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Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cable and Terminations

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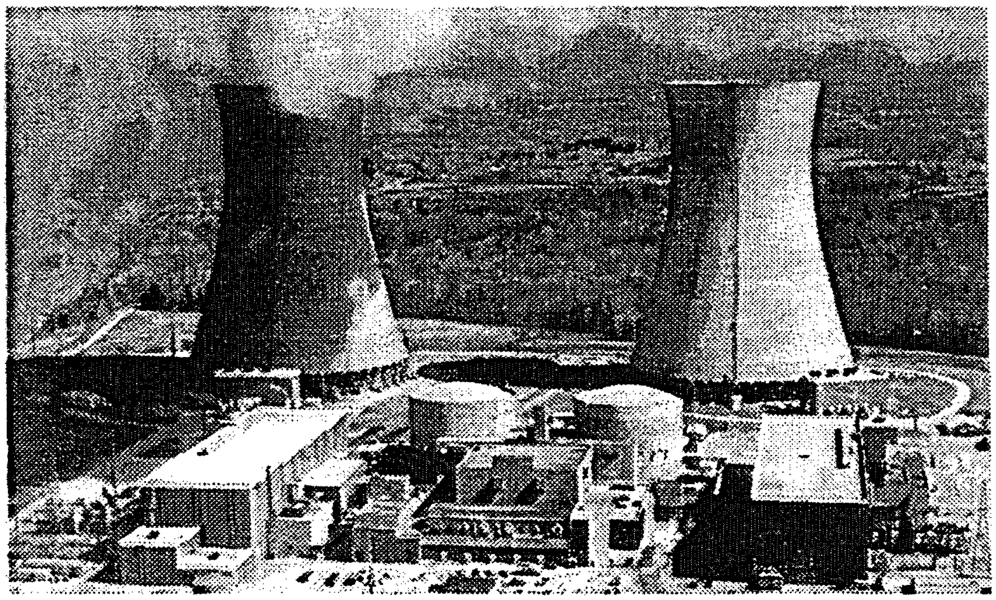

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AGING MANAGEMENT GUIDELINE FOR COMMERCIAL NUCLEAR POWER PLANTS - ELECTRICAL CABLE AND TERMINATIONS

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Abstract

This Aging Management Guideline (AMG) describes recommended methods for effective detection and mitigation of aging mechanisms in commercial nuclear power plant electrical cables and terminations within the scope of license renewal and maintenance rule activities. The intent of this AMG is to assist plant maintenance and operations personnel in maximizing the safe, useful life of these components. It also supports the documentation of aging effects management programs required under the License Renewal Rule 10 CFR 54. This AMG is presented in a manner that allows personnel responsible for performing analysis and maintenance to compare their plant-specific aging effects (expected or already experienced) and aging management program activities to the more generic results and recommendations presented herein.

Acknowledgements

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Electronic Version Availability

A number of Microsoft EXCEL spreadsheets were developed to create the tables and figures in this guideline. The spreadsheets and graphing tools were prepared in a manner that the data evaluated for this guideline can easily be replaced with plant-specific data so utility personnel can easily perform aging assessments of specific polymer formulations. Copies of the computer files, in EXCEL for WINDOWS 5.0 format, can be obtained by contacting DOE's LWR Technology Center @ Sandia at (505) 844-5379.

Likewise, the entire document is available in WordPerfect 5.1 for DOS format. Utility personnel responsible for implementing Maintenance Rule requirements or preparing License Renewal evaluations may find this document useful. Copies of the computer files (one file per section/appendix) can be obtained by contacting DOE's LWR Technology Center @ Sandia at (505) 844-5379.

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1. EXECUTIVE SUMMARY

1.1 Purpose

The continued operation of nuclear power plants for periods that extend beyond their original 40-year license may be a desirable option for many U.S. nuclear plant operators. However, to allow operation of the plant beyond this period, utilities must show that the aging of components important to license renewal is managed. Components must not degrade to the point where they are incapable of performing their safety function(s) during either normal operating or accident conditions. Therefore, to allow operation during a license renewal period, nuclear power plant operators must manage the aging of components to ensure proper function.

This document analyzes potential aging mechanisms and their effects on low- and medium-voltage electrical cable and terminations, and provides guidelines for managing significant degradation mechanisms. Effective management will ensure that these systems continue to perform their safety function(s) during both the current and the license renewal terms. Use of these guidelines will provide utilities with a basis for verifying that effective means for managing age-related degradation of cable systems have been established. The guidelines are also useful for life cycle management purposes to optimize surveillance and maintenance programs and minimize forced outages due to unexpected premature aging. Guidance for performing aging management reviews pursuant to 10CFR54 is also provided.

1.2 Scope

Low- and medium-voltage electrical cable systems consist of cables, terminations, and other associated components (such as cable trays, penetrations, and conduit) used to power, control, and monitor various types of electrical apparatus and instrumentation. The equipment covered by this guideline includes all low- and medium-voltage cables and their terminations.[1] Cable trays, penetrations, conduits, conduit seals, and other ancillary equipment are not addressed in detail. Potential interactions between these components and electrical cables and terminations and potential aging effects are discussed.

Cables and cable systems may be grouped in a number of ways. The groups of cables and terminations described in 10CFR54 as being within the scope of license renewal are as follows:

1. Safety-related

2. Nonsafety-related whose failure could prevent satisfactory accomplishment of a safety-related function

[1] High-voltage systems (≥ 15 kVac) were not included in the scope of this document because: (1) they generally constitute an extremely small fraction of the total amount of cable at a plant, and (2) they are often highly specialized in construction (e.g., oil filled) so they have little in common with the more prevalent low- and medium-voltage systems.

3. Those relied on in safety analyses or plant evaluations to perform a function that demonstrates compliance with Nuclear Regulatory Commission (NRC) regulations for

    - Fire protection (10CFR50.48)
    - Environmental qualification (10CFR50.49)
    - Pressurized thermal shock (10CFR50.61)
    - Anticipated transients without scram (10CFR50.62)
    - Station blackout (10CFR50.63).

In addition, cables not included in the above categories but which are important to the continuity of power production or some other aspect of plant operation may, at a utility's option, be included in the scope of a plant's aging management program. Typically, a utility would opt to expand the scope of the aging management program for economic and reliability reasons.

Cable systems may also be grouped according to use or function. These categories include:

- Power cables
- Control cables
- Instrument cables
- Telephone and security cables
- Local and panel wiring
- Thermocouple extension wiring
- Specialty cables[2]
- Lighting cables
- Grounding cables

Further classification of cable systems in terms of their voltage rating is possible:

- Low-voltage (≤ 1000 Vac or ≤ 250 Vdc)[3]
- Medium-voltage (2 kVac through 15 kVac)

The majority of plant circuits fall within the low-voltage category.

Included within the scope of terminations in this AMG are the following:

- Plug-in/multi-pin type connectors
- Compression fittings
- Fusion fittings
- Splice insulations (tape and heat-shrinkable tubing)
- Terminal blocks

Appendix A provides definitions of the terminology used in this report and Appendix B provides a detailed description of the components discussed.

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[2] Specialty cable is used in applications that require specific cable attributes, properties, or configuration (e.g., neutron detectors, area radiation monitors, and control rod position indicators).

[3] As in the Low-Voltage, Environmentally-Qualified Cable Industry Report, the upper range of low-voltage is defined as 1000 Vac. Typically, cables are not rated between 1000 and 2000 Vac; however, the results for low-voltage cable are applicable up to 2000 Vac.

1.3 Methodology

This study evaluated the stressors acting on cable and termination components, industry data on aging and failure of these components, and the maintenance activities performed on cable systems. It evaluated the main subsystems within cables, including the conductors, insulation, shielding, tape wraps, jacketing, and drain wires, as well as all subcomponents associated with each type of termination. The principal aging mechanisms and anticipated effects resulting from environmental and operating stresses on these systems were identified, evaluated, and correlated with plant experience to determine whether the predicted effects are consistent with field experience, recognizing that new effects may be identified in the future. Installation stressors were also examined. Then, the maintenance procedures and condition monitoring/testing methodologies used by plant operators were evaluated to determine whether the effects of aging mechanisms are being detected and managed. Other available testing and condition monitoring techniques were also identified. Where an aging mechanism was not fully managed or not considered, additional plant-specific activities to manage the aging mechanism are identified and recommended.

1.4 Conclusions

1.4.1 Historical Performance

The following conclusions were drawn from the historical performance of cables and terminations:

1. The number of cable and termination failures (all voltage classes) that have occurred throughout the industry is extremely low in proportion to the amount of installed cable. However, the data which supports this conclusion is limited in two ways: (1) there is little or no data to quantify performance under accident conditions, and (2) only a few plants have operated for more than twenty years, which is only about one-third of the total expected period of operation for these systems (i.e., 60 years).

2. Thermal embrittlement of insulation is one of the most significant aging mechanisms for low-voltage cable. Mechanical stress (vibration, etc.) was also frequently cited as a cause for failure. These thermal and mechanical aging mechanisms occur predominantly near end devices or connected loads. Thermal aging results largely from localized hot spots; aging due to the ambient environment or ohmic heating may also be present.

3. As evidenced in all of the data sources examined, localized radiolytic degradation (i.e., degradation induced by ionizing radiation) affects low-voltage cables and terminations to a lesser degree than thermal and mechanical degradation. Degradation resulting from exposure to external chemical substances occurs infrequently.

4. Localized thermal, radiolytic, and incidental mechanical damage appear to be the most significant aging mechanisms for cables located near the reactor pressure vessel, especially neutron monitor circuits.

5. Connector failures constitute a large percentage of all failures noted for low-voltage and neutron monitoring systems. A large percentage of these failures can be attributed to oxidized, corroded, or dirty contact surfaces.

6. Failures of hookup or panel wiring constitute a substantial percentage of the total number of low-voltage circuit component failures noted. A large fraction of these failures are not the result of aging influences, but rather stem from design, installation, maintenance, modification, or testing activities.

7. Wetting concurrent with operating voltage stress appears to produce significant aging effects on medium-voltage power cable.

8. Loosening and breaking of lugs are the most significant failures of compression fittings.

9. Damage to cable insulation during or prior to installation may be crucial to the cable's longevity, particularly for medium-voltage systems.

10. Based on the high reliability demonstrated by cable systems and assuming that their reliability remains high, continued reliance on visual inspection techniques for the assessment of low-voltage cable and termination aging appears warranted since these techniques are effective at identifying degraded cables.

1.4.2 Significant Aging Combinations Not Always Managed by Existing Programs

Evaluation of the components of cable systems and terminations, the stressors acting upon the components, and the operational history determined that although several "significant"[4] aging mechanisms exist, few actual subcomponent failures result. Evaluation of the general and specific failure histories for cable systems [as reflected in the Nuclear Plant Reliability Data System (NPRDS) and Licensee Event Report (LER) databases, the available literature, and information provided from host utility plants and surveys] shows that both low- and medium-voltage systems (including neutron monitoring equipment) are highly reliable and experience a generally low failure rate.

All potentially significant aging mechanisms and effects for electrical cable and terminations included in the scope of this AMG are described in Section 4.2 of this report. Examination of the relative importance and likelihood of occurrence of these effects provides a greatly reduced set of significant mechanisms; these were designated as "significant and observed" aging mechanisms for the purposes of this guideline. A comparison of this reduced set of aging mechanisms with common maintenance, surveillance, and condition monitoring techniques employed by operating plants (Table 1-1) indicated that the following combinations may require additional plant-specific aging management activities:

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[4] For the purposes of this guideline, a "significant" aging mechanism was defined as one which, if left unmitigated, could potentially affect the functionality of the equipment.

- Localized thermal, radiolytic, or mechanical degradation of low- or medium-voltage cable insulation and jacketing (where jacketing is required for environmental qualification considerations)
- Localized thermal, radiolytic, or mechanical degradation of cables located near the reactor pressure vessel, especially neutron monitor circuits
- Thermal degradation of low- and medium-voltage power cable insulation when the circuit is regularly energized, other than testing, at a significant fraction of the circuit's ampacity
- Degradation of medium-voltage power cable insulation routinely exposed to appreciable wetting or submergence
- Oxidation and/or corrosion of connector contact surfaces associated with low-voltage and neutron detecting circuits (and similar low-current or impedance-sensitive applications)
- Loosening of the bond between a compression fitting and a conductor

The following damage mechanisms, although not aging mechanisms, can limit the useful life of aged cable:

- Damage to medium-voltage cable insulation, jacketing, and shielding during installation
- Damage to low-voltage panel or hookup wire resulting from maintenance activities
- Damage to cable resulting from movement or maintenance activities
- Cracking of bonded jacket/insulation systems on environmentally qualified cable during accident exposure
- Exposure of Kapton® (polyimide) insulation[5] to high humidity (moisture), and/or mechanical damage, specifically, aging degradation of the Teflon® that binds the tape wrap on Kapton® leads

[5] Kapton® insulation is manufactured in thin sheets precoated with a Teflon® adhesive.

Table 1-1 Summary of Stressors, Aging Mechanisms, and Current Maintenance, Surveillance, and Condition Monitoring Techniques

Voltage Category	Component	Sub-component	Applicable Stressors	Aging Mechanisms	Aging Effects	Current Preventive Maintenance Techniques	Available Condition-Related Maintenance Techniques
Low	Cables	Insulation and Jacketing	Heat (environment and ohmic)	Thermoxidative degradation of organics	Embrittlement, cracking	Inspection of accessible portions during routine operations or maintenance	Visual inspection, insulation resistance (IR), polarization index, capacitance; repair or replacement
			Radiation	Radiolysis and photolysis of organics	Hardening, cracking, crazing, swelling	Inspection of accessible portions during routine operations or maintenance	Visual inspection, IR, polarization index, capacitance; repair or replacement
			External mechanical stresses	Wear or low-cycle fatigue	Cuts, cracking, abrasion, tearing	Inspection of accessible portions during routine operations or maintenance	Visual inspection, IR, polarization index, capacitance; repair or replacement
	Connectors	Contact Surfaces	Electro-chemical stresses	Corrosion and oxidation of metals	High resistance	Inspection and, if required, cleaning during maintenance	Visual inspection, time domain reflectometry (TDR), capacitance; repair or replacement
	Compression Fittings	Lugs	Vibration, tensile stress	Deformation and fatigue of metals	High resistance, breakage	Inspection during maintenance	Visual inspection, TDR; repair or replacement
Medium	Cables	Insulation	Moisture and voltage stress	Moisture intrusion; water treeing	Dielectric breakdown and fault to ground	Inspection during maintenance	Visual inspection, IR, polarization index, capacitance, TDR, hi-pot, AC power factor; repair or replacement
Neutron Detecting	Cables	Insulation	Heat (environment)	Thermoxidative degradation of organics	Embrittlement, cracking	Inspection of accessible portions during routine operations or maintenance	Visual inspection, IR, polarization index, capacitance; repair or replacement
			Radiation	Radiolysis of organics	Hardening, cracking, crazing, swelling	Inspection of accessible portions during routine operations or maintenance	Visual inspection, IR, polarization index, capacitance, TDR; repair or replacement
			External mechanical stresses	Wear or low-cycle fatigue	Cuts, cracking, abrasion, tearing	Inspection of accessible portions during routine operations or maintenance	Visual inspection, IR, polarization index, capacitance, TDR; repair or replacement
	Connectors	Contact Surfaces	Electro-chemical stresses	Corrosion and oxidation of metals	High resistance	Inspection and, if required, cleaning during maintenance	Visual inspection, TDR, capacitance; repair or replacement

1.4.3 Nonsignificant Aging Combinations

The following aging effects were considered nonsignificant:

- Embrittlement and cracking of non-bonded jackets, unless the jacket is required to shield the insulation from beta radiation or to seal a cable and prevent moisture intrusion
- Aging degradation of cable filler material
- Short-term (fault) stress on cable and termination components
- Aging of cable tape wrap, other than shielding or semi-conducting tape wrap in medium-voltage cable

1.4.4 Recommendations

Evaluations of maintenance and condition monitoring practices for cable systems (Section 5) led to the conclusion that some of the principal aging mechanisms are not fully managed by existing programs. Accordingly, the following general recommendations for addressing these mechanisms are presented:

1. Aging management activities should focus on aging susceptible applications. This will require periodic evaluations of potentially significant degradation mechanisms for the specific type of cable installed (Section 6 provides a proposed step-by-step methodology). For low-voltage systems, instances of earlier vintage or more aging-susceptible materials used to manufacture cables (such as PVC or Neoprene®) that are used in applications subject to heavy continuous loads or routed through "hot spot" areas should be considered. Particular attention should be paid to components or cable segments located in proximity to an end device. Similarly, medium-voltage power cables routinely subject to wetting or submersion, and connectors used in neutron monitoring circuits should be addressed.

2. Significant aging management efforts are generally not warranted for cable systems located in "benign" areas. Accordingly, aging management activities should be focused more on cable and terminations installed in more environmentally challenging areas, and portions of benign areas which are subject to localized stressors.

3. Accurate characterization of plant environments, especially environmentally challenging areas and areas with localized stressors, is important for effective aging management of certain cable systems. Such characterizations should be conducted to help identify the circuits and components that may undergo premature aging with respect to the rest of the systems.

4. Based on the similarity between many environmentally-qualified (EQ) and non-EQ cables and terminations, existing information and analyses related to the aging of EQ components can be effectively applied to many non-EQ components.

5. Condition monitoring is not currently warranted for all applications of medium-voltage cable. There is no known technique that is capable of effective monitoring of dielectric aging that also has negligible potential for inducing degradation due to the test itself. Preventive measures (such as prevention from wetting) should be considered as means of extending medium-voltage cable longevity.

6. In cases where condition monitoring is deemed appropriate (e.g., those cases where aging effects cannot otherwise be demonstrated to be adequately managed, or as a last resort to replacement), a program to determine baseline aging condition using a nondestructive test or evaluation method should be considered.

7. If cables are replaced, plant cable installation practices and procedures should be reviewed to ensure that the possibility of damaging cables during installation is minimized.

8. Information from continuing qualification and natural aging research programs conducted domestically and abroad should be incorporated into aging evaluations and analyses.

9. Naturally aged cable specimens removed from service should be analyzed and characterized. Data obtained from these analyses should be retained in an industry-wide, readily accessible database.

10. Environmentally-qualified cable using certain bonded jacket/insulation systems should be evaluated if the specific combination of jacket and insulation materials and the bonding process were not qualified as a system.

2. INTRODUCTION

2.1 Background

The Department of Energy (DOE)-sponsored Commercial Light Water Reactor (CLWR) Program [formerly known as the Plant Lifetime Improvement (PLIM) Program], in cooperation with EPRI's Life Cycle Management (LCM) Program, is establishing and demonstrating a predictable license renewal process for existing light water reactors (LWRs) in the United States. An important element of these programs was the development of License Renewal Industry Reports (IRs) from 1990 to 1993, which were coordinated by the Nuclear Management and Resource Council (NUMARC; now the Nuclear Energy Institute, NEI). The IRs cover critical classes of long-lived passive components such as reactor pressure vessels, reactor coolant pressure boundary piping, containment structures, and low-voltage, environmentally-qualified cables [2.1]. The DOE-sponsored Aging Management Guidelines (AMGs), supporting continued demonstration of CLWR and LCM concepts, describe and evaluate aging management approaches for groups of equipment not evaluated in the IRs, or expand upon the IRs. To date, eight AMGs have been published, all but two on active components. Topics are:

1. Battery Chargers, Inverters and Uninterruptible Power Supplies [2.2]
2. Batteries, Stationary [2.3]
3. Heat Exchangers [2.4]
4. Motor Control Centers [2.5]
5. Pumps [2.6]
6. Switchgear, Electrical [2.7]
7. Tanks and Pools [2.8]
8. Transformers, Power and Distribution [2.9]

In addition, several AMGs for long-lived passive systems, structures and components are being prepared at this time:

1. Electrical Cable and Terminations (this AMG)
2. Containment Penetrations
3. Non-Reactor Coolant Pressure Boundary (Non-RCPB) Piping and Tubing

Most AMGs evaluate components determined to be within the scope of both the License Renewal Rule (LRR), 10CFR54.21 [2.10] and [2.11], and the Maintenance Rule (MR), 10CFR50.65 [2.12]. However, this AMG evaluates all low- and medium-voltage cables and terminations, even those not covered by these rules, because the additional scope was small and the techniques are useful for the life cycle management of all cables.

