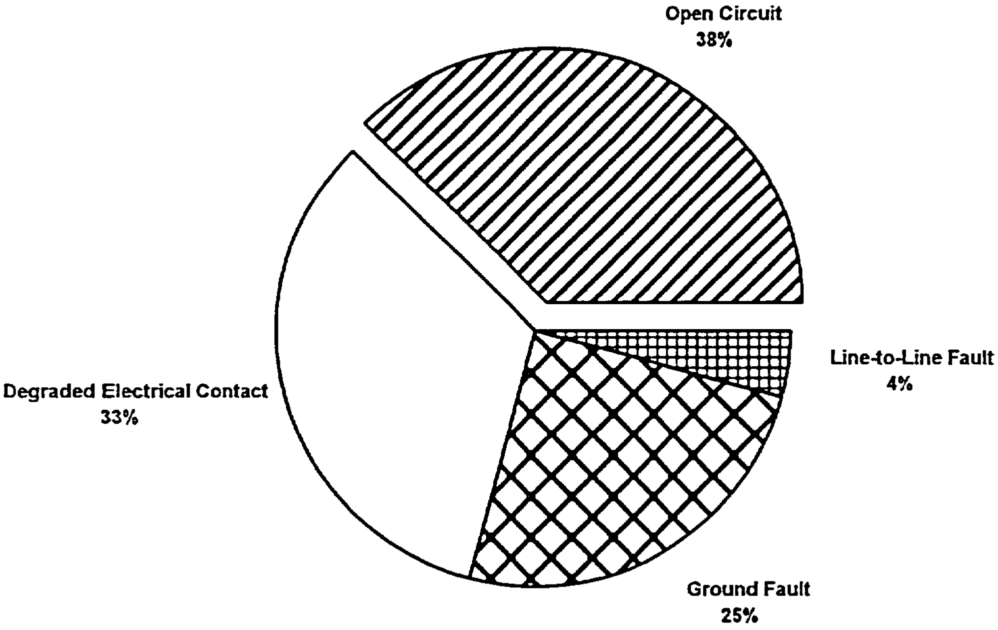


Figure 6: Failure modes for cable splice events - from NPRDS

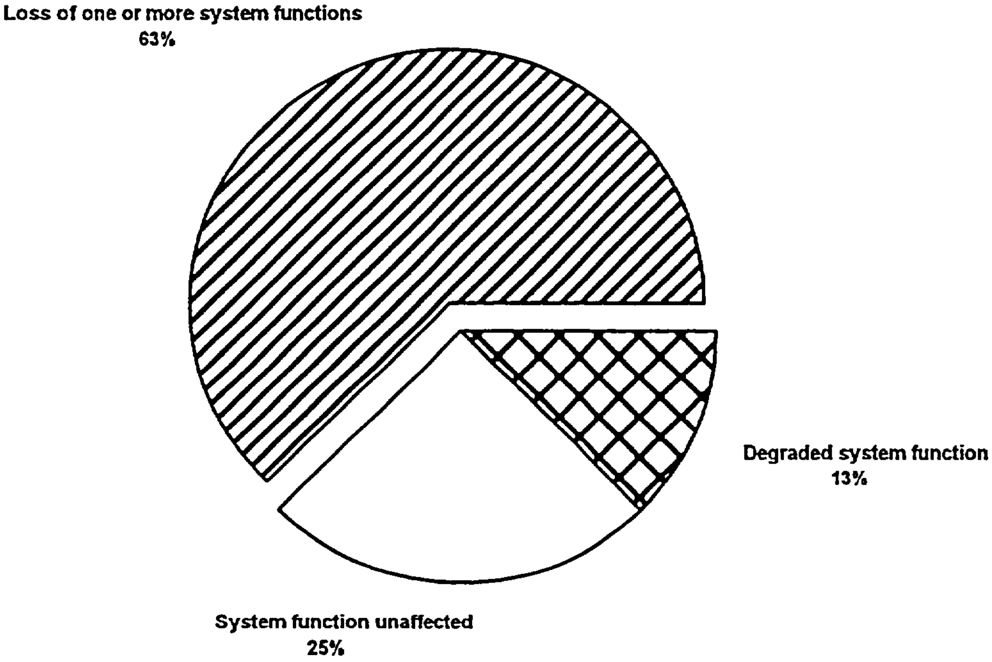


Figure 7: Effect of cable splice failures on system - from NPRDS

Finally, the method of detection was reviewed for the splice failure events. This information is presented in Figure 8. Most of the splice failures were detected during operation rather than during maintenance or surveillance activities. In 37.5% of the events, the splice failure was noted following an operating abnormality or failure to operate. A system alarm was received in 25% of the events which were caused by a splice failure. Observation was reported as the means of detection in 17% of the splice failures. Splice failures were detected by maintenance or testing in only 21% of the age-related events reported to NPRDS. This indicates that there is room for improvement in the detection of degraded or failed cable splices by adopting improved condition monitoring techniques, or specifically including splice inspection or testing in preventive maintenance or surveillance procedures for critical equipment and systems.

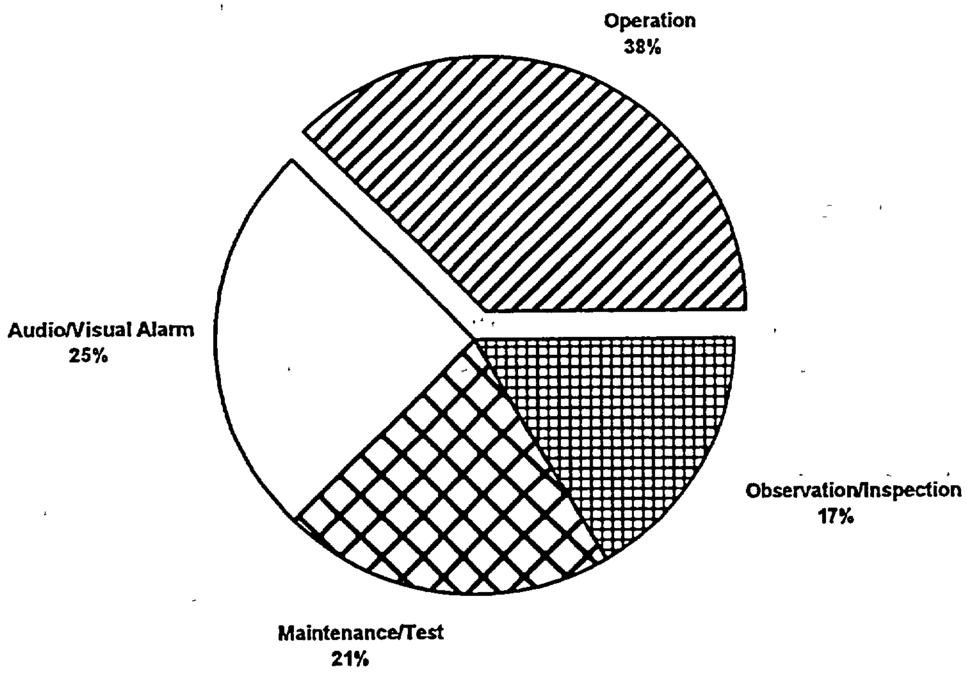


Figure 8: Cable splice failure detection methods - from NPRDS

5.2.2 NPRDS Reports Pertaining to Non-aging Cable Splice Issues

Eight NPRDS reports were found that involved non-aging cable splice installation issues including: an oversized junction box, cables pulling out of the splice box or pulling apart, human errors during installation, and inadequate design. Another report involving an installation issue that may be of greater interest is discussed below.

On September 19, 1995, at Summer 1, it was discovered that there was a broken motor lead in the auxiliary lube oil pump motor for the chemical and volume control system 'A' charging pump, which serves as the 'A' safety injection charging pump. The reason the lead was broken was attributed to excessive stress created when the lead was packed inside the motor's termination box. The motor leads inside the termination box were spliced together with Raychem. The thick Raychem splices created a crowded condition inside the relatively small termination box. The combination of the crowded condition and the way the leads were packed inside the termination box created an extra stress that was felt on one of the stator's leads, which ultimately resulted in the failure of the lead. There was no adverse effect on the system or the plant as the auxiliary lube oil pump motors do not perform a primary safety function. Also, there are 3 safety injection charging pumps and only 2 are required to be operable. The motor was replaced with a like model. Raychem splices were not used with the new motor, allowing more space in the termination box.

In addition to the non aging-related NPRDS events described above, two other NPRDS events that occurred prior to 1994 are mentioned here because they resulted in an unscheduled power reduction and taking a unit off line. They are also notable because the splice failures in both events occurred on non nuclear-safety systems. On January 18, 1980, while operating a condensate pump motor at the Indian Point 3 nuclear plant, the pump motor tripped on overcurrent due to a high resistance condition at the motor lug splice. This resulted in reduced power operation. On July 6, 1990, with the Palo Verde 2 nuclear unit operating in hot standby, water entered a 480Vac termination compartment for a main power transformer during a surveillance deluge test on the power transformer. This caused a short circuit at the cable termination connections and resulted in the nuclear unit being taken off line.

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 is the case 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 cable splice events. The search included all component types in the database related to cable splices and all records from January 1997 to August 2001. The search identified a total of 118 events that met the search criteria. Each of these events was reviewed, and only three dealt with failures of cable splices. Each of the events is discussed below.

5.3.1 Comanche Peak 1 on July 27, 1997

A component cooling water pump motor experienced an 'A' phase motor termination failure on July 27, 1997, when the motor was started. The 'A' phase termination was blown out at the Raychem splice. The motor did not trip nor did it get any relay indications. This failure was similar to the failure which occurred on the 'B' phase in December 1989. At the same time the 'A' phase was reworked, the 'C' phase was inspected. It was found to be loose and the terminal lug fell off when examined. The 'A' and 'C' phase connections were reworked by relugging and installing new Raychem termination kits. The Raychem sleeves from the 'B' phase were removed and checked. The existing lug was found to be satisfactory and a new Raychem termination kit was installed.

Since all three terminations on this motor failed or may have failed at a later date, a Generic Implication review was performed. The purpose of this evaluation was to determine if the termination problem was limited to this one motor, or if all terminations on similar motors should be considered suspect. Other than these failures, there were no other termination failures found during history reviews of CPSES Westinghouse Life Line D motors.

All three phases of the motor appear to have had motor terminations which were improperly installed. The most likely cause of the termination failures was that the motor pigtail came out of the lug and caused an arc. The de-termination occurred over a protracted period of time, and was the result of improper attachment of the lug to the motor pigtail. Specifically, the cable conductor appears to have been cut with a slight taper and the crimp was made too far up the barrel of the lug. This resulted in a termination in which the conductor was trying to be forced out of the lug barrel. Years of thermal cycling and longitudinal stress resulted in separation of the lug from the motor pigtail.

Reworking the lug per IAW site procedures and specifications provided a superior crimp that allowed visual assurance that a proper crimp was made. Termination of the motor in this manner precludes a similar failure in the future, and all three phases of this motor have been reworked.

5.3.2 Point Beach 2 on July 21, 1997

A containment high range monitor connector failed due to mechanical process and/or stress. This failure was identified as a Raychem splice misapplication. The connector was replaced on the signal cable at the penetrations inside containment and Raychem was applied to all connections.

5.3.3 Point Beach 2 on July 23, 1997

A containment high range radiation monitor lost power due to electrical process and/or short/ground. Extensive troubleshooting was performed. A number of coaxial cable connectors were replaced, including one at the detector, four at the junction box for the in-containment penetration, and two at the penetration. All coaxial cable connections were closed with Raychem splice kits per Raychem instructions.

6.0 EVALUATION OF CONDITION MONITORING TECHNIQUES

Condition monitoring for electric cable splices involves inspection and measurement of one or more indicators, which can be correlated to the condition or functional performance of a splice and the cable system in which it is applied. Furthermore, it is desirable to link the measured indicators with an independent parameter, such as time or cycles, in order to identify trends in the condition of a cable splice. Ideally, condition monitoring data and trends in cable performance indicators can guide maintenance personnel in their decisions to repair or replace electrical splices or other accessories in a cable system before they fail or may otherwise affect the safe and reliable operation of the associated components and systems.

In actual nuclear power plant practice, the types of condition monitoring performed for electric cable splices is highly dependent on a number of factors, such as, the circumstances driving the requirement for condition monitoring (a new, repaired or replacement splice versus an existing splice), the importance of the associated system or function to nuclear plant safety, the age/condition of the splice, and the voltage class of the cable system. For example, condition monitoring tests would not normally be performed for an individual splice except in the case of a new, repaired, or replacement splice. Test activities in this instance might include visual inspection, an insulation resistance test, or an applied dc high voltage test (for medium voltage cable systems) to verify the integrity of the splice and its associated cable prior to energizing the circuit. For low voltage instrumentation cables, especially in temperature measurement circuits using RTDs or thermocouples, the resistance of the splice joint might be measured, and a calibration and functional test will be performed to verify that the instrumentation circuit is operating properly and producing an accurate measurement of the monitored process parameter. If the low voltage instrumentation circuit contains one or more splices or terminations, the overall resistance may be checked by direct measurement or indirectly by performing an instrument loop calibration.

In electric cables that are already operating with existing splices, condition monitoring specifically for assessing the status of individual cable splice joints, connections, or terminations is not normally done. Rather, the entire cable system, meaning the cable, insulation, splices, connectors, terminations and its physical support and routing configuration (whether it might be conduit, raceway, cable tray, underground duct or direct burial, cable bus, an open cable run, or any combination of these), is tested or monitored periodically, in situ. If any abnormal indications are detected for the cable system during routine condition monitoring, then more specialized and localized diagnostic inspection and condition monitoring will be performed to isolate the troubled areas or cable accessories. Alternatively, if problems are identified for a specific splice or termination along a cable run via routine visual inspection, time domain reflectometry (TDR), or infrared thermography surveys, then specialized follow up testing will be concentrated at, or in proximity to, the suspected the splice or joint.

Since the majority of condition monitoring for splices will be conducted with the splice being considered as an integral part of an overall cable system, many of the condition monitoring tests and techniques will be similar to those used for electric cable. In a research program sponsored by the NRC [6], attributes of an ideal CM technique for electric cable 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

The most useful condition monitoring would provide information that can be used to determine the current ability of a cable system to perform within specified acceptance criteria, as well as to make predictions about its future 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 program, a review and evaluation of promising condition monitoring techniques was performed to determine their effectiveness for in situ use for splices in nuclear plant cable systems. 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 cable systems and associated splices are described in terms of the underlying theory and the general procedure for performance of the test. 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 or electrical based on the property measured.

6.1 Mechanical CM Techniques

In this category, condition monitoring techniques that measure a mechanical property of a cable insulation system are discussed. In general, the theory behind these methods is that, as cable insulation and jacket materials age, they undergo measurable changes in their physical and mechanical properties. By quantifying and trending such changes, and correlating cable insulation or jacket condition with a known level of cable operating performance, the condition of a cable may be determined for purposes of maintenance, replacement, and projected service life. It may be seen, that all of these methods in fact are localized tests in that they measure the condition of the material at a specific point along a cable. For this reason, these methods are all well suited for condition monitoring of individual splices, connectors, and terminations.

6.1.1 Visual Inspection

Visual inspection of a cable splice provides a qualitative assessment of its overall condition. It is an in situ test that is inexpensive and relatively easy to perform, and can provide useful information for determining the condition of a cable splice. The weakest link in a cable system is most often at the splices, connection joints, and terminations where the insulating material has been altered and reconfigured and the electrical stresses are concentrated [6]. Visual inspection can be a very good indicator of the condition of a splice joint and detecting incipient failures. The effectiveness of this method is greatly enhanced by having experienced inspectors perform regular periodic visual inspections using well-structured procedures that identify and grade the critical attributes and physical parameters that are to be monitored.

In a research program sponsored by the NRC [6] the use of 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 included: 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. As a localized inspection technique, the condition of any splices that are accessible may be examined directly at the site of interest by means of a visual inspection.

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 attributes of a cable splice are inspected and categorized. The level of experience of the inspector can also be an important factor in a visual inspection. A capable inspector will be able to recognize the signs of various insulation problems, such as, degradation or delamination of insulating tape, surface tracking, deposits, or burn marks, periodic submersion in water, and other abnormal conditions.

The most serious limitation of this technique is that the cable locations and splices to be inspected must be accessible and visible. In some cases visual inspection may not be possible: cables may be routed through closed conduits or buried beneath other cables in a cable tray. In other instances, hazardous environmental conditions may preclude physical access. Even when a cable run is visually accessible, only the outer jacket of a cable or the exterior layer of a splice joint or termination can be examined. Therefore, direct inspection of the underlying insulation is not possible, and its condition may only be surmised from the appearance of the outer jacket. Nevertheless, visual inspection of representative cables, splices and terminations that are accessible could be used to provide an indirect measure of the condition of the inaccessible portions of a cable system.

Based on the results of this study it is concluded that visual inspection should be considered for inclusion in any condition monitoring program for electric cable systems. While it does not provide quantitative data, it does provide useful information on the condition of a cable, splice, or connection that is easy and inexpensive to obtain, and that can be used to determine if further detailed investigation or testing is warranted. The most significant limitation of this technique is that the cable or splice must be visually accessible.

6.1.2 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 (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 Fahrenheit, 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 and preserve 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 [8].

Figure 9 depicts a typical infrared imaging thermogram of the three phases of a cable connection to a piece of electrical equipment [9]. The color scale at the left of the thermogram defines the temperatures

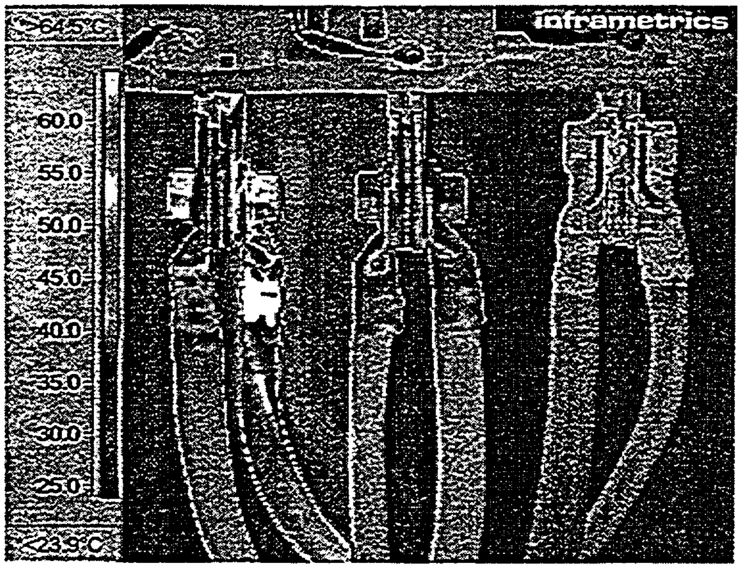


Figure 9: Infrared thermogram showing cable lug overheating due to poor connection [9]

Figure 9 depicts a typical infrared imaging thermogram of the three phases of a cable connection to a piece of electrical equipment [9]. 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 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.

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 cable systems can provide a direct measure of the performance of an electric circuit. These tests are generally performed by disconnecting one or both ends of a cable, and attaching the test equipment to one end. Hence, the electrical tests have an advantage over other techniques which require direct access to the portions of the cable that must be tested. The electrical tests may be further categorized as: 1) destructive tests, which are used after manufacture, prior to initial energization of a circuit, or to find and repair incipient failure sites to avoid in-service failures; and 2) non-destructive tests, which are used to measure and trend a circuit parameter that indicates the soundness of an insulation system. The tests discussed in this section are generally non-destructive, since they are the only ones appropriate for general in situ testing in nuclear power plants.

may be localized to an individual splice, as far as practical, by disconnecting the circuit as close to the splice as the circuit configuration will allow, when taking the measurements.

6.2.1 DC High Voltage Testing

Insulation that is in good condition 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 overpotential 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 [7].

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" [10]. 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 [7]. 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 [7].

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 [6]. When a dc voltage is applied to a test cable, the total current flowing in the insulation is equal to the sum of the capacitive charging current, the dielectric absorption current, and leakage current from the conductor to ground. 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 megohmmeter 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 for comparison, after temperature correction of the values.

Humidity and the combination of dielectric materials used in the cable insulation can affect insulation resistance measurements. These specimens 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 described in reference 6, a megohmmeter with the capability of measuring insulation resistance up to 200 teraohms ($200 \times 10^{12}\ \Omega$) was obtained 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 cables. It is therefore expected that, as part of a cable system, the condition of the insulation in splices, connectors, and terminations in the cable system may be monitored using high dc voltage testing in accordance with IEEE and ICEA standards or insulation resistance measurement.

6.2.2 Partial Discharge Measurement

Measurement of partial discharge is an 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, electrical discharges (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 [11].

In research performed by the National Institute of Standards and Technology (NIST) [12], 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 10 shows results for measurements at 6,000 volts, which demonstrate that each of the defect locations were detected using the partial discharge measurements.

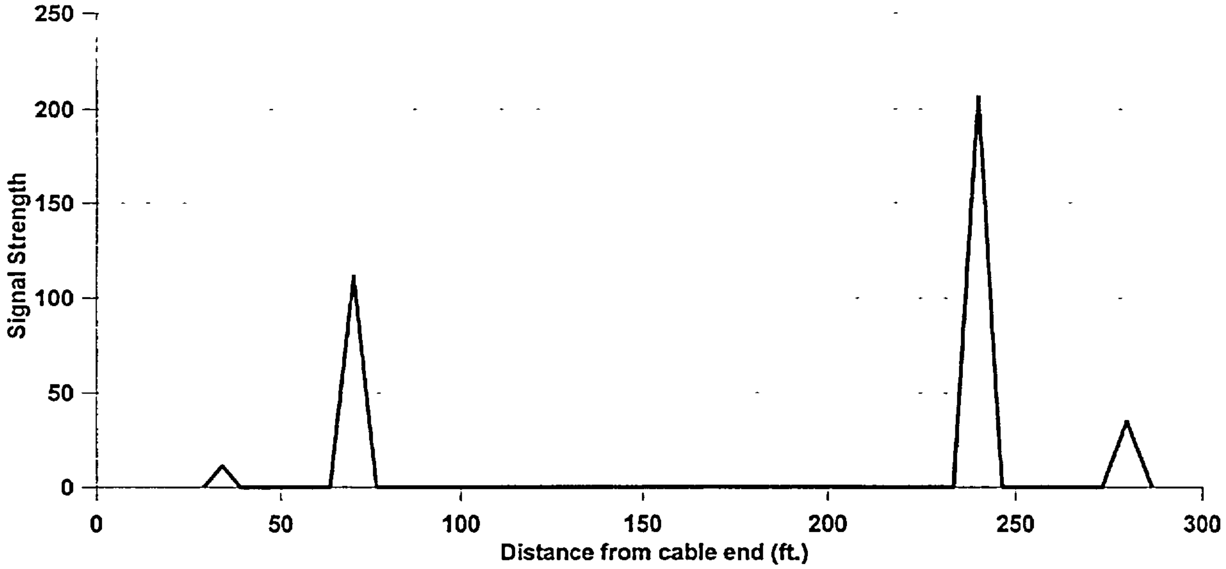


Figure 10: Partial discharge signals at 6,000 volts indicating the location of cable defect sites [12]

This test is commonly used by 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 [4].

6.2.3 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is a condition monitoring technique that has been used by BNL in its low voltage cable research program [6] and 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.

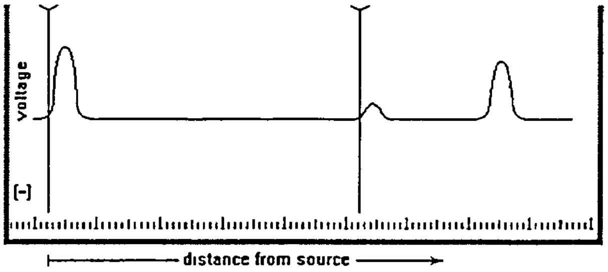
The simplest form of TDR will display the distance to a fault or the first major change in the cable impedance. More useful information is provided by a TDR that displays the actual waveform or "signature" of the cable on a CRT or LCD. This type of display can show the outgoing pulse transmitted down 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.

Simplified representations of TDR reflectograms are shown in Figure 11. 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.

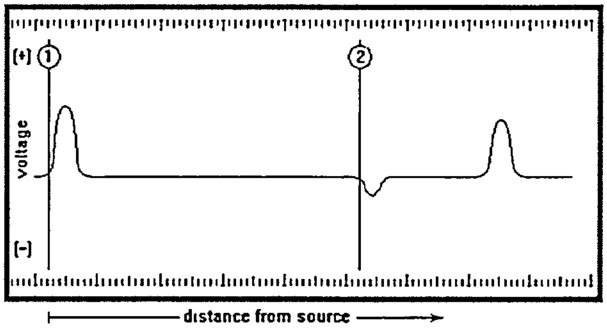
Any time two or more metallic conductors are run in close proximity, either in the same multiconductor cable or in the same tray, conduit, or raceway, that cable will present an electrical impedance to an ac current. The impedance will depend on numerous factors, including, but not limited to, conductor 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



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 11: Simplified representation of TDR reflectograms

- severity of faults or damage
- location of an in-line component
- problems causing excessive loss of ac or radio frequency signals

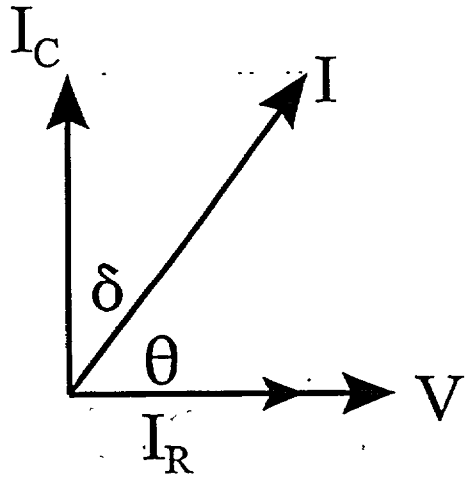
TDR testing may be used to provide initial verification of cable integrity and proper initial installation. An in situ baseline TDR waveform signature for a given cable can later be used to comparatively monitor and trend in-service degradation over time. Once the characteristic velocity of propagation 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 power, instrumentation, and control cables are: it is a non-destructive test; it provides useful information on the severity and location of a discontinuity; the testing apparatus is moderately expensive; the data are 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; transient conditions, such as water immersion, are only detected if they are present during the TDR test.