Continued operation of nuclear power plants for periods that extend beyond the original 40-year license period may be desirable for many U.S. nuclear plant operators. To obtain a renewed license and to operate a plant during a license renewal period, utilities must show that the detrimental effects of aging of components important to license renewal have been managed so that these components will not degrade to the point where they are incapable of supporting their intended function(s). Therefore, operators of nuclear power plants must manage the

detrimental effects of aging of components to ensure that intended function(s) will be performed when required. Electrical cables and terminations are specifically identified in 10CFR54 [2.11] as requiring an aging management review.

From a long-term perspective, it may be desirable to perform aging management activities such as preventive maintenance and refurbishment during the current license period even though some of these activities may not be necessary to satisfy regulatory requirements. These activities may be necessary to ensure that there is no loss of intended function(s), no unacceptable reduction in safety margins, and that higher rates of challenge to plant safety systems do not occur during the license renewal period. Beneficial preventive maintenance and refurbishment activities will typically lead to increased reliability, minimal operating and maintenance costs, and a higher capacity factor during the current license period.

2.2 Purpose

This AMG was prepared for use by plant maintenance and system engineering personnel responsible for design, maintenance, repair/replacement, and aging management evaluations. It provides information and guidance covering each aspect of an aging management program. While this AMG is intended for use by nuclear power plant operators, many of the same methods can be used to plan effective aging management of similar equipment in other facilities. An effective aging management program will ensure that each cable and termination will continue to perform its intended function(s) or will not prevent the performance of intended function(s).

This document contains analyses of potential degradation modes, including the effects of aging, presents guidelines for developing effective aging management programs, and presents a suggested methodology for performing an aging management review in accordance with 10CFR54. Note that methodologies for extending the qualified life of environmentally-qualified (EQ) components are not explicitly considered; additional information on this topic can be found in EPRI TR-100516 [2.14], EPRI TR-104063 [2.13], and other industry documents.

This AMG also provides additional value to nuclear plant operators as follows:

1. It is a well-researched technical document that can be used by maintenance and system engineering personnel to identify, characterize, and manage age-related degradation of electrical cables and terminations. It can also be used as a reference document for plants developing a license renewal application and/or plans for complying with the Maintenance Rule.

2. The information presented is based on an extensive literature search. Therefore, nuclear plant personnel can use this AMG as a substantive reference for relevant information about electrical cables and terminations. Some of the references used include:

   - License Renewal Industry Reports
   - NRC Bulletins, Information Notices, Circulars, Generic Letters, and Reports
   - Code of Federal Regulations (CFR) and the Federal Register

- Vendor Manuals
- Industry Codes and Standards [(e.g., Association of Edison Illuminating Companies (AEIC), American National Standards Institute (ANSI), American Society for Testing and Materials (ASTM), Insulated Cable Engineer's Association (ICEA), Institute of Electrical and Electronics Engineers (IEEE), National Electrical Manufacturer's Association (NEMA)]
- Miscellaneous references and technical papers

3. It consolidates historical maintenance and industry operating information into one source. The plant maintenance and system engineers will find this useful for the identification of age-related degradation (including root causes) and the verification of appropriate corrective action. Issues discussed include:

    - Operating and maintenance history from the Institute for Nuclear Power Operations (INPO) Nuclear Plant Reliability Data System (NPRDS) and NRC Licensee Event Report (LER) databases
    - Additional operating and maintenance history input from host utilities
    - Results of relevant plant surveys
    - Equipment design differences relevant to aging considerations
    - Service environments

4. Aging phenomena are described in detail. This will be useful for maintenance interval and reliability evaluations of electrical cables and terminations. The following topics are discussed:

    - Stressors acting on electrical cables and terminations
    - Identification of aging mechanisms
    - Significance of aging stressors using "if/then" criteria
    - Age-related degradation and potential failure modes
    - Maintenance-induced degradation or failures
    - Effects of aging

5. It can be an effective tool for aging management and personnel training because it:

    - Identifies the need for aging management and can be used as input for Maintenance Rule performance measures and corrective action requirements
    - Discusses both conventional and nonconventional maintenance techniques, and considers how these practices can be used to manage equipment aging effectively
    - Characterizes the initiation and progression of equipment aging for use in training personnel responsible for maintenance and inspection activities
    - Identifies concepts, principles, and methods that may be used to evaluate electrical cables and terminations not within the scope of this AMG.

2.3 Contents

This AMG evaluates low- and medium-voltage electrical cables and their associated terminations. Cable trays, penetrations[1], conduits, conduit seals, and other ancillary equipment are not addressed in detail. Potential interactions between these components and electrical cables and terminations and potential aging effects are discussed.

Section 3 lists the electrical cables and terminations evaluated and component boundaries. Section 3 also includes a detailed study of the operating history of the electrical cables and terminations evaluated from LER and NPRDS data, and from other sources.

Section 4 discusses stressors, aging mechanisms, age-related degradation, failure modes, and, most important, the effects of aging on electrical cables and terminations. Stressors produce aging mechanisms that can cause component degradation (aging effects). An aging mechanism is significant when, if it is allowed to continue without detection or mitigation measures, it will cause the component to lose its ability to perform its intended function(s). Significant and nonsignificant aging mechanisms/effects relevant to electrical cables and terminations are identified and evaluated. Operational demands, environmental conditions, failure data, and industry operations and maintenance history are considered, and the significance of the aging mechanisms and effects determined. Any time-limited aging analyses relevant to electrical cables and terminations are also identified and described. The entire set of aging mechanisms evaluated in this AMG is presented in Section 4.

Section 5 discusses aging management techniques that can be used to mitigate the aging mechanisms and effects determined to be significant (Section 4). Maintenance, inspection, qualification, testing, and surveillance techniques and programs are described. The effectiveness of these techniques or programs in managing significant aging mechanisms is described wherever historical operating data are adequate to support a conclusion. Variations in plant aging management programs or techniques are discussed. "If/then" criteria are presented whenever possible to assist plant personnel in identifying and managing component aging.

Section 6 discusses management options to address the action items identified in Section 5. Appendix A provides a list of definitions for aging terminology used in this AMG. Appendix B provides a description of the components evaluated, including manufacturers' design differences. Appendix C includes a discussion of the design requirements that apply to electrical cables and terminations, including applicable codes, standards, and regulations. Appendix D provides a list of acronyms and abbreviations. Appendix E is a list of trade names for cables and terminations. Appendix F contains a discussion of NPRDS data. Ohmic heating of electrical cable is discussed in Appendix G. Appendix H discusses regulatory requirements related to synergistic effects. Appendix I discusses the EPRI cable aging research program.

[1] Penetrations, including the cable contained therein, will be covered in the Containment Penetrations AMG.

2.4 Generic License Renewal Requirements

The License Renewal Rule [2.11], specifically 10CFR54.21, describes the current requirements for the content of technical information in a license renewal application.[2] Section 54.21 states that an application for license renewal must contain the following:

1. An Integrated Plant Assessment (IPA),
2. A list of current licensing basis (CLB) changes during NRC application review,
3. An evaluation of time-limited aging analyses (TLAA),
4. A Final Safety Analysis Report (FSAR) supplement.

An IPA must:

1. For those systems, structures, and components within the scope, as delineated in Section 54.4, identify and list those structures and components subject to aging management review,

2. Describe and justify the methods used in item 1 (scope determination) of the IPA, and

3. For each structure and component identified in item 1 of the IPA, demonstrate that the effects of aging will be managed so that the intended function(s) will be maintained for the period of extended operation.

An aging management review is intended to demonstrate that plant "programs and procedures will provide reasonable assurance that the functionality of systems, structures and components requiring review will be maintained during the period of extended operation." [2.11] The License Renewal Rule (LRR) focuses on the effects of aging rather than on a detailed review of aging mechanisms. The LRR states there must be a "reasonable assurance" that the intended function(s) of systems, structures, and components (SSCs) will be maintained.

Section 54.21 also requires an evaluation by the licensee for some SSCs which are subject to a TLAA. The TLAAs of concern are those that:

1. Involve the effects of aging,
2. Involve time-limited assumptions defined by the current operating period (40 years),
3. Involve SSCs within the scope of license renewal,
4. Involve bases or conclusions regarding the capability of the SSC to perform its intended function,
5. Were determined to be relevant to a safety determination by the licensee, and
6. Are either contained or incorporated by reference in the current licensing basis.

The requirements of analyses falling under 10CFR50.49 (environmental qualification) are particularly relevant to electrical cable and terminations. Accordingly, an applicant for license renewal will be required to (1) justify that the existing analyses are valid for the period of

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[2] NEI 95-10, "Industry Guideline for Implementing the License Renewal Rule, 10 CFR Part 54," March 1996, is another source of information regarding implementation of the proposed License Renewal Rule.

extended operation, (2) extend the period of analysis to cover the proposed license renewal period, or (3) otherwise demonstrate that the effects of aging will be adequately managed during the extended operating period. Extension of qualified life is not explicitly covered in this document; additional information on this topic can be found in various industry publications such as EPRI TR-100516 [2.14].

This AMG evaluates all potentially significant aging mechanisms and aging management practices that can be used to demonstrate that the effects of aging will be managed so that the intended function(s) will be maintained, even though the LRR does not require this level of detail. It also discusses the link between aging mechanisms and the effects of aging, and supports evaluation of a TLAA under 10CFR50.49.

Exemptions and requests for relief (pursuant to 10CFR50.12 and 10CFR50.55a, respectively) were not considered here because these issues are plant-specific in nature and, therefore, must be considered on a plant-by-plant basis.

2.5 Method Used to Define the Scope of Components to be Evaluated Under the License Renewal Rule and the Maintenance Rule

Although this AMG covers all low- and medium-voltage cables and terminations, plant licensing engineers may wish to limit the scope of their investigations to electrical cables and terminations covered under the LRR and MR. The definitions of SSCs within the scope of the LRR and MR must be evaluated to determine which cable systems are included in the scope. Table 2-1 describes the current definitions. Note that the scope of electrical cables and terminations covered under the Maintenance Rule, 10CFR50.65 [2.12], is almost the same as that covered by the License Renewal Rule, 10CFR54.21 [2.11].

2.6 Method Used to Define the Aging Mechanisms Assessed in This Study

As indicated above, the LRR does not require explicit evaluation of aging mechanisms, but does require the reasonable assurance of preserving intended function(s) that may be degraded by aging. Because the users of this AMG consist of systems engineers and plant maintenance personnel, detailed descriptions of stressors, aging mechanisms, and failure modes, as well as the effects of aging, are included.

To define aging mechanisms assessed in this study, a two-part evaluation was performed. First, the stressors (e.g., mechanical, chemical, electrical, and environmental) on equipment operation were determined. Then, aging mechanisms associated with those stressors were defined. Finally, age-related degradation mechanisms, failure modes, and effects caused by aging were described. This evaluation is contained in Section 4.

Second, industry-wide operating experience (particularly that reported in NRC LERs; Information Notices, Bulletins, and Circulars; and INPO NPRDS data) was examined. A review of the NRC Information Notices, Bulletins, and Circulars was conducted to identify age-related failures. Events described in the NPRDS data and LERs were then analyzed for age-related degradation and to determine the numbers of particular types of failures. The aging mechanisms

Table 2-1 License Renewal Rule and Maintenance Rule Scope Screening Requirements

License Renewal Rule (LRR)	Maintenance Rule (MR)
Safety-related SSCs	
1. Safety-related SSCs, which are those relied upon to remain functional during and following design basis events to ensure:	1. Same as for LRR.
i. The integrity of the reactor coolant pressure boundary,	a. Same as for LRR.
ii. The capability to shut down the reactor and maintain it in a safe shutdown condition, or	b. Same as for LRR.
iii. The capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposure comparable to the 10CFR100 guidelines.	c. Same as for LRR.
Non-safety-related SSCs	
2. All non-safety-related SSCs whose failure could directly prevent satisfactory accomplishment of any of the intended function(s) identified in paragraphs (1) (i), (ii), or (iii) of this definition.	d. Whose failure could prevent safety-related structures, systems, and components from fulfilling their safety-related function,
	e. That are relied upon to mitigate accidents or transients or are used in plant emergency operating procedures (EOPs),
	f. Whose failure could cause a reactor scram or actuation of a safety-related system.
Required by Regulation	
3. All SSCs relied on in safety analyses or plant evaluations to demonstrate compliance with the Commission's regulations for:	
- Fire Protection (10CFR50.48)	
- Environmental Qualification (10CFR50.49)	
- Pressurized Thermal Shock (10CFR50.61)	
- Anticipated Transients without Scram (10CFR50.62)	
- Station Blackout (10CFR50.63)	

associated with these failures were then determined. The review of industry-wide operating experience is contained in Section 3.7.

This multi-source analysis (i.e., using data from NPRDS and NRC documentation) provides a comprehensive characterization of equipment aging by using actual plant and vendor data to substantiate and refine those aging mechanisms postulated to occur due to stressors.

After a list of all possible aging mechanisms was developed (see Section 4), the significance of each aging mechanism was determined. Those aging mechanisms that would result in a failure having an impact on equipment operation or functionality were designated as significant. Of the significant aging mechanisms identified, those which were observed in the plant operating history or were otherwise likely to occur were considered to be "significant and observed" aging mechanisms. Significant aging mechanisms are discussed in Section 4.2.1; significant and observed aging mechanisms are discussed in Section 4.2.2. Aging mechanisms designated nonsignificant are briefly discussed in Section 4.2.3.

Maintenance, inspection, testing, and surveillance techniques or programs used to manage aging of electrical cables and terminations are discussed in Section 5.2. A discussion of commonly used activities and techniques is provided in Section 5.3. A discussion of current programs that manage aging effects is included in Section 5.4.1. Potentially significant component/aging mechanism combinations not addressed by current programs are discussed in Section 5.4.2.

2.7 References

Note: For conciseness, the references in this report omit the location of major contributors to the literature. They are the Electric Power Research Institute in Palo Alto, CA, the Institute of Electrical and Electronics Engineers in New York, NY, the Nuclear Regulatory Commission in Washington, D.C., and Sandia National Laboratories in Albuquerque, NM.

2.1 EPRI TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report," prepared by Sandia National Laboratories and Strategic Technologies and Resources, Inc., Revision 1, July 1994.

2.2 SAND93-7046, "Aging Management Guideline for Commercial Nuclear Power Plants - Battery Chargers, Inverters and Uninterruptible Power Supplies," Sandia National Laboratories, February 1994.

2.3 SAND93-7071, "Aging Management Guideline for Commercial Nuclear Power Plants - Stationary Batteries," Sandia National Laboratories, March 1994.

2.4 SAND93-7070, "Aging Management Guideline for Commercial Nuclear Power Plants - Heat Exchangers," Sandia National Laboratories, June 1994.

2.5 SAND93-7069, "Aging Management Guideline for Commercial Nuclear Power Plants - Motor Control Centers," Sandia National Laboratories, February 1994.

2.6 SAND93-7045, "Aging Management Guideline for Commercial Nuclear Power Plants - Pumps," Sandia National Laboratories, March 1994.

2.7 SAND93-7027, "Aging Management Guideline for Commercial Nuclear Power Plants - Switchgear, Electrical," Sandia National Laboratories, July 1993.

2.8 SAND96-0343, "Aging Management Guideline for Commercial Nuclear Power Plants - Tanks and Pools," Sandia National Laboratories, March 1996.

2.9 SAND93-7068, "Aging Management Guideline for Commercial Nuclear Power Plants - Transformers, Power and Distribution," Sandia National Laboratories, May 1994.

2.10 Title 10, U.S. Code of Federal Regulations, Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," published in the Federal Register, Vol. 56, December 13, 1991 (page 64943).

2.11 Title 10, U.S. Code of Federal Regulations, Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," published in the Federal Register, Vol. 60, May 8, 1995 (page 22461).

2.12 Title 10, U.S. Code of Federal Regulations, Part 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," published in the Federal Register, Vol. 56, July 10, 1991 (page 31321) and Vol. 58, June 23, 1993 (page 33996).

2.13 EPRI TR-104063, "Evaluation of Environment Qualification Options and Costs for Electrical Equipment for a License Renewal Period for CCNPP," (Calvert Cliffs Nuclear Power Plant), Electric Power Research Institute, October 1994.

2.14 EPRI TR-100516, "Equipment Qualification Reference Manual," Electric Power Research Institute (EPRI), 1992.

3. EQUIPMENT EVALUATED

3.1 General

Electrical cable systems used in nuclear power plants consist of cables, terminations, and other associated components (such as cable trays, penetrations, and conduits) used to power, control, and monitor various types of electrical apparatus and instrumentation. The equipment covered by this guideline includes site low- and medium-voltage cables and their associated terminations. Cable trays, penetrations, conduits, and other ancillary equipment are not directly covered by this guideline; however, potential aging effects or interactions of these components with cables and terminations are discussed.

Specific nuclear plant cable system components[1] covered in this AMG include:

- Cables
- Panel and hookup wires
- Terminal blocks
- Compression and fusion fittings
- Splices
- Multi-pin, single-pin, plug-in, coaxial, and triaxial connectors.

Electrical cables and terminations (and their components) manufactured by numerous companies are installed in U.S. commercial nuclear plants. The cable and termination manufacturers identified during the preparation of this report are listed in Table 3-1. Other manufacturers' equipment may be installed in nuclear plants; however, the amount of such equipment is considered to be small. Aging mechanisms and aging management techniques described here may be applicable to an unlisted manufacturer's equipment because of similarities in cable system component design, construction, and materials.

Substantial consolidation has occurred within the cable industry since the construction of the earliest nuclear plants; consequently, many of the manufacturers listed here may no longer exist or produce cable. In addition, many product lines may have been discontinued or substantially modified; varying configurations of the same general product are common. No attempt was made to analyze specific formulations or product lines; rather, general material categories and component types were examined in this study.

When considering the aging management of cable systems installed at commercial nuclear power plants, several major subsets or categories of circuits can be defined based on factors such as the circuit's function, importance to plant safety or shutdown, or installed location(s). The categories of cables and terminations that must be evaluated to satisfy the requirements of 10CFR54 are as follows:

[1] Terminal blocks, lugs, splices, seals, and connectors are all included within the designation "termination" for this AMG.