6.2.4 Dielectric Loss/Power Factor

An electrical measurement that shows promise as a cable CM technique is the dielectric loss measurement, which measures deterioration of a materials 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 12. 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 12: Power factor relationship

In a research program sponsored by the NRC [6], 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 13 shows power factor as a function of increasing age for XLPE insulated cables [6]. 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.

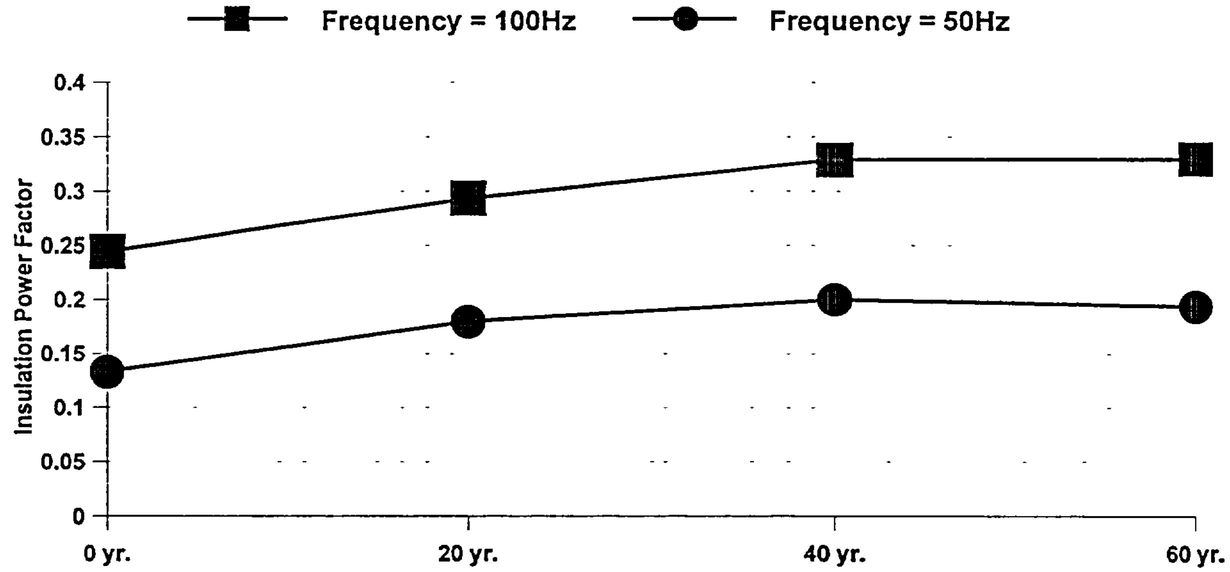


Figure 13: Power factor versus age for XLPE insulation [1]
20 yr = 648.5 hr @ 302°F + 26.1 Mrad
40 yr = 1,301.2 hr @ 302°F + 51.5 Mrad
60 yr = 1,363.8 hr@302°F + 77.0 Mrad

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 Reference 6 study, laboratory testing was performed to study 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 system 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 system 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. The procedure and test equipment used to making measurements in low-voltage cable systems for the research program may be inadequate for medium-and high-voltage cable systems.

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.

6.4 Summary of CM Methods for Cable Splices

The review and evaluations of condition monitoring methods found that there are several methods available for the monitoring of cable splices. Each has its own advantages and limitations, and the best approach is to use a combination of techniques to cover the wide variety of applications and configurations that may be encountered in nuclear power plants. Some techniques are of a localized nature, and can, therefore, focus on an individual cable splice, as long as it is accessible. Other techniques examine cable splices only indirectly by measuring the condition of an entire cable system, which may contain one or more cable splices, connections, or terminations along its length.

Table 2 summarizes the various tests available for in situ monitoring of cable splices along with their advantages and limitations.

Table 2: Summary of CM methods for in situ monitoring of cable splices

CM Method	Advantages	Limitations
Mechanical		
1. Visual Inspection	• Simple, inexpensive to perform • Provides useful qualitative information on cable condition	• Requires access to splices and cable locations to be inspected • Does not provide quantitative data on cable condition • Knowledge and experience produce the best results
2 Infrared 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
Electrical		
3. DC High Voltage Testing	• 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 system under test must be determinated to perform test
4. 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 system under test must be determinated to perform test • Testing may damage cable system insulation
5. Time Domain Reflectometry	• Provides useful information for locating defects in cables, including bad splices	• Cable system under test must be determinated to perform test • High level of training and experience required for best results
6. 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 system under test must be determinated to perform test

7.0 EVALUATION OF ENVIRONMENTAL QUALIFICATION PRACTICES

As part of this study, a review of environmental qualification test reports and analyses related to electric cable splices was conducted. The review examined the typical procedures and test conditions that are used in the industry during qualification testing for cable splices. These were compared to the approaches used by the industry for the qualification of electric cables. In addition, cable splices that were pre-aged and exposed to simulated accident conditions in a previous NRC/RES program were disassembled and inspected to gain insights into splice performance and potential failure mechanisms under harsh environments (see Chapter 8). Furthermore, industry practices for the qualification of splices were evaluated in light of the information gathered during the operational experience review for cable splices discussed in Chapter 5 in which aging degradation of these components was characterized.

7.1 Considerations for Qualification of Cable Splices

The requirements for environmental qualification of cable splices are very similar to those for electric cables. The general requirements and procedures for qualifying Class 1E electric equipment, applicable to both electric cables and cable splices, are described in IEEE Standard 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," [13] as endorsed by the US NRC in Regulatory Guide 1.89, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants" [14]. Further detailed direction and procedures for establishing type tests specifically related to the qualification of electric cables and cable splices 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" [15].

Beyond the aforementioned requirements, there are several factors relating to the environmental qualification of cable splices that must be taken into consideration. Most important is the service environment to which the splice will be exposed during both normal operation, as well as, abnormal operating and transient conditions. If the cable splice is located in a mild, low humidity environment, where there is no possibility for exposure to steam, water, chemical spray, or other corrosive substances, the specifications for the splice are very straightforward. An environmental seal is not necessary to isolate the conductors and electrical connections within the splice from stressors in the external environment. The materials used in the construction of the splice must simply be compatible with each other and the service environment, the electrical connection must be of low resistance and the proper cross-section for the current carrying capacity of the cable, and the cable/splice insulation must be capable of operating at the voltage levels specified for the circuit. Insulated crimp connectors and/or bolted connectors protected by electrical insulating tape, heat-shrinkable tubing, adhesive sealants, protective boots, or insulating barriers will suffice in most power, control, and instrumentation applications.

In those cable splice applications where moisture or complete submersion may be encountered, and in harsh nuclear environments, where high pressure steam, moisture, high radiation, high temperature, and corrosive chemical spray conditions could potentially occur in the event of a nuclear accident, environmentally qualified splices are required. These splices must provide an environmental seal to prevent moisture and other contaminants from entering the inside of the splice, where they could adversely affect the performance of the circuit. As described in Chapter 2, qualified cable splices are normally one of two types: heat-shrinkable splices or self-amalgamating tape-wrapped splices.

The important considerations for installing an effective, qualified, heat-shrinkable nuclear splice are: environmental seal length, seal integrity, use range, geometry of the splice, materials compatibility between the splice components and the cable insulation and jacket, and mechanical bending of the splice. The environmental seal length is the length of the overlap of the heat-shrinkable tubing over the outer cable insulation or jacket This is the distance that steam, moisture, or other contaminants must penetrate before they can enter into the interior of the splice.

The seal integrity is the tightness of the grip, or adhesion, between the heat-shrinkable tubing and the cable insulation or jacket, which works to block the passage of steam and moisture into the splice interior. Seal integrity can be affected by compatibility of the materials used in the heat-shrinkable tubing, adhesives and sealants, and the cable insulation or jacket. Some cable constructions may utilize metallic braided shields or braided insulating/protective coverings that could affect the integrity of the seal. These unqualified materials should be removed from the splice seal area prior to application of the heat-shrinkable tubing. As the cable and splice materials age, they may harden, shrink, or change in other ways that may affect the integrity of the seal between the overlying heat-shrinkable material and the cable. Cuts or cracks in the outer cable jacket or insulation can compromise the integrity of the seal by providing an unwanted alternate pathway for moisture and contaminants into the interior of the splice [6].

The use range of heat-shrinkable tubing is the range of cable or connector diameters over which the tubing may be effectively applied. When the tubing recovers (shrinks), the compressive force must be sufficient to create an adequate seal, but not so great as to cause excessive stress on the tubing that could damage it. Closely related to this factor is the geometry of the splice; shims must be applied when cables of different diameters are spliced together, or when various sections of a splice have different diameters. This provides a relatively uniform diameter along the entire length of a splice so that it remains within the use range of the outer heat-shrinkable tubing and avoids stress concentrations, wall thinning, and physical displacement that could occur should the tubing subsequently be exposed to high temperatures causing it to continue to recover (shrink).

Bending of the heat-shrinkable splice is also to be avoided since this can cause stresses on the material, thinning of the tubing wall, or disruption of the environmental seal. The maximum allowable bending geometry will be specified by the manufacturer of the splice kit.

The installation considerations for qualified tape-wrapped splices are similar to those for heat-shrinkable splices, and include: seal length, seal integrity, geometry of the splice, materials compatibility between the splice and the cable insulation and jacket, and mechanical bending of the splice. In addition, the overlap of each turn of the splice on the previous turn must be sufficient to ensure an adequate seal.

7.2 Review of Environmental Qualification Test Reports

To gain insights into how cable splices have been qualified, a total of seven environmental qualification test reports and analyses related to electric cable splices were reviewed. These reports dated from as recently as November 2001 back to 1970. Most of the reports reviewed were primarily qualification tests for electric cables that also included one or more splices among the specimens to be qualified by test. The most recent report, from Tyco Electronics-Energy, the present owner of Raychem-manufactured nuclear grade cable splices and accessories, documents the qualification testing of various types of electric splices and terminations. The highlights of the test reports reviewed are discussed in the following paragraphs, and are summarized in Table 3.

EDR-5336, "Nuclear Products Requalification Testing" [16], developed by Tyco Electronics-Energy in November 2001, documents their qualification test program to requalify the Raychem line of heat-shrinkable, nuclear grade, splice products, materials, and accessories in a variety of configurations to design service lives of 40 and 60 years. The types of splices tested included: in-line splices with crimp connectors, in-line splices with bolted connectors, nuclear plant transition splices, terminal block replacement kits, and nuclear motor connection kits. The testing was performed in accordance with the guidelines of IEEE Std. 323-1974 [13], IEEE Std. 323-1983, and IEEE Std. 383-1974 [15]. Unaged splices, as well as specimens thermally aged and irradiated to simulate 40 and 60 years of service at 90°C, were exposed to high pressure/high temperature steam and a chemical spray solution to simulate a LOCA environmental exposure. A dual peak LOCA profile (425°F/80psig for 10 minutes, 425°F/120psig for 5 hours), similar to that suggested in Appendix A to IEEE Std 323-1974 [13], was employed and the overall exposure cycle lasted for 32 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 [13]. The accident irradiation exposure was 165Mrads (150Mrads plus 10% margin). Specimens were energized at rated voltage and current for the duration of testing. Electrical testing included periodic insulation resistance measurements at 500Vdc for 1 minute, post-LOCA immersion in tap water for 24 hours followed by a final submerged insulation resistance measurement and submerged voltage withstand test at 80V/mil of insulation thickness. The test program successfully requalified the tested Raychem splice products, materials, and accessories for design service lives of 40 and 60 years at 90°C.

NQRN-3 "Nuclear Environmental Qualification Report for Okoguard Insulated Cables and T-95 & No. 35 Splicing Tapes" [17], performed by The Okonite Company in 1988 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 [13] and IEEE Std. 383-1974 [15]. 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 [13], 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 [13] and lasted for 30 days; steam and water spray were 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 [2], 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.

F-C5285-1 "Qualification Tests of Electrical Cables in a Simulated Loss-of-Coolant Accident (LOCA) Environment" [18], prepared by The Franklin Institute Research Laboratories for General Electric Company, Wire and Cable Business Department, in May 1980, describes qualification testing for several 600V power or control cables, including one 1/C #12 AWG Vulkene Supreme-insulated power or control cable with a Burndy-Raychem field splice. The testing was performed in accordance with the guidelines of IEEE Std. 323-1974 [13] and IEEE Std. 383-1974 [15]. The specimen was thermally aged for 240 hours at 302°F. A total of 220Mrads of service irradiation and accident irradiation was administered at an average dose rate of 0.76Mrad/hour. A dual peak LOCA profile (two peaks at 346°F/113psig for approximately 3 hours each), similar to that suggested in Appendix A to IEEE Std 323-1974 [13], was employed and the overall exposure cycle lasted for 33 days. The chemistry and spray rate of the accident spray solution were the same as that suggested in Appendix A to IEEE Std 323-1974 [13]. The chemical spray was administered during the first peak, again during the second peak, and continued for the next 24 hours. Specimens were energized at 660Vac and a current of 11A was maintained for the duration of testing. Electrical testing included: 1) periodic insulation resistance measurements following each temperature/pressure transition, once per week during the extended LOCA simulation, and post-LOCA; and 2) a 40x diameter post-LOCA mandrel bend test, followed by 1 hour immersion in room temperature tap water and a final post-LOCA submerged ac voltage withstand test in accordance with IEEE Std 323-1974 [13], Section 2.4.4. The Burndy-Raychem field splice successfully passed the post-LOCA electrical testing and was qualified by type test.