Table 3-1 Cable and Termination Manufacturers

Cables and Wire:

- American Insulated Wire (AIW)
- Anaconda
- Belden
- Bendix
- Boston Insulated Wire & Cable (BIW)
- Brand Rex
- Cerro
- Champlain
- Coleman
- Collyer
- Conax
- Continental (Cablec)
- Cyprus
- Delco-Link
- Eaton
- Ericsson
- Essex
- Galite
- General Cable
- General Electric (GE)
- Harbour Industries
- Hatfield
- ITT Surprenant
- Kerite
- Lewis Engineering
- National
- Okonite
- Omega
- Raychem
- Rockbestos
- Rome
- Samuel Moore
- Simplex

Terminations:

- Alpha
- AMP
- Amphenol
- Bendix
- Bishop
- Buchanan
- Conax
- EGS (Grayboot)
- ERD
- General Electric (GE)
- Kerite
- Kulka
- Litton-VEAM
- Marathon
- Moore
- Namco
- Okonite
- Patel Engineers
- Raychem
- Rosemount
- Scotch (3M)
- Sigmaform
- States
- Thomas and Betts
- Weidmuller
- Westinghouse

1. Safety-related cables and terminations

   Some cables may be used in circuits designated as "safety-related." Safety-related equipment is defined in 10CFR50.49 as those items designed to remain functional during and following design basis events to ensure: (1) the integrity of the reactor coolant boundary, or (2) the capability to shut down the reactor and maintain it in a safe shutdown condition, or (3) the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures comparable to regulatory guidelines [per 10CFR50.49 Section (b)(1)]. Safety-related equipment may also require environmental qualification, depending on its location and function.

2. Nonsafety-related cables and terminations, if a failure of the component could prevent satisfactory accomplishment of a safety-related function

   A plant-specific evaluation is required to define this population of cables and terminations.

3. Nonsafety-related cables and terminations required to perform a function in safety analyses or plant evaluations that demonstrate compliance with NRC regulations for:

   - Fire protection (10CFR50.48)

   - Environmental qualification (EQ) (10CFR50.49)

     A significant portion of plant circuits may require environmental qualification in accordance with 10CFR50.49. EQ equipment must be able to perform its required safety function when subjected to harsh environmental conditions resulting from a postulated design basis event (DBE). The cable may be installed in either safety-related, nonsafety-related (that could affect plant safety), and/or post-accident monitoring circuits.

   - Pressurized thermal shock (10CFR50.61)

   - Anticipated transients without scram (ATWS) (10CFR50.62)

   - Station blackout (10CFR50.63).

Plant management may opt to include additional cables and terminations in the scope of an aging management program. Discretionary categories include:

- Cables and terminations important to continued plant operations

  Some circuits may be needed to support continuous, reliable power generation. For example, circuits associated with main turbine systems are neither EQ nor safety-related in most (if not all) plants. However, a failure in the main turbine system may result in a temporary or sustained loss of plant output. From an economic perspective, such cables and terminations are of paramount importance.

- All other cable

  Numerous cables and terminations are not included in the categories listed above. These items are included in circuits and systems whose failure would have little or no appreciable effect on plant safety, operation, or continuity of power. Plant lighting and certain communications systems are common examples of these types of circuits and systems.

3.1.1 Voltage Category

Cable systems contained within the classification of cable important to license renewal may also be categorized by the following voltage ranges:

- Low-voltage (≤1000 Vac, ≤250 Vdc)[2]
- Medium-voltage (2 kVac through 15 kVac)
- High-voltage (>15 kVac)[3]

It should be noted that these voltage ranges reflect cable voltage ratings and not normal operating voltages. The rated voltage of a circuit component represents the maximum voltage at which that component can be continuously operated. Generally speaking, the voltage rating of a nuclear power plant component is much greater than the operating voltage. For example:

Voltage Rating	Normal Operating Voltage
300-V	≤48 Vdc
600-V	≤120 Vac, ≤125Vdc
600-V and 1000-V	480 to 600 Vac
5-kV and 8-kV	4160 Vac
15-kV	13.8 kVac

Circuits falling within a voltage range can be further classified by their function as power, control, instrumentation, specialty, lighting, telephone, or security cable; see Section 3.3 for additional information on these classifications.

[2] As in the Low-Voltage, Environmentally-Qualified Cable Industry Report, the upper range of low-voltage is defined as 1000 Vac. Typically, cables are not rated between 1000 and 2000 Vac; however, the results for low-voltage cable are applicable up to 2000 Vac.

[3] High-voltage systems were not included in the scope of this document because: (1) they generally constitute an extremely small fraction of the total amount of cable at a plant, and (2) they are often highly specialized in construction (e.g., oil filled) so they have little in common with the more prevalent low- and medium-voltage systems.

Specialty applications (such as coaxial- or triaxial-type cables used in nuclear instruments) may use varying voltages, depending on their function. These systems typically operate below 2 kV and will therefore be discussed with the low-voltage systems.

Transient phenomena (such as electrical switching transients or lightning-induced surges) or circuit component testing may produce voltages substantially higher than normal operating voltage for short periods. However, these short duration events are not considered representative of the voltage stress normally applied to plant circuits.

Common nuclear plant operating voltages are 120 Vac, 480 Vac, 4160 Vac, and 13.8 kVac; and 24 Vdc, 48 Vdc, 125 Vdc, and 250 Vdc. These common voltage values will be used in this guideline; however, it should be recognized that other operating voltages (such as 525 Vac) may be used at some plants.

3.1.2 Environmental Qualification (EQ)

Long-term aging has been evaluated for those cables and terminations that have been environmentally qualified (EQ). This special category of equipment has been analyzed for material composition, ambient environmental conditions, and operating parameters so that a "qualified life" could be established. [Note: The term "qualified life" is defined in IEEE Standard 323-1974 [3.1] as "the period of time for which satisfactory performance can be demonstrated for a specific set of conditions." The definition was changed in the 1983 revision of IEEE Standard 323 to be "the period of time, prior to the start of a design basis event, for which equipment was demonstrated to meet the design requirement for the specified service conditions." The 1983 revision is not formally endorsed by the NRC, and the change in definition occurred after most qualifications were established for operating plants. In practical terms, there is little significance to this distinction.]

For most installed EQ cables and terminations, the qualified life is equal to or greater than the 40-year design life of the plant. There is no regulatory requirement for 40 years, or any other specific duration. The qualified life varied depending on whether the equipment was expected to meet the requirements of the DOR Guidelines [3.2], NUREG-0588 [3.3], or 10CFR50.49 [3.4]. The specific requirements of these regulations regarding EQ and aging are described in detail in Appendix C of this AMG.

Because the overall requirements for EQ were different in the three regulations, the specifics regarding aging and aging management also varied. The discussions about them (and several related industry standards and Regulatory Guides) in Appendix C can be summarized as follows:

- For cables qualified to the DOR Guidelines [3.2], the Owner must demonstrate a qualified life if the plant was already constructed and operating and cable materials susceptible to significant degradation due to thermal and radiation aging were used in the plant's construction. Maintenance or replacement schedules were to include consideration of the specific aging characteristics of the material(s), and continuing programs were to be established to review surveillance and maintenance records to

ensure that equipment exhibiting age-related degradation was identified and replaced as necessary.

- Cables qualified to the requirements of NUREG-0588, Category II only, had to address aging only to the extent that equipment that is composed, in part, of material susceptible to aging effects should be identified and a schedule for periodically replacing the equipment and/or materials should be established.

- The qualification aging requirements for NUREG-0588, Category I and 10CFR50.49 plants were much more stringent.

Note that with respect to all of the qualification regulations described above, preaging prior to accident testing, material analysis with respect to thermal/radiation aging, qualified life determinations, and ongoing programs which review maintenance and surveillance records all constitute aging management activities that may be considered as part of the 10CFR54 aging management review.

3.2 Results of Methodology Used to Select Components Subject to License Renewal Review

For each plant entering license renewal, a review must be performed to identify electrical cables and terminations that are subject to an aging management review. Per paragraph 1 of Section 54.4 (scope of equipment subject to the license renewal rule) of 10CFR54 [3.5], all cable systems deemed safety-related are included. Paragraph 2 of the definition brings cable systems (such as those nonsafety-related systems that may prevent satisfactory accomplishment of the functions described in paragraph 1) into the scope. Paragraph 3, which addresses environmentally qualified equipment, pressurized thermal shock, and systems necessary to meet ATWS and station blackout requirements, adds additional cable systems to the list. Some circuits in the "important to continued plant operations" and the "all other cable" categories, although not subject to the license renewal rule by definition, may also be included in plant aging management programs if desired by each plant. Accordingly, all of the aforementioned categories of cable are addressed by this AMG.

3.3 Description of Components Evaluated

In addition to the sections that follow, see Appendix B of this guideline.

3.3.1 Electrical Cable and Wire

Nuclear generating stations may have thousands of miles and several hundred different types and sizes of electrical cable/wire. The majority of cables used in nuclear stations can be grouped into the following categories based on their application and design [3.6], [3.7]:

- Low-voltage power cable
- Medium-voltage power cable
- Control cable
- Panel and hookup wire
- Instrumentation cable

- Specialty cable
- Security cable
- Telephone cable
- Lighting cable
- Grounding cable

Low-Voltage Power Cable is used to supply power to low-voltage auxiliary devices such as motors (and motor control centers), heaters, and small distribution or lighting transformers. Single and multiple conductor configurations are used, usually unshielded.

Medium-Voltage Power Cable is used to supply power to larger loads and distribution centers such as reactor recirculation or service water pumps, load centers, transformers, or medium-voltage switchgear. Single and multiple conductor configurations are used, typically shielded at higher voltage ratings (i.e., 8 kV and above).

Control Cable is a type of low-voltage, low-ampacity cable used in control circuits for auxiliary components such as control switches, valve operators, control and protective relays, and contactors. Usually a multiple conductor configuration is used, with shielding for applications in proximity to high-voltage systems.

Panel and Hookup Wire is a type of low-voltage, small-gauge [synthetic thermosetting insulation for switchboard (SIS) or similar] single conductor wire commonly used inside electrical panels, motor control centers (MCCs), switchgear, motor-operated valves (MOVs), solenoid-operated valves (SOVs), or other enclosures.

Instrumentation Cable (Including Thermocouple Extension Wire) is a type of low-ampacity, low-voltage (typically less than 1000 V, with most rated at 300 V) cable used for digital or analog data transmission. Resistance temperature detectors (RTDs), pressure transducer circuits, and thermocouple extension leads usually use a twisted shielded pair configuration. Coaxial and triaxial configurations (shielded) are often used for radiation detection and neutron monitoring, or where other special requirements exist.

Specialty Cable is designed and fabricated for a specific application (e.g., combination instrumentation/power/control cable, mineral-insulated (MI) cable for high temperature applications, special fire-retardant cable).

Telephone Cable is a low-voltage (300 V), multiple-pair, small-gauge (20 to 24 AWG) cable used for connection of telephone or communications circuits. It is typically shielded and jacketed.

Security Cable is a low-voltage multi-conductor cable that is specially armored or encased to prevent cut-through.

Lighting Cable is used to supply low-voltage (120 to 277 V) power to plant lighting systems. A typical configuration includes multiple conductors which may be encased in a metallic sheath.

Grounding Cable is used to connect electrical equipment, including cable raceways and conduits, to the station ground. Size and configuration will vary depending on the application. Grounding cable is generally large gauge and may or may not be insulated.

Low-voltage power, control, and instrumentation cable collectively constitute the bulk of cable installed at a nuclear plant. Medium-voltage power cable is the next most populous type; however, it generally accounts for only a small percentage of the total number of circuits [3.8], [3.9]. The amounts of the remaining categories of cable are each generally very small in relation to the low- and medium-voltage types described above. Specialty cable such as that used for neutron monitoring systems or control rod drive position circuits may be relatively numerous; these are, for the most part, located within primary containment (although segments may be located outside of containment). Panel or SIS wire may exist in large quantities within MCCs, control boards, and switchgear. It is typically of single conductor configuration and unshielded, and used in low-voltage/low ampacity control applications.

Table 3-2 provides an illustration of the relative numbers of various types of circuits found at one nuclear plant (two units).[4]

Table 3-2 Relative Distribution of Circuit Types for One Nuclear Plant (2 Units)

Circuit Type	Approximate Number of Circuits
AC Power	6,580
DC Power	530
Control	31,500
Instrumentation	10,180
Communication	2,560
TOTAL[4]	51,350

Typical low-voltage power applications include valve operator and small pump and fan motors. Typical low-voltage instrumentation applications include thermocouples, RTDs, pressure transmitters, and nuclear instruments. The lengths of these circuits range from tens to thousands of feet, depending on the location of the loads with respect to the power supply. Most cables, however, are less than a thousand feet in total length. Medium-voltage cables are used in nuclear plants in the following applications:

[4] The approximate distribution of circuit types was obtained from a proprietary plant cable and raceway database. Note that not all circuits are necessarily included in this database; however, it is considered to be representative of the cable installed at this site.

- Auxiliary transformer primary and secondary feeders
- Connections between and feeders to medium-voltage buses
- Load center primary feeders
- Medium-voltage motor feeders
- Emergency diesel generator (EDG) power supplies

Safety-related circuits are often lightly loaded or de-energized, as the load supplied by these circuits are only in operation during abnormal plant conditions or surveillance testing. Conversely, nonsafety-related circuits (such as those serving the reactor coolant/recirculation pump or service water pump motors) may be continuously energized and loaded. Note that the safety significance of a circuit is not necessarily related to its importance to plant operation; a nonsafety-related circuit that serves a plant load important to continuous operation would fall into the category of "important to plant operation."

3.3.2 Terminations

Cable terminations may be grouped as follows:

- Compression connectors
- Fusion connectors
- Plug-in connectors
- Splice insulation systems (heat-shrink or tape)
- Terminal blocks.

Compression Connectors are physically crimped or mechanically swaged to conductors.

Fusion Connectors are welded, brazed, or soldered to conductors.

Plug-in Connectors have one or more electrical contacts that plug or screw into a mating receptacle. The junction between the conductor and connector is typically fused; however, any of the methods described in this section can be used. Plug-in connectors are usually used in instrumentation or data transmission applications, some motor-operated valves, control circuits, and limit switches.

Splice Insulation Systems (heat-shrink or tape) are used to environmentally seal cable or splice terminations or junctions. They are generally applied over a compression or fusion connection.

Terminal Blocks consist of an insulating base with fixed points for attaching wiring or terminal (ring) lugs. Terminal blocks are usually located within a device or electrical panel.

Compression fittings (such as ring lugs or barrels) are probably the most common type of termination; these devices are present in one form or another in many types of circuits and electrical components in the plant. Fusion connectors are mostly used on medium-voltage or high ampacity circuits where permanence of connection is desired. They are also commonly used with grounding cables. Splices are most often used to link specific segments of a field

cable or to repair a failed section of cable. Connectors are used in applications where ease of separation of the termination is desired, for mating to specific types of equipment, or where multiple simultaneous electrical connections must be made (such as in multi-pin connectors used on instrumentation circuits). Connectors may also be used to seal electrical housings of associated equipment and to complete the seal of the cable jacketing system. Terminal blocks are used as electrical connection points within larger electrical components (such as MCCs, control boards, and motors). Note also that some of the terminations listed above may be used within other terminations [e.g., soldered (fusion) pins used within plug-in type connectors].

A multitude of different types of lugs, splices, and connectors may be in use in the typical nuclear plant. The design and sophistication of a given termination is related to its application, voltage and current rating, and expected environments. For dry environment, low-voltage applications, ring lugs and terminal blocks of simple construction may be used. For wet environments, heat shrinkable insulation or other moisture-retardant systems may be employed to provide protection from short circuits or low insulation resistance. In circuits potentially exposed to steam or water spray environments, splices are often used in place of traditional termination systems to provide protection to the conductors from accident environment conditions. Splices may be used to provide protection from shorting and low insulation-resistance conditions in such environments. For medium-voltage circuits, much more sophisticated terminations and splices must be made to preclude degradation from voltage stress and the formation of tracking paths in the vicinity of the termination due to the higher voltages employed.

3.4 Component Boundaries

Most cable, wire, and termination components, subject to the clarifications and limitations identified below, are included in the scope of this AMG. Cable raceways (including trays, conduits, and duct banks), support or restraint systems, or other ancillary cable system components are not within scope. The following clarifications apply:

1. Bulk wire installed in MCCs or control boards is covered by this AMG.

2. Cables and connectors associated with neutron monitors, radiation detectors, and position indicators for control rod drives are within scope.

Limitations are as follows:

1. Panel or local wire for major equipment is not included in the scope. Wiring internal to (or part of) individual devices, modules, or subcomponents is not within scope because it may have special applications or conditions within the devices.

2. Containment electrical penetration leads are not within scope.

3. Cables and connectors that are internal to or originate in discrete electrical devices (such as ribbon cable used in amplifier drawers, plotters, etc., and circuit card connectors) are not within scope.

4. Motor leads (commonly called pigtails) are not within scope; however, splices or terminations to those leads are within scope.

Figure 3-1 is a schematic representation of medium-voltage cable systems which identifies the boundary between this AMG's included and excluded scope. A similar figure is not needed for low-voltage circuits because all are included in the scope of this AMG, except as noted above.

3.5 Listing of Components Evaluated

Each electrical cable or connection can consist of many different parts or subcomponents.

3.5.1 Cable (Including Wire)

Four (4) cable applications[5] and the associated subcomponents have been evaluated in this guideline:

1. Medium-Voltage Power

   - Conductor
   - Semiconducting or nonconducting shield
   - Electrical insulation or dielectric[6]
   - Filler material
   - Tape wrap
   - Shielding (including drain wire and semiconducting layers)
   - Outer jacketing
   - Armor or sheath

2. Low-Voltage Power or Control

   - Conductor
   - Electrical insulation or dielectric
   - Conductor jacketing
   - Filler material
   - Tape wrap
   - Shielding (including drain wire)
   - Outer jacketing

[5] Note that lighting, security, specialty, communications, and grounding cable use components similar or identical to these four (4) applications.

[6] The terms "insulation" and "dielectric" are often used interchangeably. Some manufacturers routinely use the latter term when referring to cable components that are used for functions other than strict electrical isolation (e.g., signal transmission in a coaxial/triaxial cable).

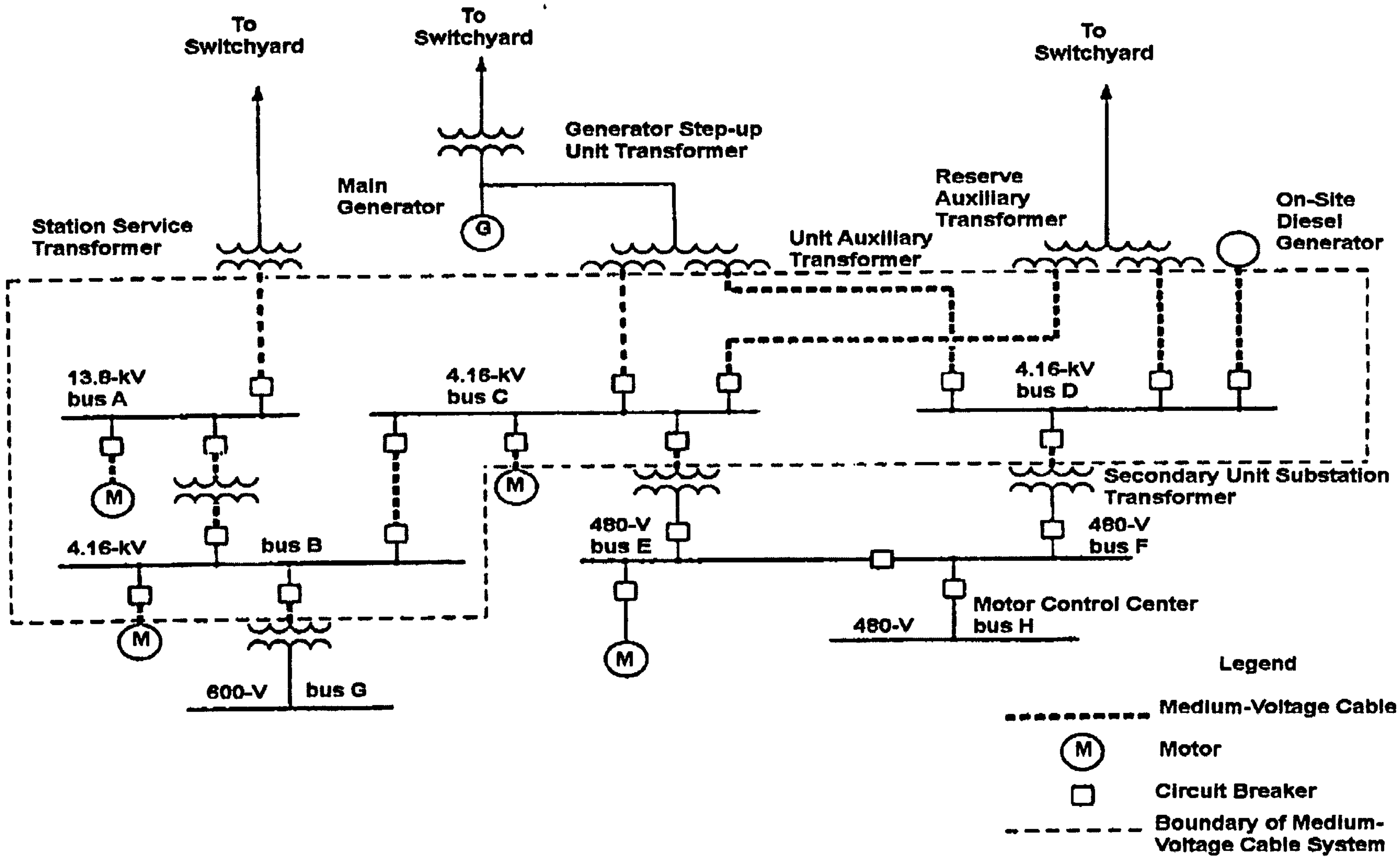

Figure 3-1 Component Boundaries of Medium-Voltage Systems

3. Low-Voltage Instrumentation (Coaxial or Triaxial)

- Conductor
- Insulation
- Dielectric
- Shielding
- Outer jacketing

4. Low-Voltage Instrumentation (Twisted-Shielded)

- Conductor
- Electrical insulation or dielectric
- Conductor jacketing
- Shielding (including drain wire)
- Outer jacketing

3.5.2 Terminations (Including Splices, Connectors, Lugs, and Terminal Blocks)

Subcomponents common to termination devices are listed below. Note that not all subcomponents are necessarily present in each termination device:

1. Compression Fittings

- Crimped lug or barrel
- Mechanical clamp (compression) mechanism

2. Fusion Fittings

- Fusion lug (welded or brazed to conductor)
- Inhibitor compound (aluminum conductors only)

3. Plug-in Connectors

- Electrical contacts (such as blades or pins)
- Electrical terminations (including soldered joints and internal terminations)
- Dielectric
- Backshell housing
- Cable clamp or other fastening mechanism
- O-rings or other environmental seals
- Coupling mechanism (i.e., retaining screws, threaded spool, snap-in housing)
- Thread sealant

4. Splice Insulation Systems

- Heat shrink
- Tape wrap
- Potting compound
- Stress cone or other voltage stress relief mechanism (shielded cable only)

5. Terminal Blocks

- Terminal block base (dielectric)
- Terminal hardware (such as posts, nuts, or sliding links)
- Mounting system
- Auxiliary components, including covers and fuse holders (optional).

3.6 Analysis of EPRI NUS Cable Database for Environmentally Qualified Cable

The EPRI NUS Cable Database is a computer-based listing of environmentally qualified cables installed in EPRI-member nuclear power plants. The database used for this task, dated April 1993, covers 67 plant sites and 101 units. Currently, there are 6 plant sites (12 units) in operation that are not included in this survey. A few units included in the database have since ceased operations.

Selected information, including plant name, manufacturer, model/type, and references, was extracted from the EPRI NUS Database. Each entry was then categorized as being either a cable, splice and/or termination, or "other" device.[7] Nonrelevant references were deleted from the entries for conciseness, and identical references were retitled to ensure common titling of all reports for sorting purposes. The scheduled commercial date of operation for each plant was added, with the purpose of identifying the range of dates during which cables were purchased and/or installed. The electrical cable listing consisted of 1660 entries; it represents 53 cable manufacturers, along with several cable types of unknown manufacture.

The database seeks to identify and provide relevant information (such as insulation/jacket material and construction) for the various cable configurations installed in EQ applications in participating plants. It may be used to generally characterize industry EQ cable as a whole because (1) most U.S. nuclear units are represented in the database (approximately 89%), and (2) those units participating are considered to have included information on the most numerically predominant types of cable installed in their plants. However, significant variance in the amount of information provided to EPRI from various reporting utilities was noted during the analysis. Examination of the data indicates that not all types of cable used in EQ applications were reported for all participating plants. In addition, the significance of each entry remains somewhat in question, as several instances of seemingly identical entries for the same unit were noted. Hence, no correlation could be made between each entry and a unique cable configuration; the entries can be differentiated by general cable type only.

With one or two exceptions, the analyses of the EPRI NUS Database discussed in the following sections of this AMG are considered generally applicable to both EQ and non-EQ circuits, based on the assumption that the same types and configurations of cable are used in both types of applications at most plants. This assumption is predicated on the fact that most plant operators originally sought to (and continue to) simplify their cable procurement specifications and maintain greater control over their warehouse inventories. Cables suitable for EQ applications were and are routinely used in other types of applications; hence, no advantage

[7] "Other" devices included area radiation monitors, transmitters, thermocouples, and nuclear instruments that are not considered to be within the scope of this AMG.

results from maintaining multiple different types of cable either during construction or for subsequent circuit replacement. Many plant operators now try to avoid the problem by maintaining only a few (or only one) brands or types of cable available for installation in any class of circuit. The most significant exception to this observation is the use of polyvinyl chloride (PVC-) insulated cable and wire. Although PVC-insulated cables were rarely used by the industry in EQ applications, PVC-insulated cable is used widely in non-EQ circuits in many plants.

It should be noted, however, that the various types of cable within a given plant may vary significantly from those listed in the tables below. For example, one pressurized water reactor (PWR) operator contacted as part of the study indicated that a very large fraction (more than half) of its installed cable was insulated with silicone rubber which, per Table 3-4, should account for only about 5% of the cable in the typical plant.

3.6.1 Manufacturer Sort

Electrical cable entries contained in the database were initially sorted by manufacturer to determine the predominant vendors. The results were tabulated in Table 3-3 and identify the number of types of cable in service or purchased from each manufacturer, the number of units where each cable is installed, and a ranking of the 10 most frequently represented cable companies by the number of cable types procured. As shown in the table, entries for Okonite cable were most numerous (359), followed by those for Rockbestos (316)[8] and BIW (150). Rockbestos cables were procured by the most units (78), followed by Okonite (77) and BIW (68). Collectively, these three manufacturers account for approximately 50% of all entries in the database. Also, entries for both Okonite and Rockbestos are more than double those of the third most numerous cable manufacturer (BIW). BIW cables, however, have been procured for nearly as many individual plants as those made by either Okonite or Rockbestos.

3.6.2 Insulation Sort

A third sort of the database was conducted based on the model/type field of the electrical cables. A majority of the entries (1215 of 1660 entries, or approximately 74%) listed the insulation material used on the cable being described. The most numerous insulation materials, trade names, or generic names listed in the database were the following (in alphabetical order): Bostrad, cross-linked polyethylene/polyolefin (XLPE/XLPO), ethylene propylene rubber (EPR), Firewall III, Flamtrol, flame retardant (FR), high-temperature Kerite (HTK), Okonite, polyethylene (PE), silicone rubber (SR), and Tefzel®.

[8] If the entries for Cerro Wire & Cable are added, Rockbestos is the most numerous.

Table 3-3 Manufacturers Listed in EPRI NUS Cable Database

Manufacturer	No. of Database Entries	Rank
Okonite	359	1
Rockbestos	316	2
Boston Insulated Wire & Cable Company (BIW)	150	3
Anaconda Wire and Cable	128	4
Kerite Company	109	5
Brand-Rex	98	6
Samuel Moore	77	7
General Electric (GE)	69	8
Cerro Wire & Cable Company (Rockbestos)	47	9
Raychem	46	10
Continental Wire & Cable Corporation	37	
American Insulated Wire (AIW)	19	
General Cable	18	
Essex Wire Corporation	17	
Rome Cable Corporation	16	
Collyer Insulated Wire & Cable	12	
Cyprus Wire & Cable	11	
Simplex Wire & Cable Company	11	
Eaton	10	
Conax	8	
ITT Surprenant	8	
Champlain Cable	6	
Belden Corporation	5	
Galite	3	
Lewis	3	
Bendix Corporation	2	
Hatfield Electronics	2	
Coleman Industries	1	
National Wire & Cable Corporation	1	
Tensolite	1	
TOTAL	1,590	

Table 3-4 lists both specific materials and manufacturer's trade names or product lines; hence, some additional investigation was required to determine the generic material in many cases (for example, Rockbestos Firewall III insulation can be categorized as a cross-linked polyethylene). Manufacturers' literature, catalogs, and environmental qualification test reports were used as the primary references for determining the generic material categories of insulations identified by trade name/product line. For some entries (such as those for cables insulated with Kerite HTK), even the dominant polymer used in the insulation is proprietary and not readily obtainable. Therefore, these materials could not be included within any of the other existing generic material categories, and were maintained as their own categories.

A total of 17 different types of generic insulation material categories were identified. Table 3-4 shows the various material categories identified in the database.

Table 3-4 Insulation Materials Listed in EPRI NUS Cable Database

Insulation Material	No. of Database Entries	% of Total
BR, butyl rubber	20	1.6
CSPE, chlorosulfonated polyethylene	28	2.3
EPR, ethylene propylene rubber	434	35.5
ETFE, ethylene tetrafluoroethylene	39	3.2
FR, flame retardant	36	2.9
Industrite	2	<1.0
Kerite	61	5.0
Mineral	12	1.0
Neoprene®	2	<1.0
PE, polyethylene	52	4.3
Polyimide	8	<1.0
Polypropylene	3	<1.0
PVC, polyvinyl chloride	12	1.0
SR, silicone rubber	63	5.2
Styrene	1	<1.0
XLN, cross-linked Neoprene®	3	<1.0
XLPE, cross-linked polyethylene	439	35.9
TOTAL	1,215	

3.6.3 Cable Size Sort

It was noted during analysis of the database that some entries contained information regarding the size/configuration of cables installed. With very few exceptions, these entries were limited to those not containing insulation/jacket material information (i.e., either insulation/jacket information or size information was present, but generally not both). All entries listed ranged from one conductor to 27 conductors, from #22 American Wire Gauge (AWG) to 500 thousand circular mils (MCM), and varied in voltage rating between 300 V and 5 kV. As in the insulation materials sort, most of the items in this listing were manufactured by the 10 major cable vendors previously identified. Most of the entries with size/configuration information were derived from a comparatively small number of plants; this appears to be an artifact of the way in which data were recorded by a particular utility and/or entered into the database.[9]

3.6.4 Splice Insulation Database

The only splice-producing manufacturer currently listed in the EPRI NUS Database is Raychem. There were six Conax seals listed and these are all at one nuclear power plant; however, these types of devices are not within the scope of this guideline.[10] The remaining splice-related entries (which number more than 100) all describe Raychem splice insulation. Other common nuclear plant splice manufacturers (such as Okonite, Scotch, and Kerite, which produce tape splice kits) were identified during the preparation of this AMG; however, none of these splices were noted and/or included in the database by the contributing plant(s). Although ostensibly based on a large percentage of the plant population, these results are not considered wholly representative based on information received directly from various plants contacted as part of this study. The other types of tape splices listed above, although not qualified by the manufacturer or maintained as part of a 10CFR50, Appendix B quality program, have nonetheless been tested and qualified by various utilities. These tape splices are known to be in use today. In addition, Conax seals are known to be used in more than the one plant indicated by the database. The reasons for the seeming disparity between the database and actual practice are unknown.

3.6.5 Conclusions Regarding EPRI NUS Database

Analyses of the data in the EPRI NUS Database indicate the following about cable used in nuclear plants:

1. **Insulation Types.** Approximately 36% (by number of entries) of all EQ insulations are XLPE/XLPO and 36% are EPR [including EP and ethylene propylene diene monomer (EPDM)]. The third largest category, silicone rubber, is only 5% of the

[9] As an alternative, the cable database for one nuclear plant was examined in an attempt to obtain more information on the typical cable size distribution. Unfortunately, this database did not identify the size of each cable separately, making the task of determining the relative amounts of each size/configuration of cable infeasible for this study.

[10] "Seals" of the type listed in the database are a distinct category of device not considered to fall within the definition of a cable, termination, or splice.

entries listed. Therefore, the remaining 23% of entries with identified insulation materials are distributed among 17 different generic insulation compounds, revealing that EQ cables are predominantly insulated with either XLPE or EPR. Because these results are assumed to be generally applicable to non-EQ cable, it can be inferred that a significant amount of the non-PVC, non-EQ cable installed in U.S. nuclear plants uses either XLPE or EPR insulation.

2. **Manufacturer.** Okonite appears to be the most commonly installed EQ cable, followed by that made by Rockbestos and BIW.

3.7 Operating and Service History

U.S. Nuclear Regulatory Commission Information Notices, Circulars, Generic Letters, and Bulletins were reviewed to determine the industry-wide operating experience with cable and terminations. Each applicable Information Notice, Circular, Letter, Bulletin, and safety evaluation report (SER) is discussed in Section 3.7.1. Some documents that pertained to cable and terminations were not considered applicable to this report (for example, failures resulting from improper design).

Cable and termination data derived from the Institute for Nuclear Power Operation (INPO) Nuclear Plant Reliability Data System (NPRDS) and NRC Licensee Event Reports (LERs) were also reviewed. Component failures described in these sources were analyzed to identify significant cable system failure mechanisms and their relative likelihood of occurrence. These analyses are discussed in Sections 3.7.2 and 3.7.3, respectively.

Finally, industry studies and literature were searched for applicable documents relating to cable and termination operating history and failures. Materials identified during this search are discussed in Section 3.7.5.

3.7.1 Industry-Wide Operating Experience with Components; NRC Documentation

The following subsections discuss various NRC documents applicable to the failure or aging of electrical cable and terminations. Note that several other NRC documents relating to cable and terminations were located; however, these were not considered relevant to component aging and are therefore not discussed further.

The following NRC documents are discussed:

- Information Notices 93-33 and 92-81
- Information Notice 92-01
- Information Notice 89-30
- Information Notice 87-52
- Information Notice 86-71
- Information Notice 86-49
- Information Notice 82-03
- Information Notice 80-08
- Circular 77-06

NRC Information Notices 93-33, "Potential Deficiency of Certain Class 1E Instrumentation and Control Cables" [3.10] and 92-81, "Potential Deficiency of Electrical Cables with Bonded Hypalon Jackets" [3.11]

IN 92-81 [3.11] describes failures of cables containing ethylene propylene rubber (EPR) insulation and bonded Hypalon® (CSPE) jackets, which occurred in qualification research testing reported in NUREG/CR-5772, "Aging, Condition Monitoring, and Loss-of-Coolant Accident (LOCA) Tests of Class 1E Electrical Cables" [3.12], and NUREG/CR-6095, "Aging, Loss-of-Coolant Accident (LOCA), and High Potential Testing of Damaged Cables" [3.13]. IN 93-33 [3.10] reported additional functional failures and low insulation-resistance values for cables in the NUREG/CR-5772 test program.

The program reported in NUREG/CR-5772 had two objectives: (1) determination of the long-term degradation behavior of typical instrumentation and control cables used in nuclear power plant applications, and (2) determination of the potential for assessment of residual cable life using condition monitoring (CM) techniques. Accelerated thermal and radiation aging was performed simultaneously at low rates (~100°C and ~100 Gy/hr [10 krad/hr]) during 3-, 6-, and 9-month periods to achieve an equivalency to 55°C for 20, 40, and 60 years, respectively (based on an activation energy of 1.15 eV). Radiation doses were 200, 400, and 600 kGy [20, 40, and 60 Mrad], respectively. The cables were then exposed to accident radiation (1.1 MGy [110 Mrad] at 6 kGy/hr [600 krad/hr]) and LOCA testing.

The objectives of the test program described in NUREG/CR-6095 [3.13] were to determine the effects of dielectric withstand voltage testing on cables and to assess functionality and survivability under LOCA conditions of radiation aged and thermally aged cables with simulated maintenance/installation damage. Testing for this program consisted of the evaluation of unaged and undamaged cable specimens to identify any damaging effects associated with high-potential (hi-pot) testing, and the aging and accident testing of damaged[11] cable specimens; a determination of the hi-pot voltage necessary to indicate impending cable failure was also included as part of this phase. The testing involved irradiation to a total integrated dose (TID) of 1.3 MGy [130 Mrad] at 3 kGy/hr [300 krad/hr], followed by thermal aging at 158°C for 336 hr[12] and LOCA steam simulation.

Bonded Jacket Failures

In the NUREG/CR-5772 test program [3.12], five cable types in the test had insulation and jackets on individual conductors. Of these, the individual jackets on two of the cable types were thought to be not bonded or very lightly bonded (probably not coextruded). Three of the cable types had bonded jackets. During the tests, some of the bonded jacket cables failed. The tested Okonite cable (1/C #12 AWG, 15 mils Okolon over 30 mils EPR) had one failure noted for a specimen aged to 60-years equivalent. Three failures also

[11] "Damaged" specimens were those with their insulation/jacket intentionally reduced in thickness to simulate the effects of damage during maintenance or installation.

[12] 158°C was chosen to provide the equivalent of 60 years at 65°C for a material with an activation energy of 1.00 eV, based on an aging time of 2 weeks (336 hr).

occurred in the Sandia test program for Samuel Moore Dekoron Dekorad cable with composite EPR/CSPE insulation/jacket.

The other failures listed in NUREG/CR-5772, and described in IN 93-33 [3.10], were of a Rockbestos Firewall III irradiation crosslinked polyethylene (XLPE) insulated conductor aged to a 60-year equivalent, and three Kapton®-insulated wires aged to 20-, 40-, and 60-years equivalent, respectively. There is no indication that the Rockbestos XLPE failure was a jacket-insulation interaction (only a 45-mil Neoprene® overall jacket was present), and *may* be considered a "random" failure.[13] Sandia noted that the most probable cause of failures for the Kapton®-insulated wires was handling damage for two of the specimens, and damage in the vicinity of the chamber penetration for another specimen (which also may have been from handling or installation). As evidenced by the EPRI NUS Database, very little Kapton® insulation exists in bulk cable runs; however, this type of wire is used in various other plant components such as penetrations and seals. EPRI Report NP-7189 [3.14] and NRC IN 88-89 [3.15] provide additional information on Kapton®-insulated wire.

Three cable types were included in the NUREG/CR-6095 tests [3.13]: (1) Okonite Okolon #12 AWG (30-mil EPR/15-mil CSPE bonded jacket); (2) Rockbestos silicone rubber (30 mils) #16 AWG; and (3) Brand Rex XLPE (30 mils) #12 AWG. Results of this testing indicated some jacket (and, in certain cases, insulation) circumferential cracking of the Okonite specimens after aging and irradiation. After the LOCA simulation, all of the Okonite specimens displayed severe damage (including splitting and longitudinal cracking and exposed conductors). All ten Okonite specimens failed the LOCA testing. It is unclear whether the circumferential cracking experienced after aging participated in any way in the longitudinal splitting observed after the LOCA testing.