Report No. PE-53 "Main Steam Line Break (MSLB) Test on Aged and Irradiated Cable Specimens" [19], prepared by the Essex Group, Inc., Power Conductor Division, for the Tennessee Valley Authority (TVA) in May 1980 is a cover letter report consolidating several disparate qualification reports into a single document for TVA's Sequoyah Nuclear Power Station, including: Essex Group Test Report No. PE-53, May 8, 1980, 1/C #12 AWG EP-insulated cables; Unnumbered Essex Group Test Report "Qualification Test of Aged and Unaged Under a Simulated LOCA/DBE by Sequential Exposure to Radiation, Steam, and Chemical Spray Environments," June 1979, 1/C #12 AWG EP-insulated cables; Unnumbered Isomedix Test Report "Qualification Test of Thermally Aged and Unaged Electric Cables Under a Simulated LOCA/DBE by Sequential Exposure to Environments of Radiation, Steam and Chemical-Spray," June 1979, 1/C #12 EP-insulated cables; Unnumbered Franklin Institute/GE Test Report "Environmental Qualification of Terminal Blocks/Boxes," March 28, 1978, GE Model EB-25 terminal board. The latter test report describes an I&C cable terminal block qualification consisting of thermal aging for 171 hours at 302°F, irradiation to a total dose of 5Mrad (dose rate not specified in the available documentation for this review), and a single peak LOCA exposure simulation (286°F/40psig for 31 hours). A chemical spray consisting of a 2640ppm boric acid solution was administered to the specimen for 24 hours and the total duration of the LOCA exposure simulation was 101 hours. Acceptance was based on the functional capability of the terminal block connection to carry rated voltage and current throughout the qualification test. No other electrical tests were provided in the documentation available for this review.

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" [20], prepared by The Franklin Institute Research Laboratories for Raychem Corporation in January 1975, describes qualification testing for several power, instrumentation, and control cables, including one #22 AWG Raychem Adverse Service Coaxial Cable with a splice covered with Raychem Thermofit WCSF-115-350 heat-shrinkable tubing. The testing was performed in accordance with the guidelines of IEEE Std. 323-1974 [13] and IEEE Std. 383-1974 [15]. The specimen was simultaneously thermally aged for 240 hours at 302°F and irradiated to a total dose of 50Mrads while energized at 600Vac and 0A. The specimens were 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 [13] 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 at 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 [13], Section 2.4.4. The Raychem coaxial cable splice successfully passed the post-LOCA electrical testing and was qualified by type test.

Engineering Report No. 141 "Qualification Tests of Electrical Cables Through Sequential Exposure to Heat, Gamma Radiation, LOCA, and Post-LOCA Simulations," [21], developed by The Okonite Company in February 1972, presents the results of the qualification testing for Okonite-insulated power, instrumentation, and control cables and one 5kV taped power cable splice described in Franklin Reports F-C 3094, July 1971, and F-C 3171, September 1971. This work predates IEEE Std. 323-1974 [13] and IEEE Std. 383-1974 [15], however, the environmental simulations were more severe than called for in IEEE Std. 383-1974 and in line with the general requirements of IEEE Std. 323-1974. The specimen was thermally aged for 168 hours at 121°C. A total of 1Mrad of service irradiation at a dose rate of 1Mrad/hr was administered followed by accident irradiation up to a total dose of 200Mrads administered at an average dose rate of 0.30Mrad/hour. The specimen was then exposed to two consecutive LOCA environment simulations: a PWR steam/chemical spray exposure (single peak at 324°F/80psig for approximately 3.33 hours) lasting 7.17 days followed by a BWR steam exposure (three peaks: 345°F/104psig for 0.25 hours, 345°F/104psig for 3.33 hours, and 320°F/75psig for 4.48 hours) lasting for slightly more than 100 days. The chemical spray, consisting of 10,000ppm boric acid buffered with sodium hydroxide to a pH of 10.5, was maintained throughout the PWR simulation. The splice specimen was energized at 660Vac and a current of 11A was maintained for the duration of testing. Electrical testing included: 1) insulation resistance measurements during major temperature/pressure transitions and periodically during the extended accident simulations, and 2) in situ voltage withstand tests during major temperature/pressure transitions and periodically during the extended accident simulations. The splice was removed prior to post-LOCA electrical testing but performed adequately for all electrical tests conducted during the accident exposure simulations.

Engineering Report No. 110E "Nuclear Qualification Tests on Insulating Compounds" [22], developed by The Okonite Company in November 1970, describes several power and control cable qualifications and two taped power cable (unknown voltage) splice qualifications performed at the Franklin Institute Research Laboratories. Although the cable specimens received thermal and radiation aging, the splice specimens received no preaging. Accident simulation consisted of a steam exposure at 60psig for 12 hours with a boric acid-based chemical spray solution and 7 days at 5psig with chemical spray. This was followed by a final 175°C exposure for 10 hours. Electrical tests for the splice specimens consisted of pre-test and post-test insulation resistance measurements and 5kV ac and dc voltage withstand tests. Both splice specimens performed adequately.

7.3 Evaluation of EQ Practices for Cable Splices

The review of splice qualification test reports shows that once the general qualification standard IEEE Std. 323-1974 had been adopted and endorsed by the NRC in the early 1970's, along with IEEE Std. 383-1974, with its more specific requirements and procedures for cable and splice qualification type testing, the requirements, procedures, and acceptance criteria for the qualification testing of these components have become very consistent. Since cable splices are an integral part of cable systems in a nuclear power plant, they are exposed to the same environmental conditions that affect electric cables. It is obvious, therefore, that the general requirements, environmental and accident simulation exposures, and other details of qualification testing procedures for splices should be nearly identical to those for electric cables. This is clearly the case in the sampling of test procedures reviewed for this evaluation, where the cable splices were often included as specimens in what are primarily electric cable qualification tests.

The most recent splice qualification test reviewed was for the Raychem line of heat-shrinkable splices, materials, and accessories (November 2001). In this test, the cable splices were subjected to even more severe environments during qualification than electric cables. In addition, the design service life to which these splices were qualified has been demonstrated, through successful completion of type testing, out to 60 years at 90°C. This anticipates the need for licensees to extend the qualified life of age-sensitive components in nuclear power plants, such as polymeric splices, from the original 40 years to 60 years as part of the license renewal review process.

The operating experience review for cable splices discussed in Chapter 5 showed that the number of age-related failures of these components is relatively small. However, the materials used in cable splices are susceptible to aging degradation. The present methods for qualification of cable splices include requirements to address the effects of aging related degradation on the polymeric materials used in the construction and sealing of cable splices. This is typically done through the application of accelerated thermal and radiation aging to the splices, as part of the qualification test, to simulate exposure to the stressors expected during their service life.

Table 3 - Summary of Review and Evaluation for Cable Splice Qualification Tests

TEST No.	TEST LAB	SPLICE		Voltage Rating	CABLE			Remarks
		Manufacturer	Configuration		Insul. Material	Jacket Material	Configuration	
EDR-5336 Revision 0 (2001)	Wyle Laboratories	Tyco Electronics (Raychem)	In-Line Splice with crimp Conn; WCSF Sealing Sleeves & Shims	600	XLPE	None	1/C #14 AWG	• Tested per IEEE Stds 323-1974 and 383-1974 • Thermal & radiation preaging to 0, 40, 60 yrs; • Two peak LOCA exposure simulation (425°F/120psig) with chemical spray; 32 day duration; • Post-LOCA acceptance criteria include submerged voltage withstand @ 80V/mil for 5 min and submerged IR @ 500Vdc for 1 min. • Exposure conditions exceed those for most electric cable qualification testing
				200	PEEK	None	1/C #16 AWG	
			In-Line Splice with Bolted Connection; WCSF Sealing Sleeves & Shims	600	XLPE	None	1/C #12 AWG	
				1000	XLPE	CSPE	1/C #4 AWG	
			Nuclear Plant Transition Splice; WCSF Shims, WCSN Sealing Sleeves & Shims, -52 molded parts	600	XLPE	CSPE	7/C #12 AWG	
			Terminal Block Replacement Kit; WCSF-S Sealing Sleeves, S1119/144 Nuclear Adhesive	600	XLPE	None	1/C #16 AWG	
			Nuclear Motor Connection Kit; WCSF Bolt Pads & Shims, -52 molded parts	600	XLPE	CSPE	1/C #4 AWG 1/C # AWG	

Table 3 - Summary of Review and Evaluation for Cable Splice Qualification Tests

TEST No.	TEST LAB	SPLICE		Voltage Rating	CABLE			Remarks
		Manufacturer	Configuration		Insul. Material	Jacket Material	Configuration	
NQRN-3 (1988)	Okonite	Okonite	T-95 & No 35 Splice Tapes; hand-wrapped, filled splice	5000	EPR	None EPR	1/C #12 AWG	• Tested per IEEE Stds 323-1974 and 383-1974 • Thermal and radiation aging to 40 yrs • Two peak LOCA exposure simulation (345°F/114psig) with chem spray; 130 day duration; • Post-LOCA submerged voltage withstand test @ 80V/mil for 5 min
F-C5285-1 (1980)	Franklin Institute Research Labs	Burndy-Raychem	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	• Tested per IEEE Stds 323-1974 and 383-1974 • Thermal and radiation aging; • Two peak LOCA exposure simulation (346°F/113psig) with chem spray, 33 day duration, • Post-LOCA submerged voltage withstand test @ 80V/mil for 5 min
Report No. PE-53 (1980)	Essex Grp (Essex, Isomedix, Franklin Institute, GE, Westinghouse)	GE	EB-25 terminal block	Un-known	Molded phenolic, cellulose-filled	N/A	Multiple point, molded phenolic, cellulose-filled, terminal block	• Thermal and radiation aging, • Single peak LOCA exposure simulation (286°F/40psig) with chem spray, 101 hours duration, • Seismic test; • Acceptance based on functional capability to maintain rated voltage and current

Table 3 - Summary of Review and Evaluation for Cable Splice Qualification Tests

TEST No.	TEST LAB	SPLICE		Voltage Rating	CABLE			Remarks
		Manufacturer	Configuration		Insul. Material	Jacket Material	Configuration	
F-C4033-1 (1975)	Franklin Institute Research Labs	Raychem	Adverse Service Coaxial Cable Splice	1000	Alkane-imide polymer/ Rayolin R Radiation X-linked poly-olefin	Flamtrol over braided Cu shield	1/C #22 AWG, 0 008" alkane-imide polymer/0.049" Rayolin R radiation X-linked polyolefin, braided Cu shield, 0.034" Flamtrol jacket with splice covered with Thermofit WCSF-N heat-shrinkable tubing splice cover	• Qualification test in accordance with IEEE Stds 323-1974 and 383-1974 • Simultaneous thermal and radiation preaging followed by simultaneous exposure to steam, chemical spray, and radiation to simulate LOCA conditions; • Single peak LOCA exposure simulation (357°F/>70psig); 30 days duration, • Post-LOCA submerged voltage withstand test @ 80V/mil for 5 min

Table 3 - Summary of Review and Evaluation for Cable Splice Qualification Tests

TEST No.	TEST LAB	SPLICE		Voltage Rating	CABLE			Remarks
		Manufacturer	Configuration		Insul. Material	Jacket Material	Configuration	
Eng. Report No. 141 (1972)	Okonite	Okonite	T-95 Splice & T-35 Jacketing Tapes; Hand-wrapped, filled splice	5kV	EPR	CSPE	1/C #4/0 AWG, 0.140" Okoguard, 0.065" Okolon with a hand-wrapped, filled splice	• These tests predated the IEEE standards; • 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; • Consecutive 7½-day steam and chemical spray PWR accident simulation exposure followed by 100 day steam BWR accident simulation exposure; • In situ submerged IR and voltage withstand test for splice

Table 3 - Summary of Review and Evaluation for Cable Splice Qualification Tests

TEST No.	TEST LAB	SPLICE		Voltage Rating	CABLE			Remarks
		Manufacturer	Configuration		Insul. Material	Jacket Material	Configuration	
Eng. Report No. 110E (1970)	Okonite	Okonite	T-95 Splice Tape; Hand-wrapped, filled splice	600	Unknown	None	Two (2) unknown cable configurations with hand-wrapped, filled splice	• This test predated the IEEE standards; • No thermal or radiation preaging; • Single peak LOCA exposure simulation (60psig for 12 hours) with chemical spray solution; 7 days duration; • Post-LOCA 5kV ac and dc voltage withstand test and insulation resistance measurement

As indicated in Table 1, problems with electrical connections in splices can be caused by oxidation and corrosion (exacerbated by moisture intrusion), or by metal fatigue or loosening of the connectors caused by vibration, thermal or mechanical cycling, electrical transients, or mechanical stress. The former problem is not likely to occur in a correctly installed nuclear grade splice with an effective environmental seal. In any event, the present methods of qualification testing, particularly the submerged voltage withstand acceptance criterion, adequately address oxidation/corrosion and moisture intrusion problems.