The Sandia tests indicate a possibility of interactions between the individual conductor jacket and insulation. The failures of one type of specimen indicate that a failure mode exists at some given aging level for this cable that results in longitudinal splitting of the conductor jacket/insulation system after exposure to accident steam conditions. The longitudinal splitting observed may be precipitated by swelling of the EPR under irradiation/high temperature thermal exposure, which produces a rupture of the bonded jacket. This failure mode seems to be just beginning on the 60-year (equivalent) aged Okonite specimens under the test conditions of NUREG/CR-5772, yet has progressed completely under the NUREG/CR-6095 test conditions. Note that the differences in the test conditions include a different aging temperature (100°C versus 158°C), a different aging sequence (simultaneous thermal and radiation aging followed by accident radiation exposure versus total accident plus aging dose followed by thermal aging), and dose rates (100 Gy/hr [10 krad/hr] versus 3,000 Gy/hr [300 krad/hr]). The disparity in results between the two programs can be attributed to one or more of these differences.

Bonding of the individual conductor jacket to the insulation may tend to localize tensile stress on the surface of the insulation. As the tensile stress on the jacket reaches a value sufficient to induce rupture of the jacket, the failure of the jacket may produce tearing on

[13] Only one failure was noted for six Firewall III specimens tested.

the surface of the insulation to which it is bonded because the tensile stress is now applied primarily to the surface of the insulation, and is focused in the area of the jacket rupture. One implication of the Sandia results is that a jacket composed of less aging-resistant material that is bonded to the underlying insulation may fail due to cracking before an unbonded or even unjacketed conductor. No qualification testing of this size and configuration of bonded EPR/CSPE low-voltage cable was performed by Okonite; hence, the existence of bonded jacket interactive mechanisms cannot be directly refuted.

Conclusions

Although the results of the testing described in NUREG/CR-6095 initially indicated potentially severe problems with aged, bonded jacket/insulation systems under accident conditions, further examination of the aging and test conditions shows that the failures of the cables tested can be attributed to the severity of the test regimen. The aging temperature of 158°C and aging dose of 1.3 MGy [130 Mrad] are comparatively high, and the aging sequence used during the NUREG/CR-6095 testing was one that is known to produce rapid degradation of EPR compounds. This adds further support to the proposition that the aging regimen applied by Sandia may have induced physical phenomena within the materials which would not otherwise occur under actual plant aging/accident conditions (i.e., exposure to full aging and accident doses followed by thermal aging and subsequent LOCA is not a situation that could realistically occur in any plant). Although the aging temperature and total dose of the NUREG/CR-5772 program were substantially lower (100°C and 0.6 MGy [60 Mrad] maximum, respectively), the lower dose rate used (approximately 100 Gy/hr [10 krad/hr]) is one at which significant dose rate phenomena have been observed for EPR [3.16], [3.17]. In addition, the 0.6 MGy [60 Mrad] aging dose applied to the 60-year specimens (the group in which the only bonded jacket conductor failure occurred) is somewhat higher than that which would be experienced at most plants, even inside primary containment. However, the NUREG/CR-5772 results may be conservatively interpreted to indicate that some effect due to interaction of the bonded jacket and insulation may occur at levels of aging anticipated to occur beyond the original 40-year operating period. Current data suggest that additional research and evaluations may be warranted for use of bonded-jacket cables that are exposed to aging conditions that may promote jacket cracking. This is particularly important if the cable test specimens were not representative of the installed bonded-jacket cables.

<u>NRC Information Notice 92-01, "Cable Damage Caused by Inadequate Cable Installation Procedures and Controls" [3.18]</u>

IN 92-01 describes cable damage caused by improper cable installation techniques at one Tennessee Valley Authority (TVA) nuclear plant. Specifically, cable was removed from conduit to inspect for damage thought to have occurred as a result of welding in the area. Inspection of the removed cable revealed damage (some of the cable had exposed conductors) that was not attributable to the welding activities. Further analysis of the cable indicated that this damage was the result of cable pull-bys, an installation practice by which cable is installed in conduit over the top or beside existing cable.

This Information Notice is significant because damage to cables occurring as a result of the installation process may ultimately produce failure of the cable under either normal or accident service environments. Installation damage, although not an aging mechanism, can dramatically affect the longevity of a cable.

NRC Information Notice 89-30, "Excessive Drywell Temperatures" [3.19]

IN 89-30 discusses the effects of localized high temperatures on safety systems and related equipment that may have an impact on the service temperature basis used to establish the thermal aging life of installed EQ equipment. The Information Notice describes events at various boiling water reactor (BWR) plants which resulted in elevated drywell temperatures and degradation of various components including electrical cable. Relevant conclusions of the Information Notice state that (1) BWRs routinely operate at or near their drywell EQ temperature limit, (2) substantial temperature gradients may exist in these drywells, and (3) the drywell head region (i.e., upper elevations) is most susceptible to high temperature. These conclusions are applicable to drywell cable and termination aging in that high general area temperatures within the drywell will age organic insulation materials at an accelerated rate.

NRC Information Notice 87-52, "Insulation Breakdown of Silicone Rubber-Insulated Single Conductor Cables During High Potential Testing" [3.8]

IN 87-52 discusses the high-potential testing of low-voltage No. 14 AWG silicone rubber-insulated cable at one nuclear plant. This testing was initiated in response to concerns raised regarding the installation of the cables (specifically, that some may have been damaged during receipt, storage, or installation, and that this damage may have reduced the dielectric strength of the insulation) and a lack of vertical support. Silicone rubber cables from three separate manufacturers (including AIW and Rockbestos) were installed in the plant. Six silicone cables (16 conductors, normally energized at 125 Vdc) were tested at 10,800 V to address the vertical support issue. Three of the six cables experienced breakdown (the lowest at 7500 V) and one had a low polarization index. Additional cables were then hi-pot tested; a total of 9 failures occurred out of 91 conductors tested.

Subsequent investigation of the first six silicone-insulated cables tested showed no evidence of external damage to the cable outer braid. However, laboratory analysis showed that the insulation for each cable was cut (presumably by the conductor) at localized points on the inside of the insulation surface; these points tended to coincide with one another along the length of the cable. The lowest remaining insulation thickness found in these locations was 8 mils. This indicated a lateral or side impact to the cable prior to installation, such as having a heavy object dropped on or rolled over the cables while they were laid out, rather than pulling damage or lack of vertical support. The AIW cable was found to be particularly soft and had a low impact strength, and six of the nine cables which failed testing were made by AIW. All of the AIW cables were eventually replaced.

The utility also performed subsequent qualification (LOCA) testing on specimens with intentionally reduced insulation thickness. Specimens with as little as 4 mils of remaining

insulation were shown to pass mandrel bend and hi-pot testing following the aging and LOCA exposure.

NRC Information Notice 86-71, "Recent Identified Problems with Limitorque Motor Operators" [3.9]

IN 86-71 discusses the aging of electrical wiring inside Limitorque motor operators caused by localized high temperatures. This aging resulted from improper energization of space heaters inside the limit switch compartments; these heaters were intended for energization during storage only to prevent the accumulation of moisture.

NRC Information Notice 86-49, "Age/Environment Induced Electrical Cable Failure" [3.20]

IN 86-49 discusses age/environmentally induced failure of electrical cables caused by localized high temperatures. The Information Notice describes the importance of periodic inspection and walkdowns of cable systems to identify environmental conditions that may adversely affect their longevity or function. In addition, the need for a comprehensive maintenance and surveillance program for medium-voltage cable is identified.

NRC Information Notice 82-03, "Environmental Tests of Electrical Terminal Blocks" [3.21]

This Information Notice published the results of a test conducted to investigate the deterioration of terminal blocks' insulators under accident conditions. The Information Notice describes the importance of clean terminations and terminal blocks in safety-related circuits and discusses regulations for establishing appropriate procedures to ensure cleanliness and installation integrity of these devices. Licensees are reminded that the plant preventive maintenance program in use at their facilities should ensure that (1) proper operation of all essential components is achieved throughout the life of the plant and that (2) terminations and terminal blocks are periodically inspected for cleanliness and installation integrity following any maintenance activity affecting them.

NRC Information Notice 80-08, "The States Company Sliding Link Electrical Terminal Block" [3.22]

This Information Notice discusses defects with States Company sliding-link terminal blocks relating to cracking between the threaded screw hole and the side of the U-shaped link. This crack widens when the screw is tightened, resulting in a poor or intermittent electrical connection. The defective link is impossible to cinch tightly and may be difficult to detect by visual inspection. This defective mechanical connection can ultimately result in an electrical circuit malfunction.

NRC IE Circular 77-06, "Effects of Hydraulic Fluid on Electrical Cables" [3.23]

This Circular documents the effects of exposing various low-voltage power, instrumentation, and control cables to phosphate-ester electro-hydraulic control (EHC) fluid

at one nuclear plant. The fluid, which had been leaking from a piece of plant equipment, had migrated into nearby cable pans and resulted in swelling and plasticization of the outer jacket of the cable. All cables were jacketed with PVC (a material that is highly susceptible to degradation by esters), and were insulated with either polyethylene or butyl rubber. An inspection of the cables revealed that only the PVC jacket was plasticized.

Although not considered a common occurrence, exposure of cables and terminations to chemical substances and foreign materials has been documented at several plants, and can result in degradation of the component's performance and functionality. These effects are generally localized.

3.7.2 Evaluation of NPRDS Data

To substantiate the postulated stressors and aging mechanisms for electrical cable and terminations, plant component failure data were reviewed. One of the primary sources of this type of failure data is the INPO NPRDS. Failure records contained in the NPRDS include such information as the voltage rating, type of equipment, date of discovery, cause category, and a brief narrative describing the event.[14] NPRDS data are not focused directly on component aging, as NPRDS does not necessarily address the root cause or mechanism of component degradation. In addition, not all degradations observed during maintenance activities are identified in the database. Not all plants have provided NPRDS data, and those which have may not have reported for their entire period of operation. Furthermore, cables and terminations are not uniquely classified or categorized within the database. As a result of these limitations, the database is not well suited to providing probabilistic information about the reliability of a specific population of cable and/or termination components with respect to age-related degradation. However, the data can be used to identify those cable and termination components that have a high incidence of degradation or failure relative to other components, as well as types of applications and environments which are conducive to degradation or failure.

The NPRDS database was searched by using keywords in the narratives. This method was chosen because, as previously stated, no separate classification or descriptive category for "cable" or "terminations" was included in the NPRDS system, and many cable or termination failures are reflected in reports regarding the connected load or intervening device (such as motors or electrical switchgear) rather than the circuit component itself. Hence, extremely broad limits were set on the search to ensure that as many pertinent reports as possible were identified. Keywords used in the narrative search included "wir(e)", "cabl(e)," "term(ination)," "conn(ector)", and "splic(e)."[15] This search generated 5260 potentially applicable reports, whose event dates ranged from November 1975 through mid-1994. Data pertinent to cable and termination component failures were identified; those pertaining to equipment not within scope (such as wiring failures at the component or subcomponent level) were deleted. The remaining reports were then individually evaluated to determine their applicability to aging and aging mechanisms.

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[14] The cable or termination manufacturer was identified in only a few instances.

[15] The more general forms of these words were used as database search keywords to avoid excluding related reports. For example, if the word "wire" were used as a keyword, reports containing the word "wiring" (as opposed to wire) would be excluded.

Based on analysis of the NPRDS data, a total of 1458 reports applicable to low- and medium-voltage cable and termination failure were identified. Table 3-5 presents a summary of the NPRDS failure data, and shows the distribution of failure reports within each voltage category. Components related to "high voltage" neutron monitoring systems were included in a separate category due to their significant differences from other cable types and applications.

Table 3-5 Summary of NPRDS Failure Data

Voltage Range	Component	Number of Failures[1]	Percentage of Total[2]
Low (Max. 1000 Vac)	Cable	150	14.5
	Connector	314	30.3
	Compression/Fusion Fitting	132	12.8
	Hookup and Panel Wire	377	36.4
	Terminal Block	36	3.5
	Splice/Insulation	26	2.5
	Total	1,035	100.0
Medium (Max. 15 kVac)	Cable	24	68.6
	Connector	4	11.4
	Splice/Insulation	6	17.1
	Compression/Fusion Fitting	1	2.9
	Total	35	100.0
Medium (Neutron Monitor; 1 kV to 5 kV)	Connector	321	82.7
	Cable	67	17.3
	Total	388	100.0
	TOTAL	1,458	

Notes: 1. Number of failures does not include those attributed to maintenance or other personnel error.
2. Percentages shown are rounded to nearest tenth of 1 percent.

Many of the reports reviewed in this analysis required a substantial degree of interpretation; incomplete and even contradictory descriptions of the circumstances surrounding the failure were sometimes noted. Such reports were estimated to comprise roughly 20% of the total number. In cases where the ambiguity could not be resolved with any degree of certainty, the report in question was not used. Due to the uncertainty inherent in some of the data, the relative proportions of various types of failures may differ somewhat from the "actual" values; this potential error was assumed to be evenly distributed (that is, reports erroneously attributed were assumed not to affect one component, failure mode, or failure cause grouping disproportionately in relation to another).

As previously discussed, one type or category of termination may be included as a subcomponent of another type of termination; for example, a compression fitting may be used

inside a multi-pin connector, and so forth. In such cases, the failure report was classified based on the subcomponent level unless information on the component was included. Accordingly, a report describing only a failed compression fitting would be categorized as a compression fitting failure, whereas a report describing the same fitting within a multi-pin connector would be classified as a connector failure. In the case of splices, only splice insulation failures were categorized as splice failures; degradation of the underlying compression/fusion fitting was classified as a compression/fusion fitting failure. Failed compression fittings attached to terminal blocks were included as compression fitting failures because these components are not part of the block itself.

Several additional difficulties were encountered in analyzing the NPRDS data. These considerations are discussed further in Appendix F of this guideline.

Those NPRDS reports resulting from prior equipment installation, maintenance, modification, or surveillance testing (as differentiated from events detected during these activities) were classified as "maintenance-induced." Maintenance-induced events, although not an aging mechanism, do constitute a mechanism for degradation of cable and termination components over time. Failures resulting from maintenance-induced causes are identified in each of the discussions presented below, and treated as a separate category of failure.

The operating voltage for each failed component was also noted. Failure reports were categorized as describing either low- or medium-voltage systems or those relating to nuclear instruments (low current, high-sensitivity neutron detector applications). The latter distinction was based on the large number of reports applicable to neutron monitoring systems and the significant differences between these systems and other medium-voltage applications. By far, the largest percentage of the total number of reports described low-voltage systems, with a substantially smaller percentage relating to nuclear instrument systems, and a very small percentage to medium-voltage systems. Reports relating to higher voltage systems (>15 kV) were excluded; however, these constituted an extremely small number of reports (<1%).

The "voltage rating" field of the NPRDS report was not always a reliable indicator of the voltage to which the component was exposed; for example, some reports describing failures of auxiliary components on large electrical devices (such as power transformers) were often coded with the voltage rating of the transformer rather than that of the failed component. Hence, careful interpretation of many reports was required. In general, the greater part of circuits in the typical nuclear plant are low-voltage; therefore, it was expected that the failures would occur in rough proportion.

3.7.2.1 Low-Voltage Systems

3.7.2.1.1 Low-Voltage Component Failure Analysis

A total of 1342 events from more than 50 different nuclear units were recorded for low-voltage cable and terminations of the type considered by this guideline. Of these 1342 events, 307 were considered maintenance-induced and were deleted from further analysis. Table 3-5 shows the failure data compiled for the remaining 1035 reports. Hookup and panel wire failures constituted the highest single percentage of low-voltage failures (377 reports/36.4%), followed by connector components (30.3%). The next most prevalent component to fail was field cable (14.5%), followed by compression/fusion fittings (12.8%), terminal blocks (3.5%), and splices (2.5%). Figure 3-2 is a graphical representation of these data.

Note that the failure data presented in this guideline was collected during normal plant operation. Failure data for design basis event (DBE) conditions are not available.

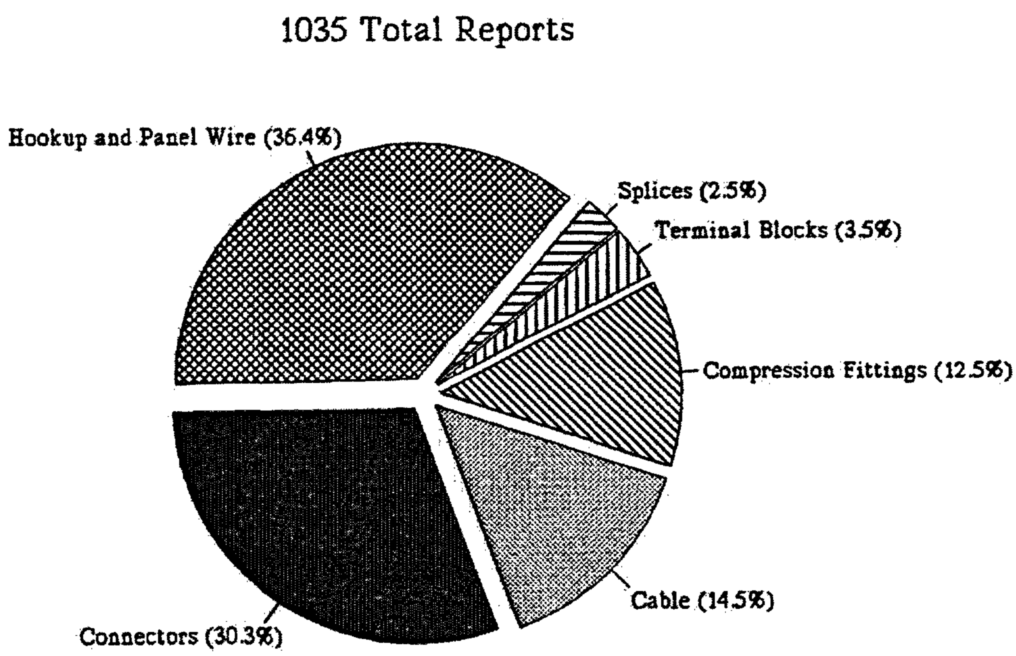

Figure 3-2 NPRDS Failure Data for Low-Voltage Components

3.7.2.1.2 Hookup and Panel Wire

Of the 545 failure reports covering hookup and panel wire, 168 were considered maintenance-induced and subsequently excluded. It should be noted, however, that although no numerical data were gathered, a large percentage (estimated at a third or more) of these "maintenance-induced" reports were the result of pinching or shorting of wires in doors or covers (such as control board panel doors or MOV access covers).

Failed subcomponents included insulation (56%) and conductors (39%). The single most common failure mode for hookup and panel wire was a short circuit to ground (45% of all reports), followed by high resistance/open circuit (including broken conductors) (44%). Only 2% listed an unidentified failure mode.

Significant failure causes included mechanical stresses (17%) and heat damage (11%); 59% of the reports could not be attributed to any specific cause.

The majority of failures noted in the reports (64%) were detected during operation; 16% and 10% of the total number of reports were detected during surveillance testing and maintenance, respectively. Of the 64% of the failures detected during operation, 62% affected the required function of the equipment; the remaining 2% had no effect on the circuit's required function. See Figure 3-3.

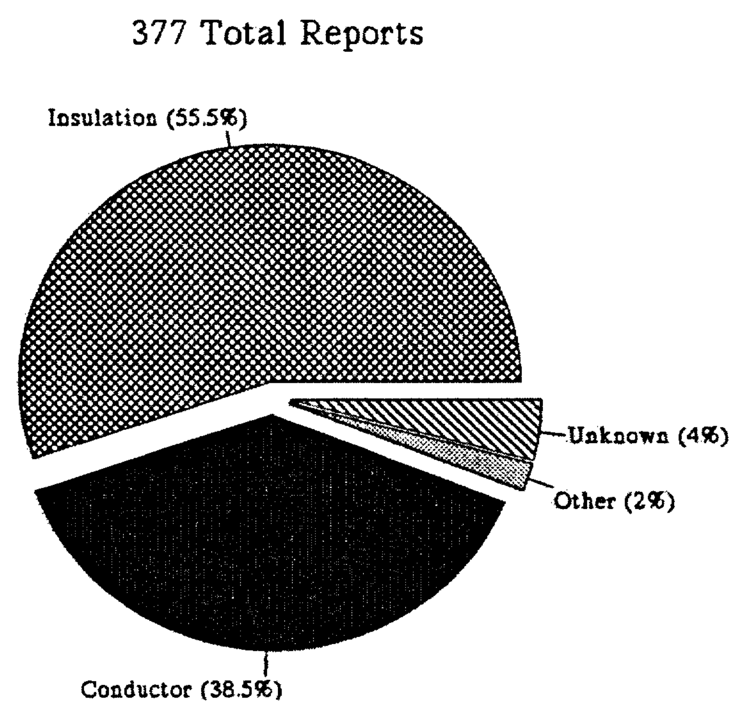

Figure 3-3 NPRDS Failure Data for Low-Voltage Hookup and Panel Wire

3.7.2.1.3 Low-Voltage Connectors

Of the 335 failure reports covering electrical connectors, 21 were considered maintenance-induced and therefore excluded. The most prevalent failed subcomponents included contacts/pins (31%) and miscellaneous hardware (5%). Fifty-eight percent of all reports related to connectors did not identify the affected subcomponent(s).

The single most common failure mode for connectors was high resistance/open circuit (48% of all reports), followed by bent or deformed components (24%), and shorts to ground (12%). Thirteen percent of the 314 reports did not identify a failure mode.

The most significant failure cause was oxidation/corrosion/dirt (44%); 39% of the reports did not list any specific cause. The remaining 22% noted failures caused by normal aging (5%), wear (3%), moisture intrusion (3%), unrelated work in the immediate area (3%), mechanical stress (2%), and heat (1%).

The majority of failures noted in the reports (68%) were detected during operation of the connector; 16% and 6% of the total number of reports were detected during surveillance testing and maintenance, respectively. Of the failures detected during operation (68%), 67% affected the required function of the equipment. See Figure 3-4.

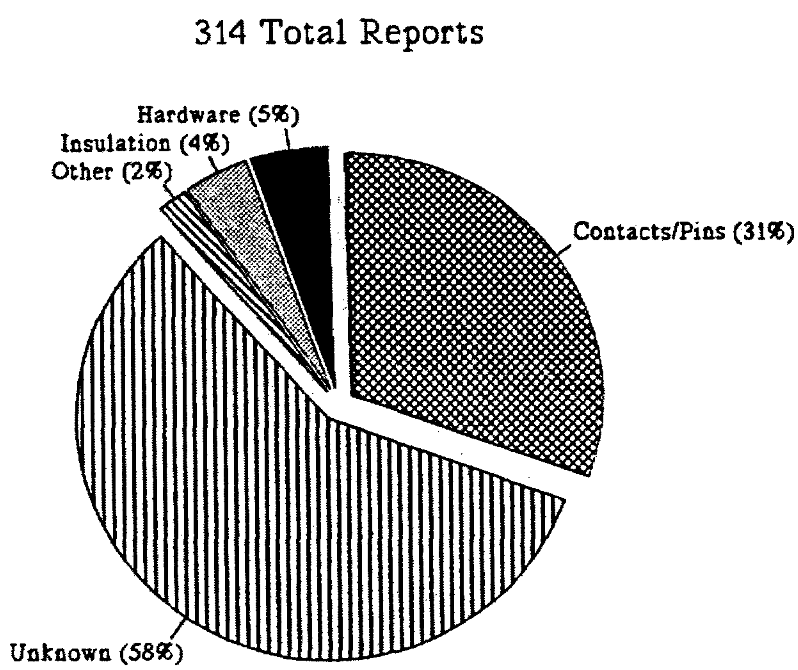

Figure 3-4 NPRDS Failure Data for Low-Voltage Connectors

3.7.2.1.4 Low-Voltage Cables

Of the 173 failure reports covering field cable, 23 were considered maintenance-induced and excluded from further consideration. The most prevalent failed subcomponents included insulation (65%) and conductors (19%); 12% of the reports had unidentified failed subcomponents.

The single most common failure mode for cables was a short to ground (54% of all reports), followed by open circuit/high resistance (23%). Eleven percent of the reports did not list a failure mode.

Significant failure causes included heat or high temperature (18%) and mechanical stress such as vibration or tensile stress (15%); 49% of the reports could not be attributed to any specific cause.

The majority of failures noted in the reports (51%) were detected during operation of the cable; 12% and 10% of the total number of reports were detected during surveillance testing and maintenance, respectively. Of the failures detected during operation (51%), all affected the required function of the circuit. See Figure 3-5.

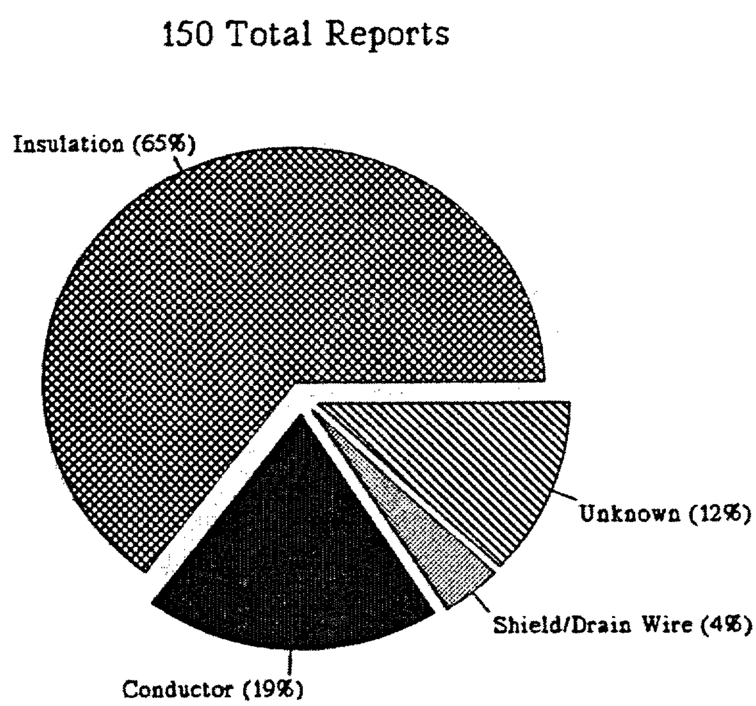

Figure 3-5 NPRDS Failure Data for Low-Voltage Cables

3.7.2.1.5 Low-Voltage Compression and Fusion Fittings

Of the 165 failure reports covering low-voltage compression and fusion fittings, 33 were considered maintenance-induced and excluded from further consideration. The most prevalent failed subcomponents included the lug itself (83%) and associated hardware such as compression bolts (15%).

The single most common failure mode for compression/fusion fittings was loosening or breakage (71% of all reports), followed by high electrical resistance (17%). Only 2% of the 132 reports listed an unidentified failure mode.

Significant failure causes included mechanical stress (16%) and oxidation/corrosion/dirt contamination (17%); 61% of the reports could not be attributed to any specific cause.

The majority of failures noted in the reports (51%) were detected during operation; 33% and 9% of the total number of reports were detected during surveillance testing and maintenance, respectively. Of the failures detected during operation, all affected the required function of the circuit. See Figure 3-6.

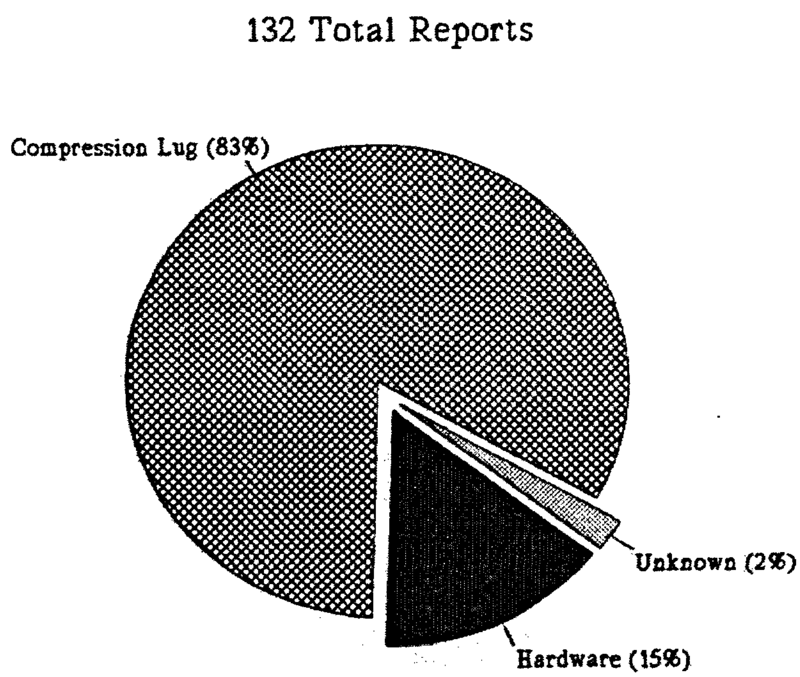

Figure 3-6 NPRDS Failure Data for Low-Voltage Compression and Fusion Fittings

3.7.2.1.6 Low-Voltage Terminal Blocks

Of the 38 failure reports covering terminal blocks, 2 were considered maintenance-induced and excluded from further consideration. The most prevalent failed subcomponents included terminal posts/hardware (54%) and insulating blocks (29%). The single most common failure mode was broken or loose components (67% of all reports), followed by short circuit to ground (21%).

The only significant failure cause identified was mechanical stresses (13%); 67% of all reports were the result of unknown causes. Half of the failures noted were detected during operation (all affected functionality); 25% and 13% of the total number of reports were detected during surveillance testing and maintenance, respectively. See Figure 3-7.

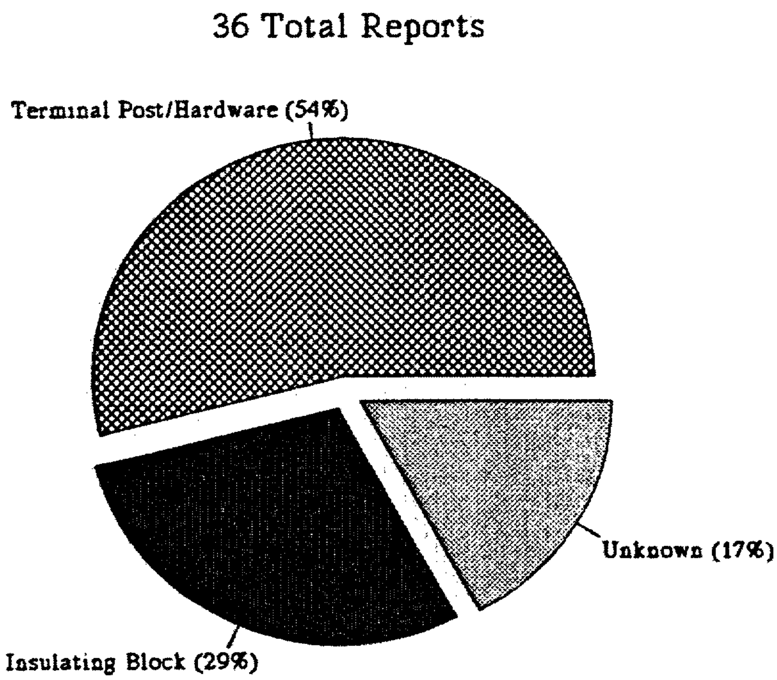

Figure 3-7 NPRDS Failure Data for Low-Voltage Terminal Blocks

3.7.2.1.7 Low-Voltage Splices

Of the 32 failure reports covering low-voltage cable splices, 6 were considered maintenance-induced and excluded from further consideration. The most common failed subcomponents were insulation (18%) and conductors (18%); 53% of the applicable reports listed no failed subcomponent. The most common failure modes for splices were a short circuit to ground and high electrical resistance/open circuit (29% each). Six of the 26 reports (24%) listed an unidentified failure mode. See Figure 3-8.

The only significant failure cause noted was mechanical stress (24%); 47% of the reports could not be attributed to any specific cause. A total of 47% of failures noted in the reports were detected during operation of the cable (all affected operation); 35% were detected during surveillance testing.

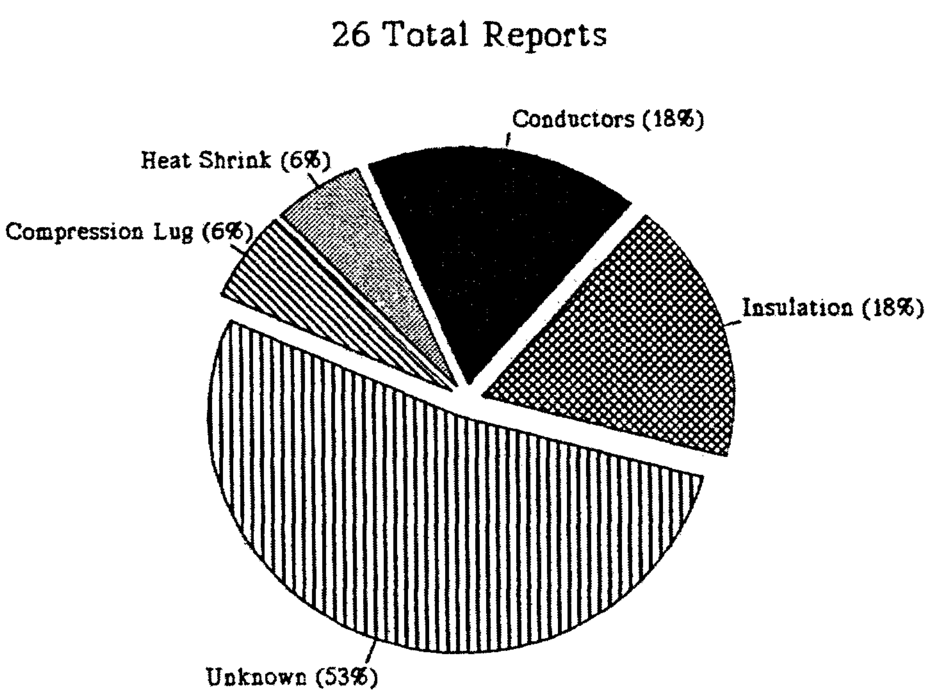

Figure 3-8 NPRDS Failure Data for Low-Voltage Splice Insulation

3.7.2.2 Medium-Voltage Systems

3.7.2.2.1 Medium-Voltage Component Failure Analysis

A total of 41 events from 12 different nuclear units were recorded for medium-voltage cable and terminations. Of these 41 events, 6 were considered maintenance-induced and were discounted from further analysis. Figure 3-9 presents a graphic representation of the failure data compiled for the remaining 35 reports, and shows that cable failures constituted the highest single percentage (24 reports/69%), followed by splices (17%), and connectors (11%). The low number of total reports is consistent with the relatively small fraction of plant cable systems operating at medium-voltage levels. Due to the small amount of data, no inferences regarding medium-voltage component reliability can be drawn.

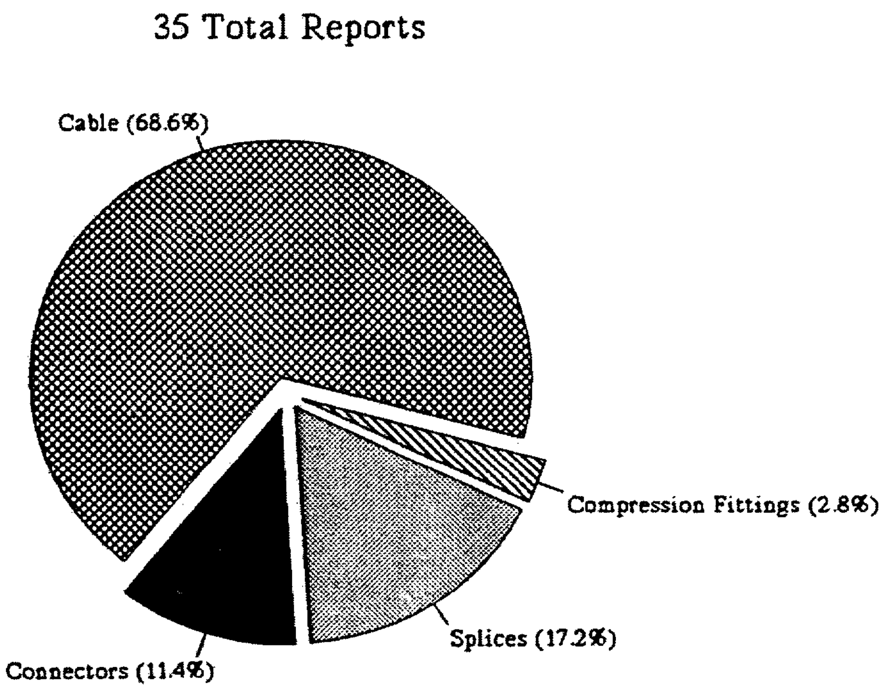

Figure 3-9 NPRDS Failure Data for Medium-Voltage Components

3.7.2.2.2 Medium-Voltage Cables

Of the 26 failure reports covering medium-voltage field cable, 2 were considered maintenance-induced and were discounted from further analysis. The most prevalent failed subcomponent was insulation (92%). The single most common failure mode for cable was a short circuit or grounding (62% of the 24 applicable reports), followed by cutting, breaking, or cracking of the insulation (21%); 54% of the failure reports could not be attributed to any specific cause.

The majority of failures noted in the reports (70%) were detected during operation of the cable. Two failures were detected during maintenance, and none during surveillance. Of the failures detected during operation, 79% affected the required function of the equipment; the remaining 21% had no effect on the circuit's required function.

3.7.2.2.3 Medium-Voltage Splices

Six failure reports were applicable to cable splices. Insulation failure accounted for all six reports. All six reports included shorting to ground as the failure mode. The failure cause and method of detection showed no significant trend.

3.7.2.2.4 Medium-Voltage Compression and Fusion Fittings

Five failure reports were applicable to medium-voltage compression and fusion fittings, four of which were maintenance-induced. The remaining failure resulted from breakage of the fitting due to mechanical stress, and was detected during operation.

3.7.2.2.5 Medium-Voltage Connectors

Four failure reports were applicable to medium-voltage connectors, which appear to be rarely used in nuclear plant applications. None was considered maintenance-induced. No subcomponent failure was prevalent. Broken or loose subcomponents accounted for three of the four failures, which were each detected during operation.

3.7.2.3 Neutron Monitoring Systems

Neutron monitoring systems (including source, intermediate, and power range monitors) were separated into their own category based on (1) their substantial differences with typical low- and medium-voltage power, control, and instrumentation circuits, and (2) the relatively large number of reports related to these devices and identified in the database.

Neutron detectors are frequently energized at what is commonly referred to as "high" voltage, usually between 1 kV and 5 kV. This is not high voltage in the sense of power transmission voltage, but rather elevated with respect to other portions of the detecting circuit. The non-detector portions of typical neutron monitoring equipment operate at lower voltages and reports relating to these devices were included with the low-voltage equipment described in previous sections. Failure reports relating to the 1 kV to 5 kV neutron detectors are described in the following paragraphs.

3.7.2.3.1 Component Failure Analysis

A total of 443 events from more than 30 different nuclear units were recorded for cable and terminations associated with neutron detectors. Of these 443 events, 55 were considered maintenance-induced and were excluded from further consideration. Of the remaining 388 reports, connector failures constituted the highest single percentage of failures (321 reports/83%), followed by cable (67 reports/17%).