The loosening of the electrical connectors in splices is the predominant aging mechanism for cable splice failure identified in the operating experience review. This mechanism can lead to some of the commonly observed failure modes of "open circuit" or "degraded electrical connection" that were noted during the review. This failure mechanism can be caused by various stressors, such as, vibration, thermal or mechanical cycling, electrical transients, or mechanical stress. While the IEEE qualification standards include requirements to address aging degradation that would encompass these stressors, they were not specifically addressed in the qualification tests that were reviewed. These stressors are application specific, and would only be a potential problem in applications where such stressors are actively involved. Motor connectors might be one instance of this, where these additional environmental stressors or other factors might be incorporated into qualification testing. However, if splices are qualified in a generic sense, it might be appropriate to address these stressors during the accelerated aging portion of the qualification process.

In many cases, the best way to manage application specific stressors is by maintenance, inspection, and condition monitoring. An overview and evaluation of many of the inspection and condition monitoring techniques for cable splices is provided in Chapter 6.

Although it is not age-related, another cause of splice problems that was noted during the operating experience review, and should be pointed out here, was improper installation. Splice installation problems were also discussed in US NRC IE Notice 86-53 [23]. Testing has demonstrated that the materials used in heat-shrinkable and tape-wrapped splices perform exceptionally well when used in a properly engineered and installed cable splice. However, the operating experience review has shown that, in practice, these materials are often misapplied, improperly installed, or damaged during installation or subsequent service. Section 4.1.2 describes an event in which tape-wrapped splices installed in the drywell of a nuclear plant were found to be unraveling. This was a safety concern since, during an accident, moisture could enter the splice and adversely affect circuit performance. It was determined that this problem was due to improper installation in wrapping the splices.

7.4 Observations

As a result of the review of past environmental qualification test reports on splices, the following observations were made regarding current qualification practices:

- Since IEEE Standards 323-1974 and 383-1974 were adopted and endorsed by the NRC, the requirements, procedures, and acceptance criteria for the qualification testing of cable splices have become very consistent. Cable splices are treated as an integral part of cable systems in a nuclear power plant, and current qualification practices are consistent with that philosophy.

- From the qualification tests reviewed, cable splices are sometimes subjected to more severe environments during qualification than the electric cables to which they will be applied.

- The currently accepted IEEE standards for qualification of cable splices adequately address the effects of aging related degradation on the design and materials used in the construction and sealing of cable splices. However, qualification testing used for the purpose of generically qualifying a specific splice design or construction may not address all of the stressors that may be important for the degradation of a splice in all applications. Loosening of the connectors in splices, caused by vibration, thermal or mechanical cycling, electrical transients, or mechanical stress, was identified as the predominant aging mechanism for splices in the operating experience review. However, none of these stressors was specifically addressed in the qualification tests that were reviewed for this study. These stressors are application specific, and would only be a potential problem in applications where such stressors are actively involved. In many cases, the best way to manage application specific stressors is by maintenance, inspection, and condition monitoring.

- Qualification testing has demonstrated that the materials used in heat-shrinkable and taped splices perform exceptionally well when used in a properly engineered and installed cable splice. However, splice performance will be adversely affected if these materials are misapplied, improperly installed, or damaged during installation or subsequent service.

8.0 DISASSEMBLY AND INSPECTION OF NUCLEAR CABLE SPLICES

In the late 1990's, Brookhaven National Laboratory, sponsored by NRC/RES, conducted a research program addressing issues related to the environmental qualification process for low-voltage electric cables used in commercial nuclear power plants. From 1997 to 1999, Brookhaven performed a series of six loss-of-coolant accident (LOCA) exposure simulations to study the performance of several types of low-voltage instrumentation and control (I&C) cables under postulated nuclear accident conditions. The results of this research program were documented in NUREG/CR-6704 [6].

Several different sizes and types of cable, from five different cable manufacturers, were tested as part of the research program. The I&C cable types tested were: Cross-Linked Polyethylene (XLPE) with a Neoprene Jacket, Ethylene Propylene Rubber (EPR) insulation with a bonded Chloro-Sulphonated Polyethylene (CSPE) jacket, EPR insulation with an unbonded CSPE jacket, and Ethylene Propylene Diene Monomer (EPDM) insulation with an unbonded CSPE jacket. The cables received accelerated thermal and radiation aging to simulate 20, 40, or 60 years of qualified life in nuclear plant service. In addition, naturally aged cables of the same types were obtained from decommissioned nuclear power plants for testing. The cables were subjected to simulated LOCA conditions that included the application of accident irradiation followed by exposure to high temperature and pressure steam and chemical spray similar to that suggested by Appendix A to IEEE Standard 323-1974 "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," [13].

The testing protocol called for functional testing of the cables throughout the LOCA simulation by energizing them at 24Vdc, as part of a 4-20ma instrument loop circuit, to monitor the effects of accident environment conditions on the accuracy of a typical instrument circuit, such as would be found in a nuclear power plant. This required the installation of cable splices to connect the cable specimens under test to monitoring and instrumentation facility lead wires. These lead wires were then brought outside the environmental test chamber through pressure penetrations in the removable test chamber head that had been sealed with 3M Scotchcast potting compound. Since the splices would be located inside the test chamber, nuclear grade, environmentally sealed splices were specified to assure that the measurements and performance parameters being observed during LOCA testing were indeed attributable to the cables-under-test and not due to any shortcomings of the splices nor the Teflon-insulated facility test leads. Nuclear grade, heat-shrinkable, splices manufactured by the Raychem Corporation were selected for this purpose because of their proven performance and the widespread use of these products in the nuclear power industry.

8.1 LOCA Performance of Cable Splices in the Low-Voltage Cable Test Program

The heat-shrinkable nuclear splices used in the low-voltage cable test program performed adequately with the exception of those applied on severely degraded cables in the first and the third of the six LOCA exposure tests [6]. In fact, test specimen performance anomalies noted during these tests were determined to be the result of an inadequately specified installation and misapplication of the cable splices in the first LOCA test run, and misapplication of the cable splices in the third LOCA test run. The heat-shrinkable tubing material, Raychem WCSF, performed satisfactorily and was generally observed to be more resilient to the environmental exposures than the jacket and insulation materials on the cables being tested.

For the first LOCA exposure test, the splices were applied by the testing laboratory personnel in accordance with their own general installation procedures. Following thermal aging, service irradiation aging, and accident irradiation, but prior to being placed into the test chamber for the first LOCA exposure test, the two-conductor (2/C #14 AWG XLPE/Neoprene) cable specimens were connected to the Teflon-insulated facility lead wires with uninsulated crimp-type butt splices. Approximately 2-inch long heat-shrinkable sleeves were installed, centered over the butt splice connectors, on each conductor and overlapping the test cable insulation on one side and the shimmed facility lead wire on the other. An overall heat-shrinkable sleeve, approximately 6.5 inches long, was applied over the area overlapping the test specimen cable jacket on one side and the shimmed facility lead wires on the other. This configuration was adequate for those cable specimens with little or no aging degradation. However, the cables that had been thermally aged for 648.5 hours at 302°F and irradiated to 26.1 Mrad total integrated dose prior to the LOCA exposure, had experienced embrittlement and cracking of the Neoprene jackets. During the LOCA exposure test, high pressure steam and moisture entered the cracked jackets of the test cables and penetrated into the splice via the interior of the jacket, and possibly through microcracks in the insulation [6]. In addition, the ground wire in the facility lead wire was left inside the splice, uncapped, in close proximity to the butt splice. This provided a potential leakage path to ground should moisture get into the interior of the splice. Consequently, the severely aged cables with damaged jackets experienced excessive leakage currents during the LOCA exposure simulation test.

To correct this problem, Raychem provided custom engineered splice kits for the cables in the remaining five LOCA exposure tests. The improvements included sleeves of at least 6 inches centered over the butt splice, heat-shrinkable tubing specified to the cable sizes and lead wires identified in each splice, longer shims and sleeves, and a greater overall splice length, typically 17 to 20 inches. This provided longer seal lengths and improved seal integrity at the ends of the splice, as well as over the butt splice sealing sleeves for the individual conductors. This can be seen in Figure 14, which compares cross-sections of a typical splice configuration used in the first LOCA test with an engineered splice kit applied to the same cable type for a subsequent test. The butt splice is located at about 9 inches under the thickened overlap area in Splice 0604A

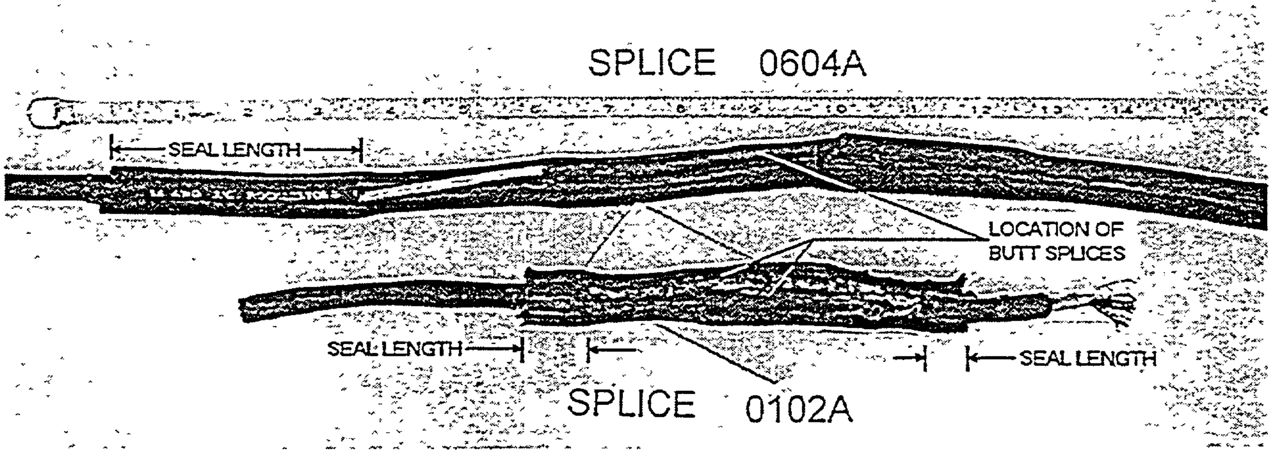


Figure 14: Comparison of LOCA Test 1 splice (bottom) with custom engineered splice (top)

and at about the 8.75 inch mark for Splice 0102A. Also note the difference in seal lengths for 0604A, with about 3.5 inches overlap over the jacket of the test cable, compared to 0102A, where it is slightly less than 1 inch. The butt splice sealing sleeves for the custom engineered splices were approximately 6 ½ inches long compared to approximately 2 inches for the splices in LOCA test 1, as shown in Figure 14.

The test facility technicians were provided with training in the installation of the nuclear grade splice kits. Using the custom engineered splice kits, no problems were encountered in the second LOCA exposure test, which had milder preaging conditions and a less severe LOCA temperature/pressure profile than those specified for the first LOCA exposure test.

The third LOCA exposure test repeated the cable type and conditions of the first test with the exception that the thermal and radiation preaging were doubled, to simulate 40 years of service at 90°C. Higher leakage currents were observed again during the LOCA exposure test for those cable specimens that had received the 40 years of accelerated aging. Post-LOCA disassembly of the splices revealed that "...moisture was still observed inside the splices. The high pressure steam in the LOCA chamber environment forced moisture into the cable through cracks in the jacket, where it was driven along the interior of the jacket, directly into the interior of the splice. Once there, cracks in the insulation allowed the moisture to provide a conductive path between cable conductors." [6] Despite the precautions and care taken to handle the aged cable specimens gently, the embrittled jackets and insulation may have been damaged unavoidably during handling for installation of the cable splices and/or the performance of condition monitoring activities.

To further minimize the potential for handling damage during the remaining three LOCA exposure tests, 2 to 3 foot long pigtails of Teflon-insulated facility lead wire were spliced to the conductors of each cable specimen using Raychem nuclear grade splices prior to administering any accelerated aging. The pigtails were sleeved with Raychem heat-shrinkable tubing and shielded from the conditions of accelerated thermal and radiation aging to minimize degradation. After preaging had been completed, the facility lead wires were finally connected to the pigtails on the test specimens using a second nuclear grade splice, which also stayed within the LOCA test chamber [6].

8.2 Disassembly of Nuclear Grade Cable Splices

Although the main focus of the loss-of-coolant accident (LOCA) exposure simulations was to study the performance of low-voltage instrumentation and control cables, the presence of nuclear grade splices on nearly all of the test specimens provided a unique opportunity to gain insights into the performance of this important component of nuclear plant cable systems.

As observed during the LOCA exposure testing described above, the installation of splices on cables with cracked or damaged jackets and or insulation can lead to failures when the cables are exposed to such environmental stressors as high pressure steam and moisture. This was further confirmed by disassembly and inspection of several of those splices shortly after the completion of the LOCA exposure testing, as discussed in Reference 6.