3.7.2.3.2 Neutron Monitor Connectors

Of the 374 failure reports covering neutron monitor circuit connectors, 53 were considered maintenance-induced and excluded from further consideration. The most prevalent failed subcomponents include contacts/pins (19%) and hardware associated with the connector (8%); 66% of the failures did not identify the failed subcomponent.

The single most common failure mode for connectors was high resistance/open circuit (47% of all reports), followed by bent or deformed components (17%) and shorting to ground (15%). Ten percent of the reports listed no failure mode.

Significant failure causes included oxidation/corrosion/contamination (34%), unrelated work in the immediate area (15%), and moisture intrusion (13%); 24% of the reports could not be attributed to any specific cause. It should be noted that an apparently large percentage[16] of the reports associated with connectors involved those located under or in proximity to the reactor pressure vessel; this is consistent with the characteristically severe thermal and radiation environment, relatively high level of moisture, and limited space available in these areas.

The majority of failures noted (63%) were detected during operation; all of these failures affected circuit or equipment functionality; 14% and 15% of the total number of reports were detected during surveillance testing and maintenance, respectively. See Figure 3-10.

321 Total Reports

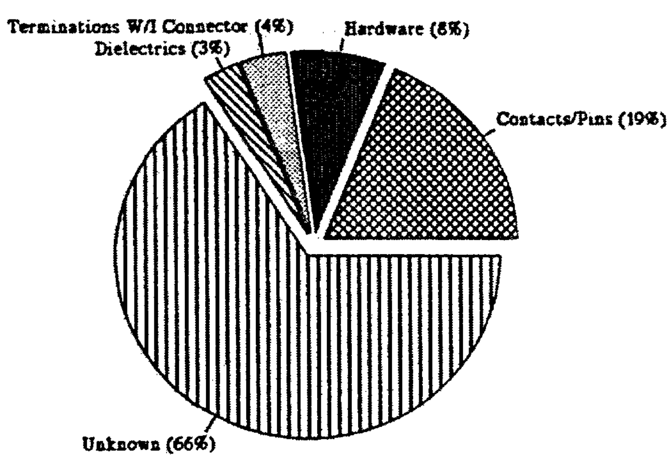

Figure 3-10 NPRDS Failure Data for Neutron Monitor Connectors

[16] No numerical data regarding locations of failed connectors were recorded during this study.

3.7.2.3.3 Neutron Monitor Cables

Of the 69 failure reports covering neutron monitor cables, 2 were considered maintenance-induced and were excluded from further consideration. The most prevalent failed subcomponents included insulation (83%) and conductors (9%).

The single most common failure mode for cable was a short to ground (61%), followed by damaged or overheated insulation (18%). Six of the 67 reports (9%) listed an unidentified failure mode. The most significant cause of failure was exposure to high temperature (18%); 55% of the reports could not be attributed to any specific cause. Thirty percent of the failures noted in the reports were detected during operation of the cable; all affected the required function of the equipment. The method of detection could not be ascertained for 45% of the reports. See Figure 3-11.

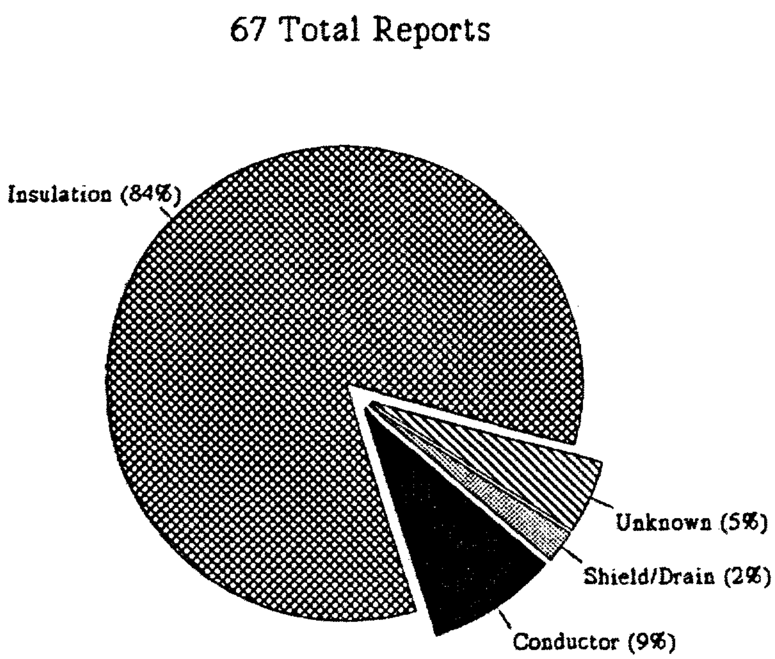

Figure 3-11 NPRDS Failure Data for Neutron Monitor Cables

3.7.2.4 Conclusions from NPRDS Review

Low-Voltage Systems

1. Hookup and panel wire and electrical connectors constituted the highest percentage of the total failures noted (each roughly one-third of all low-voltage reports). In contrast, splices and terminal blocks each constituted a very small percentage of the total failures noted, indicating a comparatively low failure and/or use rate. Cable and compression/fusion fittings fell roughly between the two groups.

2. The most significant failure mode for cable and wire collectively was a short to ground (approximately half of all cable and wire failures). It can be inferred that these failures are the result of failure of the dielectric (insulation). Open circuiting/high resistance was the second most common mode (roughly one-third of all cable and wire reports), indicating degradation or breakage of the conductor(s). High temperature aging and mechanical stresses (such as vibration or tensile stress) were cited most often as the primary causes for both cable and wire failures.

3. The most common failure mode for low-voltage electrical connectors (approximately half of the connector-related reports) was high electrical resistance/open-circuiting. Oxidation, corrosion, and dirt buildup on contact surfaces were the most common causes of failure (44%).

4. The most common failure mode for low-voltage compression/fusion fittings was loosening or breakage (71%), and was most often caused by mechanical stress or oxidation/corrosion.

5. Roughly two-thirds of all low-voltage cable and termination failures noted were detected during operation, and affected the functionality of the circuit/connected load. Percentages of such failures ranged from 47% for splices to 68% for connectors, thereby indicating some degree of consistency between components. Surveillance testing and maintenance were the next most common methods of detection, respectively, accounting for roughly 20% of all reports collectively. Hence, surveillance testing and maintenance activities may identify only a fraction of incipient low-voltage cable system component failures or instances of degradation. However, the significance of this conclusion must be considered in light of the overall failure rate of these systems; see Section 5.4.2 for additional information.

6. Hookup and panel wire failures had the highest incidence of maintenance-induced failure (31% of all reports noted); hence, roughly one-third of all wiring failures are the result of causes that are not related to aging. This was significantly higher than that for any other component in any voltage range (next highest was low-voltage compression fittings at 20%).

Medium-Voltage Systems

1. Cable failures constituted the highest percentage of the total failures noted for medium-voltage systems, roughly two-thirds of all reports. Splices and connectors each constituted substantially smaller percentages. (Note: The overall number of reports applicable to medium-voltage systems was very low, 35 in total.) Insulation was the most common failed subcomponent (92%), with the most significant failure mode being shorting to ground (approximately two-thirds of all medium-voltage cable failures).

2. Insulation failure resulting in shorting to ground was noted for all six reports pertaining to medium-voltage splices. Therefore, although the failure rate of these devices appears comparatively low, there is seeming commonality in their mode of failure.

Neutron Monitoring Systems

1. Connectors were by far the most problematic component, comprising more than four-fifths of all failures in this category. The most common failed subcomponent was contacts/pins, and the most common failure mode was high electrical resistance/open circuiting. Oxidation, corrosion, and dirt buildup were the most common cause of failure.

2. Although not as significant as that for connectors, failure of the cabling associated with detectors was noted. Shorting of the cable from damaged insulation resulting from exposure to heat and possibly radiation or mechanical stress was most common. This result is consistent with the type of environment in which these systems typically operate (i.e., within the drywell near the reactor pressure vessel, and subject to periodic motion during operation).

3.7.3 Evaluation of LER Data

NRC Licensee Event Reports (LERs) are another source of cable and termination failure and degradation data. LERs are issued by nuclear plant operators when equipment failures and plant operating events meet the reporting requirements specified in 10CFR50.73. As with NPRDS data, LERs do not directly record data related to component aging. In addition, the criteria for issuance of an LER do not encompass all component failures (especially those of little or no consequence to plant safety). Hence, evaluation of LER data provides only a partial picture of failure information; accordingly, the data may or may not be representative of general equipment failure behavior. LER data can be used, however, as support for the findings derived from other data sources (such as NPRDS and industry studies), as well as for verification of postulated aging mechanisms.

The LERs used in this analysis covered the period from early 1980 through April 1994. The abstracts of 2536 LERs were identified through a keyword search of the LER database maintained by Oak Ridge National Laboratory. The reports generated by this search were individually reviewed; in cases where the applicability of a given report to a topic could not be

reliably determined, the report was discarded. Of the 2536 reports reviewed, 640 (25.2%) were ultimately retained as being applicable to electrical cable and terminations of the type considered by this AMG; 16 of the reports were considered maintenance-induced and not analyzed further. The remaining 624 reports were then categorized by voltage range (low, medium, or neutron monitoring, to be consistent with the NPRDS data), component, subcomponent, failure mode, failure cause, and method of detection. Categorization by manufacturer was not practical due to the nearly complete lack of information on component manufacturer.

Of the total 624 applicable reports, 344 (55.1%) were related to connector failures, 136 (21.8%) were related to cable failures, and 88 (14.1%) were related to failures of wire. The remaining 9% were distributed among terminal blocks, splices, and compression/fusion fittings. For all components and voltage ranges, the great majority of failures noted were detected during operation of the component, and affected its functionality. This result is somewhat expected, in that the criteria specified in 10CFR50.73 are primarily concerned with reporting of operational failures.

3.7.3.1 Low-Voltage Systems

3.7.3.1.1 Component Failure Analysis

The data contained in the LER database described 566 events related to low-voltage systems. Of these reports, 13 were maintenance-induced. The distribution of the remaining reports was: connector failures (58%), cable failures (19%), wire failures (14%), terminal blocks (4%), compression/fusion fittings (3%), and splices (2%). See Figure 3-12.

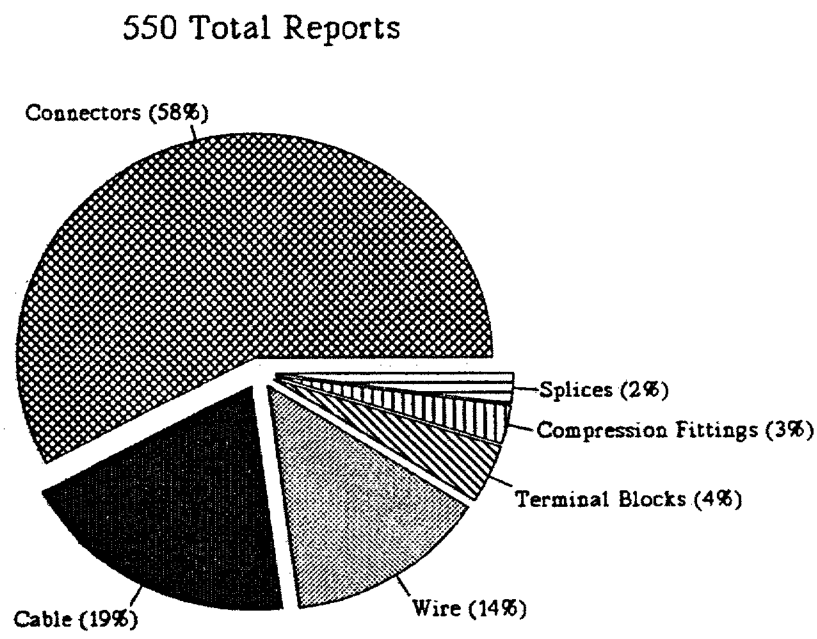

Figure 3-12 LER Failure Data for Low-Voltage Components

OAGI0000073_000073

3.7.3.1.2 Low-Voltage Connectors

Of the 323 failure reports covering electrical connectors, 7 were considered maintenance-induced and were excluded from further consideration. Most (86%) reports related to connectors did not specifically identify a failed subcomponent, and the remaining reports indicated no particular pattern. The single most common failure mode for connectors was loose or broken subcomponents (59% of all reports). Thirty percent of the 319 reports did not list a failure mode. The most significant failure cause was oxidation/corrosion/dirt (13%); 75% of the reports did not list any specific cause. The remaining failures (12%) were caused by normal aging, moisture intrusion, and mechanical stress, in roughly equal proportions.

3.7.3.1.3 Low-Voltage Cables

Of the 102 failure reports covering low-voltage cables, 1 was considered maintenance-induced. The most prevalent failed subcomponents included insulation (20%) and conductors (8%). A total of 66% of the reports had unidentified failed subcomponents. The most common failure mode for cable was a short to ground (16% of all reports), followed by loose or broken components (10%). Fifty-five percent of the reports did not list a failure mode. The most significant failure causes included moisture intrusion (10%) and corrosion of conductors (6%); 62% of the reports could not be attributed to any specific cause.

3.7.3.1.4 Hookup and Panel Wire

Eighty failure reports covered hookup and panel wire; none of the failure reports were considered maintenance-induced. Failed subcomponents included insulation (34%) and conductors (41%). A total of 18% of the reports did not identify the failed subcomponent. The single most common failure mode for hookup and panel wire was breakage (42% of all reports), followed by short circuits (40%). A total of 18% of the reports listed an unidentified failure mode. No significant failure causes could be identified; 90% of the reports could not be attributed to any specific cause.

3.7.3.1.5 Low-Voltage Compression and Fusion Fittings

Twenty-two failure reports covered low-voltage compression fittings; none of the failure reports were considered maintenance-induced. The most prevalent failed subcomponent was the lug itself (89%). The single most common failure mode for compression fittings was loosening or breakage (68% of all reports). A total of 10% of the reports listed an unidentified failure mode. No significant failure causes were evident; 74% of the reports could not be attributed to any cause.

3.7.3.1.6 Low-Voltage Terminal Blocks

Of the 25 failure reports covering terminal blocks, 4 were considered maintenance-induced and were excluded from further consideration. The most prevalent failed subcomponents included insulating blocks (38%) and terminal posts/hardware (24%). The most common failure mode was broken or loose components (24% of all reports); the remaining reports (16) were

distributed among several other failure causes such that their numbers were insignificant. No significant causes of failure were identified (40% were unidentified).

3.7.3.1.7 Low-Voltage Splices

Of the 11 failure reports applicable to low-voltage cable splices, 1 was considered maintenance-induced. Conductors were cited as the failed subcomponent in 5 of the 10 reports, yet no trend in failure mode or cause of failure was detected.

3.7.3.2 Medium-Voltage Systems

The LER database contained 50 reports related to medium-voltage circuits. A total of 52% of these reports were related to cable, 40% to connectors, and the remainder to compression/fusion fittings and splices. See Figure 3-13.

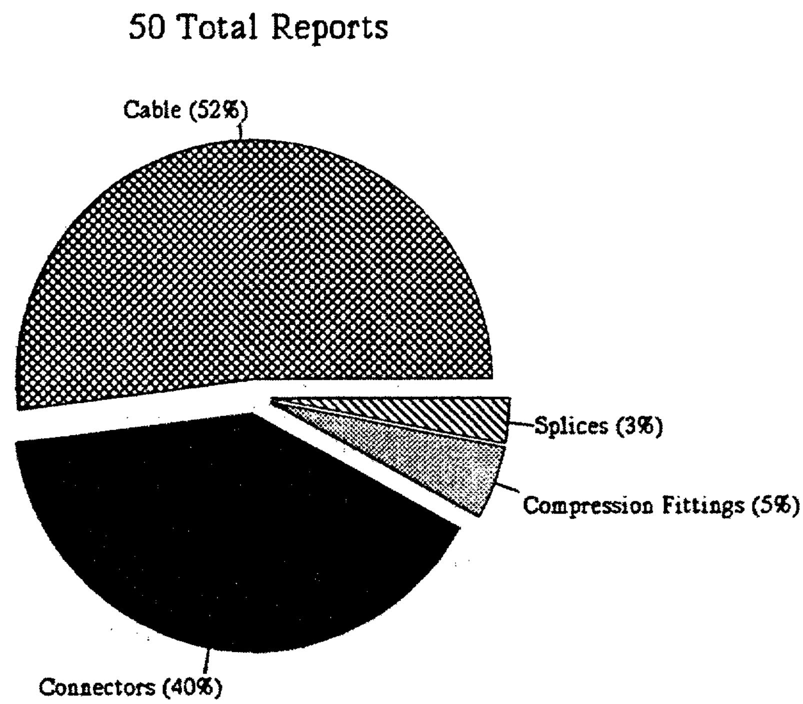

Figure 3-13 LER Failure Data for Medium-Voltage Components

3.7.3.2.1 Medium-Voltage Cables

Twenty-six failure reports covered medium-voltage cables; none of the failure reports were maintenance-induced. The most prevalent failed subcomponents were insulation (27%) and conductors (19%); 54% were unidentified. The single most common failure mode for cable was a short circuit or grounding (27% of the 26 applicable reports); 54% of the failure reports could not be attributed to any specific cause.

3.7.3.2.2 Medium-Voltage Connectors

Twenty failure reports covered medium-voltage connectors; none of the failure reports were considered maintenance-induced. Significant failed subcomponents included hardware (70%) and contacts/pins (30%). Broken or loose subcomponents accounted for 55% of the failures. The majority of medium-voltage connector reports (95%) did not identify a cause.

3.7.3.2.3 Medium-Voltage Compression and Fusion Fittings

Three failure reports covered medium-voltage compression and fusion fittings; none of the failure reports were considered maintenance-induced. These three failures resulted from loosening or breakage of the fitting due to mechanical stress.

3.7.3.2.4 Medium-Voltage Splices

Two failure reports covered medium-voltage cable splices; one of which was maintenance-induced. Insulation failure accounted for the remaining failure, which was caused by moisture intrusion.

3.7.3.3 Neutron Monitoring Systems

Of the 23 LERs covering neutron monitoring system cable and terminations, 2 were maintenance-induced. Of the remaining 21 LERs, 76% involved cables and 24% connectors. No significant failed subcomponents, failure modes, or failure causes could be identified because the majority of reports did not provide any of this information.

3.7.3.4 Conclusions from LER Review

General observations regarding cable and termination failures as described by the LER database are summarized in the following paragraphs. It should be noted that the LER data, in comparison with the NPRDS data, had less information regarding failed subcomponents, failure modes, and causes. Very high percentages of each category were listed as "unknown," thereby making meaningful observations or inferences difficult.

Low-Voltage Systems

1. Connector failures were the most prominent, accounting for more than half of the low-voltage reports. The next highest were cables, which were related to 19% of all low-

voltage failures. The most common failure mode for the connectors was loose or broken subcomponents.

2. Conductor breakage and insulation degradation (resulting in short circuit) are the most likely aging-related failures to occur in hookup and panel wiring.

3. Loosening or breakage of the lug was the most common failure for compression and fusion fittings.

Medium-Voltage Systems

1. Medium-voltage cable and connector failures were most common. Due to the comparatively low number of reports for both components (26 and 20, respectively) and the lack of detailed information, no real inferences regarding subcomponent, mode, or cause can be postulated.

Neutron Monitoring

1. Cables (as opposed to the connectors reflected in the NPRDS data) appeared to result in the most failures associated with neutron monitoring systems (roughly three-fourths).