To obtain additional insights into splice performance and potential failure mechanisms, disassembly of other representative cable splices from the low-voltage cable test program was performed as part of the current study, as outlined in Table 4. The insulation resistance of each splice was measured immediately prior to disassembly. These values are given in Appendix B. The splices were inspected for integrity of the environmental seal, evidence of moisture intrusion, adhesion of the sealing elements, use of shimming, and any other damage that may have occurred during the testing. Observations from the disassembly of the representative splices are provided in the following paragraphs. The identification numbers cited refer to the cable test specimen on which the splice was installed during the low-voltage cable test program. A complete description of the test specimens, along with the test protocol and the accelerated aging each specimen received is provided in Reference 6.

8.2.1 Splices Installed on Rockbestos Cables

The Rockbestos specimens tested in the low-voltage cable test program were 2/C #14 AWG cables insulated with cross-linked polyethylene (XLPE) and covered with a Neoprene overall outer jacket. Comparison of the inadequately specified splice (Splice 0102A) and the engineered splice (Splice 0604A) installed on unaged Rockbestos cable specimens, illustrated in Figure 14, was discussed above.

Splices 0604A, 0314B, 0622A, installed on Rockbestos cable specimens which had received no preaging, 40 years of aging, and 60 years of aging, respectively, were disassembled for inspection and comparison. Splice 0604A was installed on a control specimen that received no preaging, therefore, the splice also received no preaging. Splice 0314B was installed on a specimen that received preaging to simulate 40 years of service. However, the splice was installed after the preaging was completed, thus, the splice itself received no preaging. Splice 0622A received the same 60 years equivalent preaging (1363.8 hours at 302°F and 77.02 Mrad total integrated dose at a dose rate of 0.390 Mrad/hr) as the cable specimen on which it was installed. This was the most severe preaging administered during the entire low-voltage cable research program.

Prior to disassembly, insulation resistances measured for Splices 0604A and 0622A at 500Vdc after 1 minute were 6.8TΩ and 37TΩ, respectively. The insulation resistance for Splice 0314B was 0.159TΩ. The cable specimen 0314 circuit had maximum leakage currents of 12mA during LOCA exposure testing, and other 40 year aged cable splices in that same group, disassembled shortly after LOCA testing, were found to contain moisture in their interiors.

Disassembly of the unaged Splice 0604A, pictured in Figure 14, showed that the environmental seals at both ends of the 19 inch splice assembly were in good condition and tight. The cable specimen jacket within the splice sleeve looked and felt like new, with no discoloration compared to the exposed Neoprene jacket. It was protected from the LOCA steam and chemical spray conditions by the environmental seal with the overall WCSF-300 (28/8) heat-shrinkable outer sleeve. The interior of the splice was observed to be clean with no evidence of moisture intrusion. The butt splice sealing sleeves on the individual conductors, consisting of approximately 6 ½ inch lengths of WCSF-070 (8/2) heat-shrinkable tubing, were found to be in good condition and tightly sealed to the cable insulation.

Unaged Splice 0314B, installed on the 40 year aged cable, was found to have an adequate seal at the facility lead end of the assembly. At the other end of the splice, however, the cable specimen jacket was badly degraded, very brittle, and had many cracks. This area of the splice is pictured in Figure 15. The individual conductors within the splice were discolored, degraded, and possibly cracked. The 5¼ inch environmental seal with the outer splice sleeve was in poor condition and there was evidence of water intrusion (see Figure 15): rust and tan-colored deposits could be seen inside the splice as far as the location of the butt splice. The butt splices were covered by 6½ inch WCSF-070 (8/2) sealing sleeves, which appeared to be intact.

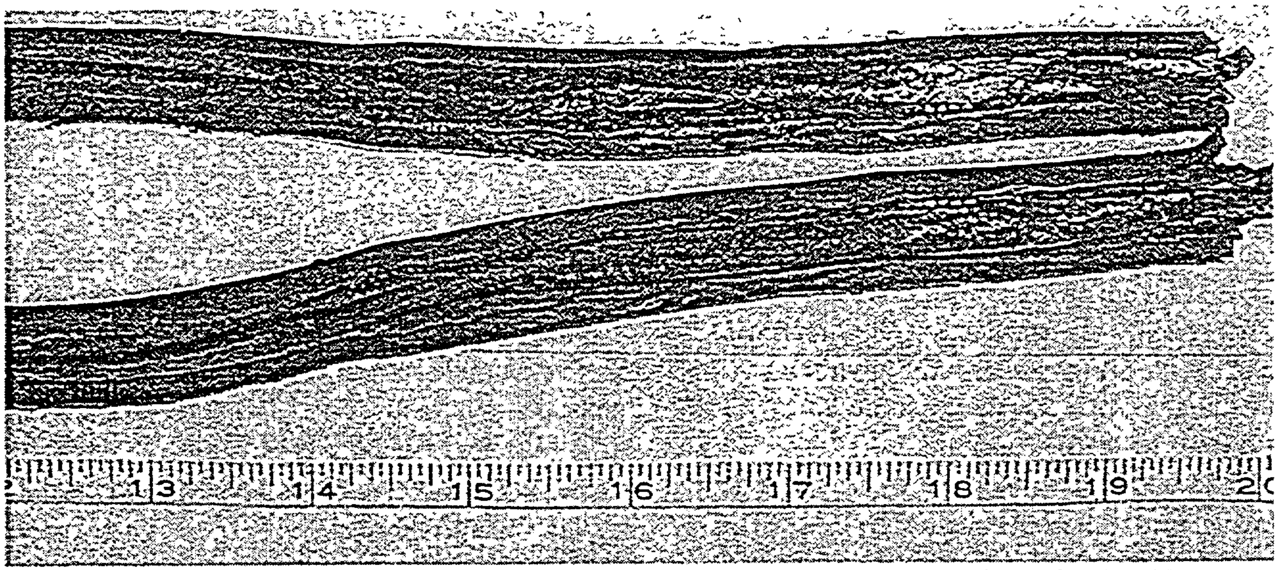


Figure 15: View of 5¼ inch environmental seal to degraded cable jacket in Splice 0314B

Aged Splice 0622A, installed on the 60 year aged cable, was found to have an adequate seal at the facility lead end of the assembly. The cable specimen jacket was badly degraded and was separating from the conductors inside of it. The 4½ inch environmental seal with the outer splice sleeve at the cable specimen end of the splice seemed to be tight, but there was evidence of water intrusion through the interior of the cable specimen jacket. Tan-colored deposits could be seen inside the splice as far as the shimmed area between the end of the cable specimen jacket and the end of the butt splice sealing sleeves. The butt splices were covered by 6½ inch WCSF-070 (8/2) sealing sleeves, which appeared to be intact. The environmental seal at the facility lead end of the splice was found to be adequate. The 19 inch splice assembly was still flexible but was noticeably stiffer than the other two splices. The surface of the WCSF-300 (28/8) overall sleeve felt as if it had hardened. It was also more prone to tear during disassembly than the material that had received less preaging.

8.2.2 Splices Installed on American Insulated Wire (AIW) Cables

The AIW specimens tested in the low-voltage cable test program were 3/C and 4/C #16 AWG with ground cables insulated with ethylene propylene rubber (EPR) and a chlorosulfonated polyethylene (CSPE) individual jacket on each conductor, covered with a CSPE overall outer jacket. Splices 0603A, 0207A, 0213A, and 0613A, installed on AIW cable specimens which had received no preaging, naturally aged cable (about 24 years of actual in-plant service), 20 years of aging, and 60 years of aging, respectively, were disassembled for inspection and comparison. Splice 0603A was installed on a control specimen that received no preaging, therefore, the splice itself also received no preaging. Splices 0207A and 0213A were installed on cable specimens after preaging had been completed, therefore, these splices also received no preaging. Splice 0613A received the same 60 years equivalent preaging (252.1 hours at 302°F and 38.65 Mrad total integrated dose at a dose rate of 0.590 Mrad/hr) as the cable specimen on which it was installed. This was the least severe 60 year preaging administered during the entire low-voltage cable research program.

Prior to disassembly, insulation resistances measured for Splices 0207A, 0213A, and 0613A at 500Vdc after 1 minute were greater than 3.3TΩ. The insulation resistance for Splice 0603A was 0.605GΩ. No leakage currents were detected during LOCA exposure testing for any of the cable specimens on which these splices were installed.

No unusual conditions were noted for any of the four splices with the exception of Splice 0603A, which had a slight indication of tan-colored deposits in the shimmed area inboard of the environmental seal at the cable specimen end of the splice assembly. This section of Splice 0603A is pictured in Figure 16. A green spot was also noted on the bare stranded copper ground wire, which is indicative of the intrusion water into the area causing the copper to oxidize. The environmental seal between the cable specimen jacket and outer WCSF-300 (28/8) heat-shrinkable sleeve did not appear to be tight and may have permitted the intrusion of steam or moisture under high pressure.

8.2.3 Splices Installed on Okonite Cables

The Okonite specimens tested in the low-voltage cable test program were 1/C #12 AWG cables insulated with EPR and a bonded CSPE individual jacket on each conductor. The splices disassembled (0501A, 0505A, 0511A, and 0605B) were applied to Okonite specimens representing no aging, 20 years of aging, 40 years of aging, and 60 years of service aging, respectively. All splices received the same quantity of preaging as the cable specimens on which they were installed.

Prior to disassembly, insulation resistance values measured for all four splices at 500Vdc after 1 minute were greater than 5.5TΩ. During LOCA exposure testing, the EPR insulation with bonded CSPE jacket covering cable specimens 0511 (40 years of aging) and 0605 (60 years of aging) split open longitudinally along large portions of the length of the specimens. Despite the failure of these materials external to the splice, the WCSF-115 (9/3) heat-shrinkable sealing sleeve protected the cable insulation and bonded jacket within the environmental seal area of the splice from damage during both the preaging and the LOCA exposures.

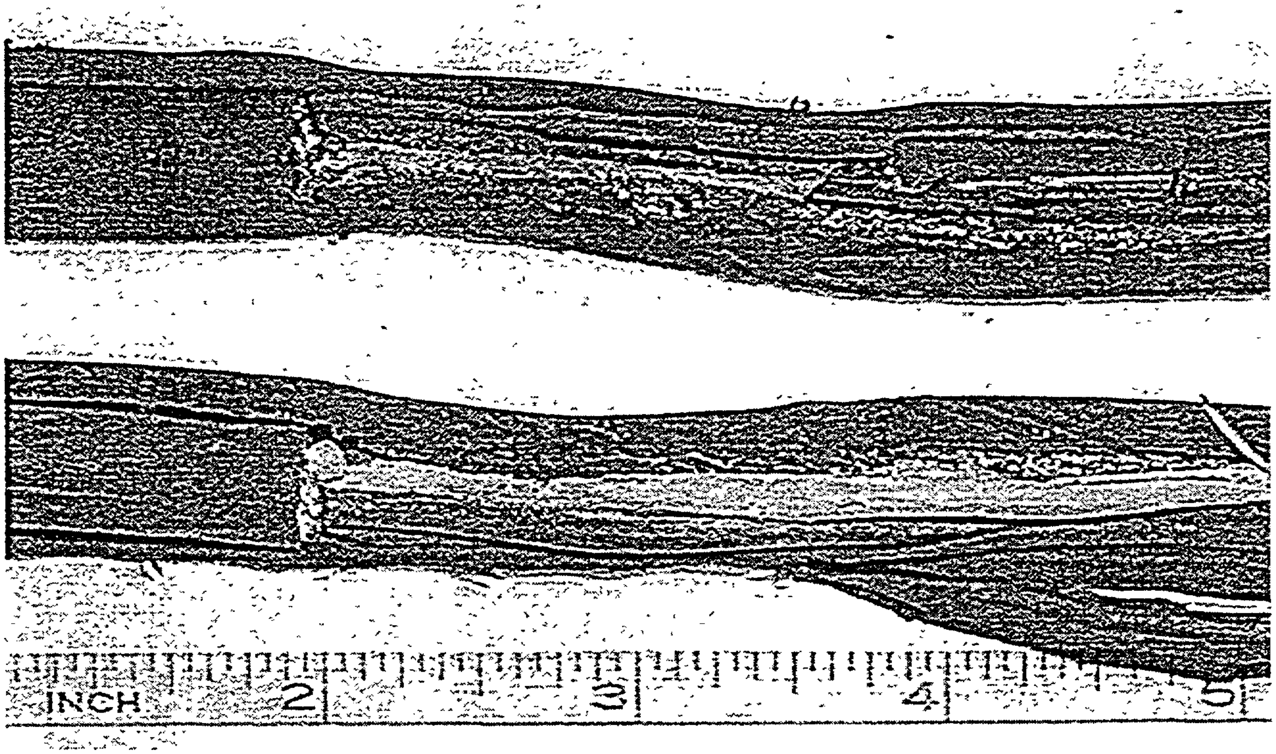


Figure 16: Deposits and oxidized copper inboard of cable jacket in Splice 0603A

No major problems were noted with these splices. All environmental seals appeared to be in good condition. Butt splice connectors for the 20, 40, and 60 year splices, seen in Figure 17, appeared to be slightly darker than the butt splice connector with no preaging. Some moisture may have infiltrated into the splices on the 40 and 60 year splices by passing through the split insulation/bonded jackets and along the interior spaces of the conductor strands. This is evident on the 60 year preaged Splice 0605B, where the butt splice connector metal is darkened and rust or other brown deposits can be seen on the end closest to the cable specimen jacket in Figure 17. The outer splice sealing sleeves remained flexible but became stiffer with greater preaging. Some hardening of the surface of the outer splice sleeve was noted and some surface melting may have occurred as evidenced by a granular, pebbled texture.

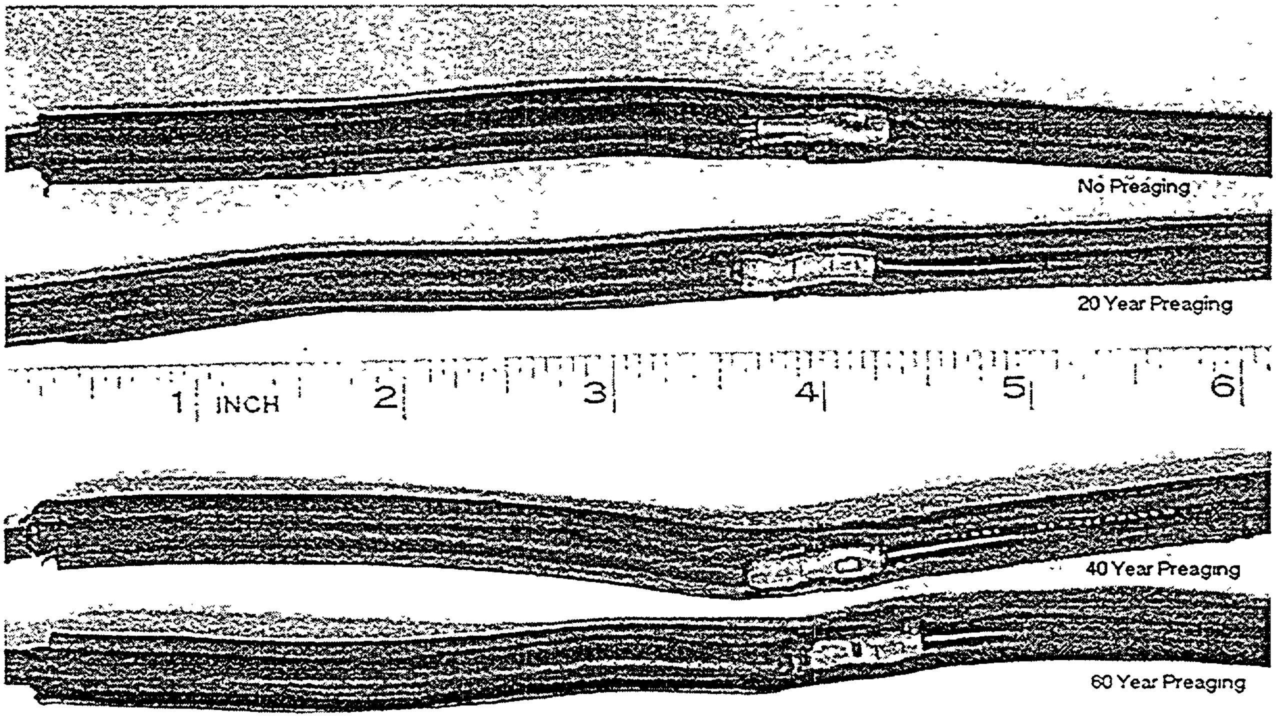


Figure 17: Post-LOCA condition of Splices 0501A, 0505A, 0511A, and 0605B

8.2.4 Splices Installed on Samuel Moore Cables

The Samuel Moore specimens tested in the low-voltage cable test program were 2/C #16 AWG cables with ground, insulated with ethylene propylene diene monomer (EPDM) insulation and a CSPE individual jacket on each conductor, and a CSPE overall outer jacket. The splices disassembled (0502A, 0507A, 0514A, and 0609A) were installed on Samuel Moore specimens representing no aging, 20 years of aging, 40 years of aging, and 60 years of service aging, respectively. All splices received the same quantity of preaging as the cable specimens on which they were installed.

Prior to disassembly, insulation resistance values measured for all four splices at 500Vdc after 1 minute were greater than 2.4TΩ. During LOCA exposure testing, no anomalies were noted for any of the cable specimens on which these splices were installed. Cable specimen 0609 was not able to pass the post-LOCA submerged voltage withstand test at the intended test voltage of 2400Vac. Although Splice 0609A was not immersed in water during the test, the failure of the cable specimen meant that jacket and or insulation damage was present, possibly providing a pathway for high pressure steam and moisture to infiltrate into the interior of the cable splices.

Disassembly of unaged Splice 0502A showed that the environmental seal at the facility lead wire end of the splice was not intact. As illustrated in Figure 18, there were white deposits evident in the spaces between the facility lead wires, that had been sleeved with WCSF-115 (9/3) heat-shrinkable tubing, and the insulated

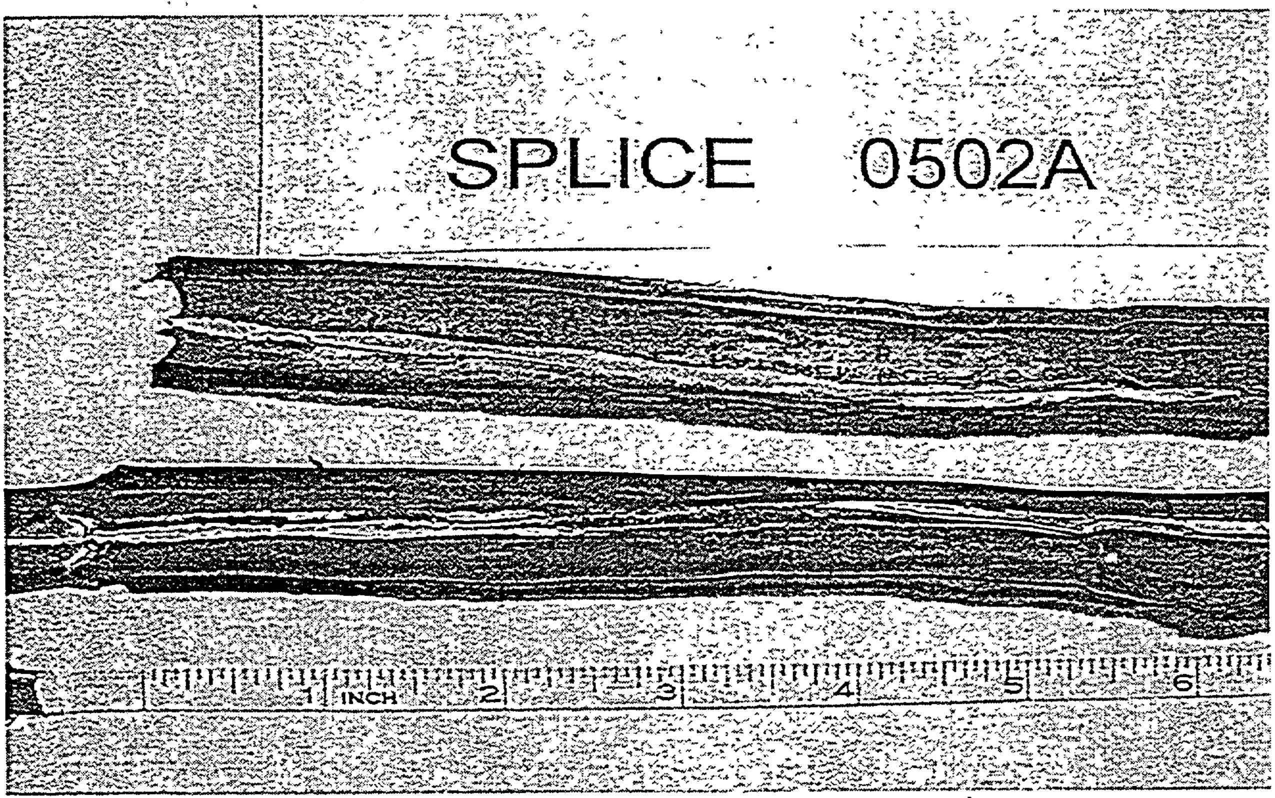


Figure 18: Indications of moisture intrusion through seal at facility lead end of Splice 0502A

facility ground wire that all entered the overall 18½ inch long WCSF-300 (28/8) heat-shrinkable tubing covering the entire splice. The whitish deposits could be seen throughout the splice interior, but did not seem to cause noticeable corrosion of the butt splice connection to the bare copper conductor of the cable specimen. The butt splices for the individual conductors were covered by 6½ inch WCSF-070 (8/2) sealing sleeves and these appeared to be intact. If more nuclear adhesive sealant had been applied to the sleeved facility lead wire and insulated facility ground wire, the spaces may have been sealed better. The other three splices used a greater amount of nuclear adhesive sealant with the result that the environmental seals at the facility leads end of those splices were tight.

White deposits were also noted where the individual conductors emerged from the cable specimen jacket. The environmental seal between the cable specimen jacket and the overall WCSF-300 (28/8) sleeve appeared to be intact. However, moisture may have entered the cable specimen jacket through a damaged area and then was driven along the interior of the jacket by the high LOCA pressure, and on into the interior of the splice.

Splices 0507A (20 years of aging) and 0514A (40 years of aging) were both found to have problems with the environmental seal at the cable specimen end of the splice. Whitish deposits were noted and the bare ground conductor was green indicating the presence of moisture, which oxidized the copper.

A ⅞ inch long crack was noted in the 18 inch overall WCSF-300 (28/8) sleeve covering Splice 0514A. A closeup view of the damaged area is shown in Figure 19. The crack was about 3 inches from the cable specimen end of the splice, which placed it within the area of the outer environmental seal. This could have compromised the seal by providing an access pathway for the entry of high pressure steam and moisture.

There are several possible causes for the cracking observed in Splice 514A. The WCSF-300 heat-shrinkable tubing may have recovered (shrunk) too much during installation, thereby placing excessive stress on the material in that area. When it was exposed to high temperature steam and chemical spray conditions during the LOCA exposure simulation, additional recovery by the material may have caused it to tear or crack. Wall thinning or a manufacturing defect are other possible causes for the cracking; the weakened area would be susceptible to damage during the harsh conditions of the LOCA exposure. Another possibility could be that a pocket of air was entrapped in the interior of the splice during installation; expansion of the gas during exposure to the high temperatures of the LOCA simulation could then have caused the heat-shrinkable tubing to rupture at a weak spot. The slightly puckered appearance of the material surrounding the tear, acquired after the internal pressure was relieved and the material had cooled, could be consistent with the latter scenario.

No problems were noted during the disassembly of Splice 0609A (60 years of aging).

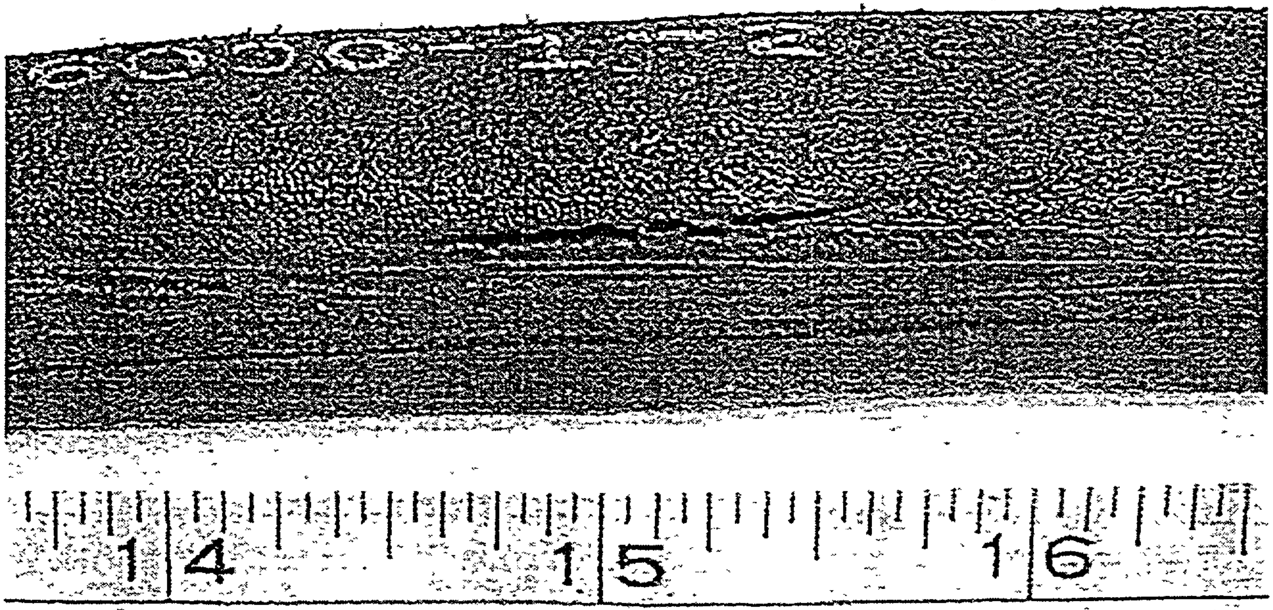


Figure 19: Crack in outer WCSF-300 heat-shrinkable sleeve covering Splice 514A

8.2.5 Splices Installed on Anaconda Cables

The Anaconda specimens tested in the low-voltage cable test program were 3/C #12 AWG cables, insulated with EPR and having a CSPE overall outer jacket. The splices disassembled (0503A and 0509A) were installed on Anaconda specimens representing no aging and 20 years of service aging, respectively. Both splices received the same quantity of preaging as the cable specimens on which they were installed.

Prior to disassembly, insulation resistance measured for Splice 0503A at 500Vdc after 1 minute was 22TΩ. The insulation resistance for Splice 0509A was 5.05TΩ.

No problems were observed during the disassembly of these splices. The interiors of both splices were clean and no contamination was noted. Environmental seals all appeared to be tight and in good condition.

8.3 Observations

The splices disassembled and inspected are summarized in Table 4.

During the disassembly inspection of splices, a number of installation-related problems were noted that could adversely impact the performance of the splice. These include the following:

- Inadequate heat-shrink tubing seal length
- Improper shim size/installation
- Improper use of padding on sharp corners or surfaces, or on bolted connections
- Exceeding the recommended bend radius limitations for the splice
- Improper/inadequate application of sealant under heat-shrink tubing
- Misapplication of the splice in the intended use range

The importance of training, the proper engineering and specification of splices for specific applications, and the proper installation of splice kits in accordance with manufacturer's instructions should be emphasized. A deficiency in any one of these areas can impact the aging degradation of the splice and adversely affect the performance of the splice during accident conditions.

Other observations from the disassembly and inspection are:

- Installation of splices onto cables that had been exposed to accelerated thermal and radiation preaging can be problematic. Hardening and cracking of the cable jackets can make it difficult to obtain a good seal when heat-shrinkable material is applied over it. Cracked and damaged cable jackets can provide a leakage pathway for high pressure steam, moisture-borne deposits, chemical spray, and other contaminants to enter into the interior of cable splices and adversely affect performance.

- In multi-conductor splice geometries sheathed by an overall covering of heat-shrinkable sleeving, high pressure steam, moisture-borne deposits, chemical spray, and other contaminants can enter into the interior of cable splices via the spaces between the multiple conductors if these areas of the splice have not been properly sealed. A sufficient quantity of nuclear sealant must be applied to assure that these areas are properly blocked and sealed against the environment.

Table 4 - Representative Cable Splice Disassembly Matrix

Cable Mfg.	**Mat'ls**	**Identification Number of Splices Disassembled from each Simulated Service Year Group**				
		No Aging	**NAC**	**20 Years**	**40 Years**	**60 Years**
Rockbestos	XLPE/Neo	**0102A** **0604A**	-	**0112-0116** (disassembled after LOCA 1)	**0314B**	**0622A**
AIW	EPR/CSPE	**0603A**	**0207A**	**0213A**	-	**0613A**
Okonite	EPR/CSPE	**0501A**	-	**0505A**	**0511A**	**0605B**
Sam Moore	EPDM/CSPE	**0502A**	-	**0507A**	**0514A**	**0609A**
Anaconda	EPR/CSPE	**0503A**	-	**0509A**	-	-

AIW = American Insulated Wire
NEO = Neoprene
XLPE = Cross-linked Polyethylene
EPR = Ethylene Propylene Rubber
CSPE = Chloro Sulphonated Polyethylene
EPDM = Ethylene Propylene Diene Monomer

NOTES:

- The splice identification number is the same as the cable test specimen identification number on which it was installed during the low-voltage cable test program (see Ref. 6).
- All splices in LOCA Tests 1 through 3 (ID nos. 01XX, 02XX, and 03XX) were unaged prior to the accident simulation exposure, even though some were installed on preaged cables
- All splices in LOCA Tests 4 through 6 (ID nos. 04XX, 05XX, and 06XX) were exposed to the same preaging as the cable test specimens on which they were installed.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Effects of Aging on Cable Splices

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

- Cable splice 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 splice failure, although these failures have been infrequent.
- Cable splices 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, including the loss of function of safety-related equipment, loss of safety system redundancy, reactor scrams, and unscheduled reductions in power.
- The predominant aging mechanism for cable splice failure is loosening of the connectors, which can result in intermittent operation of the equipment or complete failure. Other important aging mechanisms are corrosion of the connectors, short circuit to ground or another conductor, and arcing at loose connections.
- The failure mode most commonly found is "open circuit," in which the conductive pathway of the splice is broken. Almost equally important failure modes are degraded electrical connection, in which the degradation of electrical contact surfaces causes either high resistance or intermittent output, and electrical short circuits to ground or to other conductors.
- The number of cable splice events reported in the various databases is relatively small, suggesting that splice failures are infrequent. However, there may be a number of splice events that were judged to be of insufficient importance to report by the utility.

While the number of failures is relatively low, the data indicate that cable splices are susceptible to aging degradation that can lead to failure. Cable splices are not typically replaced on a periodic basis, unless there is a problem with the cable. As nuclear power plants age and the splices 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 splice insulation and connectors will increase. This could lead to an increase in the number of splice failures in later years of plant life. An aging management program to monitor and mitigate the effects of cable splice aging would be beneficial in anticipating these potential problems.

9.2 Managing Aging

Aging management of cable splices 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 splices appears to be feasible. The following recommendations are made with respect to the establishment of a monitoring program:

- Visual inspection should be considered as a first step for all cable splices, connectors, and terminations that are physically accessible. This is an inexpensive, simple technique that can provide valuable information on the overall condition of a cable joint. The qualitative information obtained from visual inspection by experienced personnel can be enhanced by grading important specified parameters and attributes of a splice in the context of a well-structured inspection procedure.

- Imaging infrared thermography and time domain reflectometry are two techniques that appear to be very well suited to identifying, locating, and monitoring problems in cable splices, connectors, and terminations.

- It is recommended that any situ monitoring program include the use of several different CM methods. The method chosen for a particular application should be based on the location, configuration, accessibility, materials, and voltage class of the cable splice, connection, or termination.

- Insulation that is in good condition can, without damage, sustain the application of a dc potential equal to the system basic impulse level for very long periods. In contrast, most insulating materials will sustain degradation from ac overpotential. Consequently, high dc potential should normally be used for periodic field testing of cable and splice insulation, and care should be exercised in the selection of the test voltage levels and the frequency of testing.

9.3 Qualification Practices

The observations made during the evaluation of current qualification practices for splices have resulted in the following conclusions:

- In addition to the thermal and radiation preaging, vibration, temperature cycling, high humidity or other location-specific conditions should also be considered as preaging stressors in the qualification testing of cable splices for generic applications.

- Prior to applying a splice to an aged cable, the condition of the cable insulation and jacket should be evaluated to determine if a good seal can be made. Evidence of hardening or cracking should be considered an indicator that proper sealing will be difficult or impossible.

- The importance of training, proper engineering, and proper specification of splices for specific applications, and the proper installation of splice kits in accordance with manufacturer's instructions should be emphasized. A deficiency in any one of these areas can lead to poor splice performance.

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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 wear out 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.
wear out	Failure produced by an aging mechanism.

APPENDIX B: CABLE SPLICE INSULATION RESISTANCE MEASUREMENTS - PRE-DISASSEMBLY

Table B-1 Cable Splice Insulation Resistance Measurements - Pre-Disassembly

	Source	Cbl	Cbl Materials		Equiv Age (yrs)		IR Test		IR in Tera-ohms		Temp	Polarization	
SPLICE	Sample	Mfg	Insul/Jacket	Configuration	Cable	Splice	Date	Cnd	@ 1 Min	@ 10 Min	(F)	Index	RH %
0201A	PNI74AI025	AIW	EPR/CSPE	3/C#16 w/gnd	0	0	03/08/2002	BW	14.5	55	69	3.79310345	32
0603A	PNI74AI035	AIW	EPR/CSPE	3/C#16 w/gnd	0	0	02/21/2002	BW	0.000605	0.000615	71	1.01652893	26
0603B	PNI74AI035	AIW	EPR/CSPE	3/C#16 w/gnd	0	0	02/22/2002	BW	11.5	19.5	69	1.69565217	15
0213A	PNI74AI028	AIW	EPR/CSPE	3/C#16 w/gnd	20	0	03/08/2002	BW	9.5	35	69	3.68421053	32
0213A	PNI74AI028	AIW	EPR/CSPE	3/C#16 w/gnd	20	0	03/13/2002	BW	19.5	80	68	4.1025641	33
0207A	PNI74AI015	AIW	EPR/CSPE	3/C#16 w/gnd	NAC	0	03/12/2002	BW	3.3	17.2	67	5.21212121	31
0611A	PNI74AI035	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	02/22/2002	BW	0.024	0.062	69	2.58333333	15
0611A	PNI74AI035	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	03/04/2002	BW	0.049	0.103	66	2.10204082	14
0611B	PNI74AI035	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	02/22/2002	BW	0.00029	0.00046	69	1.5862069	15
0611B	PNI74AI035	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	03/04/2002	BW	0.00035	0.00086	66	2.45714286	14
0612A	PNI74AI036	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	02/22/2002	BW	0.00335	0.0032	69	0.95522388	15
0612A	PNI74AI036	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	03/04/2002	BW	0.00087	0.00098	66	1.12643678	13
0612B	PNI74AI036	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	02/22/2002	BW	0.62	3.4	69	5.48387097	15
0612B	PNI74AI036	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	03/04/2002	BW	7.6	31	66	4.07894737	13
0613A	PNI74AI030	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	03/01/2002	BW	5.6	19	66	3.39285714	17
0613B	PNI74AI030	AIW	EPR/CSPE	3/C#16 w/gnd	60	60	03/01/2002	BW	0.00111	0.0013	66	1.17117117	17
0503A	DNP78AN008	Ana	EPR/CSPE	3/C#12	0	0	03/13/2002	BW	22	90	68	4.09090909	33
0509A	DNP78AN008	Ana	EPR/CSPE	3/C#12	20	20	03/05/2002	BW	5.05	34	64	6.73267327	9
0501A*	LNI81OK020	Oko	EPR/CSPE	1/C#12	0	0	03/11/2002	CE	80	200	64	2.5	11
0505A**	LNI81OK020	Oko	EPR/CSPE	1/C#12	20	20	03/12/2002	CC	17	55	67	3.23529412	31
0505A***	LNI81OK020	Oko	EPR/CSPE	1/C#12	20	20	03/15/2002	CC	5.5	10.2	70	1.85454545	45
0511A**	LNI81OK020	Oko	EPR/CSPE	1/C#12	40	40	03/12/2002	CC	17	55	67	3.23529412	31
0605B***	LNI81OK020	Oko	EPR/CSPE	1/C#12	60	60	03/15/2002	CC	5.5	10.2	70	1.85454545	45
0604A	PNI79RB188	Rock	XLPE/Neo	2/C#14	0	0	03/15/2002	BW	6.8	17.5	68	2.57352941	26
0102A	PNI79RB188	Rock	XLPE/Neo	2/C#14	0	0	03/01/2002	BW	11	49	65	4.45454545	16
0314B	PNI79RB188	Rock	XLPE/Neo	2/C#14	40	0	03/06/2002	BW	0.159	0.158	68	0.99371069	26
0622A	PNI79RB188	Rock	XLPE/Neo	2/C#14	60	60	03/04/2002	BW	37	200	65	5.40540541	13
0622B	PNI79RB188	Rock	XLPE/Neo	2/C#14	60	60	03/04/2002	BW	80	200	65	2.5	13
0502A	DNI80SM010	SM	EPDM/CSPE	2/C#16 w/S&G	0	0	03/12/2002	BW	7.1	22	67	3.09859155	31
0507A	DNI80SM010	SM	EPDM/CSPE	2/C#16 w/S&G	20	20	03/08/2002	BW	4.4	14	69	3.18181818	32
0514A	DNI80SM010	SM	EPDM/CSPE	2/C#16 w/S&G	40	40	03/08/2002	BW	2.4	6.8	69	2.83333333	32
0609A	DNI80SM010	SM	EPDM/CSPE	2/C#16 w/S&G	60	60	03/01/2002	BW	5.05	10.7	66	2.11881188	17
0609B	DNI80SM010	SM	EPDM/CSPE	2/C#16 w/S&G	60	60	03/04/2002	BW	13	26	66	2	14

* Insulation resistance (IR) for Splice 0501A was measured from conductor to a grounded cable tray

** Splices 0505A and 0511A were placed together in a cable tray and the IR between the two 1/C splices was measured

*** Splices 0505A and 0605B were placed together in a cable tray and the IR between the two 1/C splices was measured

NAC - Naturally aged cable, removed from a nuclear power plant after 24 years of service

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10 SUPPLEMENTARY NOTES

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11 ABSTRACT *(200 words or less)*

An evaluation of aging and environmental qualification practices for safety-related cable splices 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 cable splices have been reviewed. Based on the results of the aforementioned reviews, predominant aging characteristics are identified and potential condition monitoring techniques are evaluated. As part of this study, a review of environmental qualification test reports and analyses related to electric cable splices was conducted. In addition, cable splices that were pre-aged and exposed to simulated accident conditions in a previous NRC/RES Program were disassembled and inspected to gain insights into splice performance and potential failure mechanisms under harsh environments.

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