3.7.4 Studies Providing Industry-Wide Operating Experience for Low- and Medium-Voltage Electrical Cable and Terminations

The following industry reports were reviewed for relevant operating history and other insights related to cable and termination aging:

- EPRI TR-103834-P1-2, "Effects of Moisture on the Life of Power Plant Cables" [3.24]

- EPRI NP-5002, "LWR Plant Life Extension" [3.25]

- NUREG/CR-3122, "Potentially Damaging Failure Modes of High- and Medium-Voltage Electrical Equipment" [3.26]

- EPRI TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report" [3.27]

- NUREG/CR-5461, SAND89-2369, "Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants" [3.28]

- EPRI EL-3501, "Characterization of Failed Solid-Dielectric Cables: Phase I" [3.29] and EPRI EL-5387, "Characterization of Failed Solid-Dielectric Cables: Phase II" [3.30]

- EPRI NMAC NP-7485, "Power Plant Practices to Ensure Cable Operability" [3.7]

The reports are discussed individually in the following paragraphs.

EPRI TR-103834-P1-2, "Effects of Moisture on the Life of Power Plant Cables" [3.24]

Concerns have been expressed that medium- and low-voltage cables may degrade more rapidly when exposed to water. Two studies were performed by EPRI. One evaluated the types of failures occurring in medium-voltage cables used in power plants to determine the types of failures and the need for a condition evaluation technique that would predict residual life. The second evaluated the available data concerning the effects of wetting and submergence of low-voltage cable to determine if further research is necessary.

Medium-Voltage Cable

Fossil and nuclear power plant operators were surveyed to determine the number and types of medium-voltage (4 to 15 kV) cable failures that have occurred and the causes of failure. Utility personnel were also asked if there is a need to develop a test for evaluating the condition and estimating the continued service life of medium-voltage in-plant cables. The types of condition evaluation techniques currently in use were also identified.

Information representing 50 plants was compiled from telephone interviews with 35 persons from 25 utilities. The surveys indicated that the bulk of the failures were related to wetting in conjunction with manufacturing defects, damage during installation, or deterioration of terminations. The survey identified only 27 failures in almost 1000 plant-years of experience. Only one plant continues to use dc high-potential testing for condition monitoring purposes, but is looking at alternative means of cable evaluation. Some plants use insulation resistance testing; some do not perform condition monitoring testing. The consensus from the survey was that there is currently insufficient interest to support development of a condition evaluation test method for medium-voltage cable used in power plants.

Low-Voltage Cable

A review of the literature and surveys of utility personnel were used to evaluate the effects of moisture on the operability and aging of low-voltage cable. The feedback from operations indicated that moisture-related failures of low-voltage cable are not occurring at any appreciable rate (see Section 3.7.3.1.2 of this guideline, which indicates approximately 10 moisture-related failures of low-voltage cable in the LER database). Only two isolated types of failure were identified. The first involved very low insulation resistance values for old natural rubber cables immersed for a long period in water-filled conduits in fossil fuel power plants. The second related to degraded noise immunity in certain instrumentation and closed circuit television circuits that resulted from periodic immersion in water at nuclear power plants. The second problem related to moisture tolerance of the jacketing system rather than to insulation capabilities.

The evaluation determined that current electrical test methods could identify the presence of moisture in insulation systems; however, the tests cannot assess the effects of moisture on cable longevity. Therefore, while water can be detected to allow it to be

removed from conduit systems, its effect is not readily assessable. The overall conclusion of the study was that moisture-related degradation is not a significant concern for general applications.

EPRI NP-5002, "LWR Plant Life Extension" [3.25]

EPRI NP-5002 provided interim results from the pilot plant life extension studies conducted at Surry Unit 1 (PWR) and Monticello (BWR). These pilot studies were initiated in 1984 to identify specific research and development needs related to plant life extension and to serve as a basis for power system aging and life extension guidelines for the nuclear industry. The study considered many different plant components, including electrical cable located inside primary containment. The evaluation of the Surry containment cable assessed the impact of (1) low-voltage power, control, and instrumentation cable; (2) medium-voltage power cable; and (3) thermocouple extension cable on the possibility of extended life operation for Surry Unit 1. The cable insulation materials evaluated included EPR, XLPE, and silicone rubber. The findings and conclusions of the study are as follows:

- Based on Arrhenius analysis of organic materials used in the insulation of these cables, a 60- to 80-year life is achievable with an insulation operating temperature of 50 to 75°C (122 to 167°F).
- EQ instrument cable was originally qualified for 40 years based on an ambient temperature of 55°C (131°F); requalification would be required for life extension.
- Where accessible, cables inside containment should be visually inspected at regular intervals to (1) identify signs of bulk insulation degradation and (2) to help ensure that localized high temperature degradation is not occurring.
- Termination and connector capability should be further evaluated.
- The effects of jacket aging on instrument cable shield and connected load performance should be further evaluated.
- A more detailed evaluation of cable for life extension should be made.

The study identified several aging mechanisms for cable insulation and conductors, including thermal and radiation aging, voltage stress of medium-voltage power cables, moisture intrusion, and long-term mechanical (tensile) stress. In addition, the study recommended the following monitoring requirements:

- Comparison of the performance capability of the cables with the actual in-plant environments over the entire cable length
- Regular measurement and recording of ambient air temperatures within various portions of the containment
- Performance of radiation surveys for background radiation levels

- Development of current loading history for power cables
- Consideration of replacement of cables that have a history of being moved or flexed

NUREG/CR-3122, "Potentially Damaging Failure Modes of High- and Medium-Voltage Electrical Equipment" [3.26]

NUREG/CR-3122 considers the effects and circumstances surrounding electrical faults of cables, connectors, and other electrical components used in both nuclear and nonnuclear facilities. The scope was limited to equipment with voltage ratings of 4100 Vac and above. As part of the study, several sources of failure information were consulted. The Nuclear Safety Information Center (NSIC) database was searched for applicable reports, and the study also examined proceedings from the Doble Clients Annual Conference (an industry forum for issues and technology related to electrical components) for pertinent data. Plant visits and interviews were also used.[17]

The study concludes that cables and connectors will have a predictably long service life if properly installed and not subject to mechanical forces, moisture, or excessive temperatures. This lifetime is generally dictated by the aging of the insulation; failures of cable appear random and generally affect only segments of a cable run. Cables located in open trays may affect other cables through movement or heating.

EPRI TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report" [3.27]

This report (commonly referred to as "the Cable Industry Report") assessed the viability of low-voltage (i.e., less than 1000 V) environmentally qualified cable for license renewal. Splices to loads, panel or switchboard wire, connectors, terminal blocks, and component leads were not included in the scope; digital circuit cables, Kapton® leads, and butyl rubber-insulated cable were also not included due to their unique design attributes or specialized applications. Specifically excluded from consideration were degradations due to (1) design nonconformances, (2) unintended long-term submergence, (3) unintended chemical exposure, and (4) improper maintenance. The report indicates that plant-specific evaluations are required to assess the relevance of the devices, their degradations, and other aspects of the report.

The general methodology of this report was similar to that of this AMG, in that relevant components and their service/operating history were described, significant aging mechanisms were identified, and in cases where current acceptable programs could not be shown to effectively manage these mechanisms, options for managing component aging were discussed. An aging mechanism was considered significant if, when allowed to continue without any additional preventive measures, the continued functionality of the component could not be demonstrated. To determine relevant operating history, both LERs and NRC documentation (Information Notices) were examined. LERs affecting cable both

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[17] Doble Clients information is a proprietary source of information, and was therefore not available for use in this guideline.

inside and outside of containment were examined for the period 1968 to 1992. After screening out nonapplicable reports, only 87 LERs were identified. It was concluded through review of the time to detection that a large fraction of the failures occurred within the first few years of cable operation, many of which resulted from mechanical damage. The number of failures decreased significantly after 10 years, with no indications of significant long-term degradation or age-related failure. The report provided the following overall conclusions:

- Changes in insulation electrical properties, conductor/shield corrosion, loss of fire retardants, corona breakdown, and water treeing were not significant aging mechanisms for low-voltage cable.
- Embrittlement of jacket materials was not significant under certain circumstances.[18]
- Embrittlement of insulation is a significant aging mechanism for low-voltage EQ cable.
- All significant component/aging mechanism combinations were addressed by current programs (e.g., EQ and maintenance programs).

NUREG/CR-5461, SAND89-2369, "Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants" [3.28]

This Sandia report examined the aging of cables and terminations; specifically, equipment design and materials were characterized, aging mechanisms and stressors identified, and current industry maintenance and testing practices were described. This study also analyzed LERs from mid-1980 through 1988 related to the aging or accident survivability of cables. Cables installed both inside and outside containment were included. The study demonstrated that the number of LERs for cable and connections is very small considering the number of plants and the number of circuits/connections in the typical plant.

The LER search located a total of 151 reports applicable to "cable" and 196 events related to "connections." These tallies are assumed to include cable and connections from all voltage ranges. More than half of the cable-related reports involved electrical faults (shorting or grounding), whereas 13% were the result of open circuits. One quarter of the reports (38 of the 151 total) were attributed to design errors. Forty-two percent involved cable located inside containment, whereas 58% involved cables located outside containment.

For connections, 32% were attributed to loose connections, 28% to "bad" connections (the term "bad" being used when the type of connection failure was not specified), and 8% to shorted connections. Twenty-two percent were design related. Almost two-thirds of the failures were outside containment.

[18] These circumstances include (1) instances where the jacket is not bonded to the insulation (see Section 3.7.1 of this guideline), (2) instances where the jacket is not required to provide beta radiation shielding to demonstrate environmental qualification in accordance with 10CFR50.49, (3) electrical shield isolation is not important, and (4) the jacket's physical integrity is not necessary for qualification of cable connectors or splices.

The NUREG/CR-5461 cable failure rates covering a period of 8 years compare very favorably with 14 years of LER results summarized in Section 3.7.3 of this AMG. The results for connections show somewhat more disparity, which can be attributed to some differences in scope, as well as differences in method of categorization (i.e., many reports attributed to "loose connections" in NUREG/CR-5461 would be attributed to wiring, cable, or connector components in this AMG). Overall, however, both results indicate a very low rate of failure relative to the number of devices in operation during the period(s) of coverage. (See also Reference [3.31], which summarizes the findings of NUREG/CR-5461.)

EPRI EL-3501, "Characterization of Failed Solid-Dielectric Cables: Phase I" [3.29] and EPRI EL-5387, "Characterization of Failed Solid-Dielectric Cables: Phase II" [3.30]

The principal objective of this program was to identify and verify factors that affect the longevity of XLPE- and high molecular weight polyethylene (HMWPE-) insulated underground medium-voltage cables. This objective was accomplished in two discrete phases. Phase I consisted of the collection of data and relevant information on medium-voltage cable insulation failures from a group of 15 individual plant operators. This information was loaded into a database to facilitate statistical analysis of potential "predictor" variables for insulation failure. Findings of this analysis indicated that some statistically significant predictors were identified (namely, operating voltage stress, volatiles, and the presence of halos [microvoid-containing volatiles]), with a higher level of statistical significance for HMWPE than for XLPE. Phase II used actual service-aged HMWPE- and XLPE-insulated cable samples provided by various U.S. utilities to test the hypotheses formulated in Phase I. Results of this phase showed some consistency with the Phase I findings; perhaps the most significant finding is that the combination of greater age and thinner insulation walls would produce a higher failure rate. Also, the presence of peroxides and peroxide decomposition products was found to have some correlation with the electrical integrity of the insulation.

EPRI NMAC NP-7485, "Power Plant Practices to Ensure Cable Operability" [3.7]

This report evaluated the operability criteria for nuclear plant cables, as well as cable maintenance, surveillance, and installation practices. As part of this evaluation (Section 7.0), data from the NRC's Nuclear Plant Aging Research (NPAR) program (LERs through February 1984) were examined. The study concluded that failures during operation of cable are rare, and that most failures are the result of physical damage during or after installation, or poorly made terminations. The study also cites a search conducted by Duke Power of the NPRDS database which indicated that the cable failures noted were related primarily to installation errors, termination problems, or misapplication.

In addition, a number of experts (including cable manufacturers, utility personnel, and government/university researchers) were interviewed in order to identify aging mechanisms of low-voltage cable. The consistent result from these interviews was that low-voltage cable as a whole has experienced a very low failure rate, and that failures are primarily the result of external environments outside design limits. Medium-voltage cables are subjected to elevated electrical stress by virtue of their operating voltage, and small imperfections in

the insulation may result in cable failures; however, the overall failure rate of medium-voltage cable has been low as well.

3.7.5 Host Utility Operating Experience and Plant Surveys

As part of the development of this AMG, information relating to cable systems was obtained from "host" utilities through interviews with plant maintenance and supervisory personnel and review of plant documents and records. There were three host utilities for this study, whose units included mid-1970s PWRs, mid-1980s PWRs, and mid-1980s BWRs. Some of the more notable instances of cable and termination degradation occurring at these host facilities are discussed in the following paragraphs. These discussions are not intended to comprehensively recount all cable-related degradation or failures occurring at the host plant; to the contrary, no effort was made to determine the total numbers of failures of each type. Rather, the intent was to validate observations noted in the analysis of the NPRDS and LER data,[19] as well as the aging mechanisms and effects discussed in Section 4.

In general, the plants interviewed indicated that the single most common type of aging observed was thermal embrittlement of organic cable and termination materials, especially near hot end devices and/or in high ambient temperature spaces.[20] Some primarily radiation-induced effects (such as embrittlement and/or swelling of neutron detector cables in close proximity to the reactor pressure vessel) were noted at some plants; however, comparatively few effects attributable to radiation were identified. These observations appear to be in agreement with the NPRDS and LER data discussed above, which cite shorting to ground due to insulation degradation as the most common low-voltage failure mode (NPRDS and LERS), and high temperature exposure and mechanical stress as the most frequently listed failure causes (NPRDS). Note also that instances of low-voltage cable and wire shorting to ground induced by moisture (as indicated by the LERs) may, in fact, be due to moisture intrusion through preexisting cracking, an effect of thermal and/or radiation exposure. In some regard, more confidence can be placed in the host plant observations for identifying relevant root causes because a very large percentage of both NPRDS reports and LERs describe no failure cause and/or mode.

Host Utility No. 1 (Mid-1980s BWRs)

Thermal Aging of Low-Voltage Steam Tunnel Cable

Cable runs located at various elevations in steam tunnel spaces were thermally aged according to (1) their elevation in the space and (2) their proximity to steam piping. Some thermal stratification within the space was evident for cables not located near steam piping; cables at low elevations showed less aging than similar runs at high elevations. Cables located in trays in proximity to steam piping showed degradation and embrittlement according to radiant energy patterns (i.e., some cables were partially shielded by the trays and other cables). In

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[19] Very few of the NPRDS reports or LERs discussed the mode and cause of a given failure with sufficient specificity to validate the existence of some of the aging mechanisms hypothesized in Section 4. For example, no instances of UV radiation degradation of nuclear plant cables were found in the data.

[20] Few instances of observed degradation on high-ampacity circuits were noted.

some cases, two cables in the same tray showed dramatically different levels of aging (based on visual and physical inspection), depending on their position in the tray. No failures of the affected cable have occurred to date. This type of aging represents a significant exception to the general observation that localized thermal aging occurs primarily at the end device.

Ultraviolet Degradation of Polyethylene-Insulated Cable

Instrumentation cables located in close proximity to fluorescent indoor lighting have developed spontaneous circumferential cracks in exposed portions of the insulation. These cables are insulated with polyethylene and have a light-colored (white) appearance. The cracking is believed to be due to the emission of ultraviolet (UV) radiation from the lighting, which is known to degrade materials that are not UV-stabilized. Similar cables with insulation of different colors exposed to the same environment showed no signs of such cracking. For some of the affected cables, the cracking was severe enough to expose the underlying conductor. However, no operational failures were documented as a result of this degradation.

Host Utility No. 2 (Mid-1980s PWRs)

Failure of 12-kV Circulating Water Pump Cable

Two failures of cables used to supply power to a circulating water pump have occurred. The cables supplying the motor were EPR insulated, Neoprene® jacketed with two extruded semiconducting layers, one taped semiconducting layer, and a copper tape shield. The Neoprene® jackets of some of the affected cables had softened and completely dissolved due to (1) the operating temperature of the cable, (2) foreign chemical substances (fatty acids and ethyl ester compounds) in a nearby sump that inadvertently drained into the cable ducting, and (3) the presence of salt (chlorides) from ocean water spray in the sump. Once the integrity of the jackets was lost, the salt/chemical solution rapidly corroded the copper tape shield; the cables eventually suffered a single-point failure of the EPR insulation. The exact cause of the EPR failure was unknown; subsequent investigation yielded no indication of cable damage during installation.

Host Utility No. 3 (Mid-1970s PWRs)

Aluminum Termination Failures

Cracking of the tang to barrel connections on Thomas and Betts aluminum terminal lugs used on 10 AWG and larger cables has been observed. This cracking appears to have occurred primarily on large machines where frequent maintenance involving the termination occurred. Very few actual circuit failures have occurred as a result of this problem. At present, only copper lugs are being used by the plant, with the aluminum lugs being replaced as a standard maintenance activity.

Tape Splice Failures

Several splice failures also occurred at this host plant as a result of use of a specific tape product in fabrication of 480-V and 4-kV tape splices. These failures were the result of creeping and loss of overlap of the tape, thereby reducing the dielectric strength of the insulation systems and resulting in shorting. Once the problematic tape was identified, its use was discontinued and the failures ceased.

Plant Surveys

A limited number of mail surveys were received from operating plants (other than host utilities) as part of the study; these surveys requested information on the types of cables/terminations installed, common maintenance activities, and types/relative quantities of aging degradation being experienced. No effort was made to determine the number of a given type of failure for each plant, as this was felt to be more accurately characterized by the other failure data (such as NPRDS and LERs).

In general, the surveys showed results which were consistent with the information obtained from NPRDS, LERs, EPRI NUS database, and the host utilities. Thermal damage appeared to be the most significant aging effect; several instances of heat damage [to source range monitor (SRM)/intermediate range monitor (IRM) cables on BWRs, as well as localized degradation of main steam isolation valves (MSIV) and safety/relief (SRV)] were noted. Loosening and breakage of low-voltage compression fitting lugs were also listed in several cases. One plant reported overheating and failure of residual heat removal (RHR) motor lead lugs due to improper crimping/filling of the oversized lugs. One plant noted two failures of circulating water pump motor cables resulting from improper manufacturing (insulation compounding); no operational failures of medium-voltage cable due to water treeing were identified.

3.7.6 Overall Conclusions Regarding Historical Performance of Equipment

Six primary sources of information were used in this AMG to characterize the historical performance of electrical cables and terminations, namely,

- NRC Information Notices, Bulletins, Circulars, and Generic Letters
- NPRDS data
- LER data
- Industry information provided by previous analyses and reports
- Information obtained from operating nuclear plants acting as host utilities
- Plant surveys

These sources each provide a somewhat different perspective on aging of cables and terminations. Several limitations are inherent in any comparison of these results, stemming primarily from the variations in equipment types within the population, the differing scope of equipment included, classification of failures, and criteria used in the analysis. Accordingly, no statistical inferences (such as mean-time-between-failure) can be drawn concerning component failure probability or rate. Despite these limitations, the following generic observations were made:

1. The number of cable and termination failures during normal operating conditions (all voltage classes) that have occurred throughout the industry is extremely low in proportion to the amount of cables and terminations (see Section 5.4.2 for analysis of cable and termination failure rates by class based on NPRDS data).

2. Thermal aging and embrittlement of insulation is one of the most significant aging mechanisms for low-voltage cable, based on (a) the large percentage of low-voltage cable reports (both NPRDS and LER) that are attributable to insulation degradation and shorting,[21] (b) the conclusions of other industry studies, and (c) information obtained from host utilities/surveys. Mechanical stress (including vibration, bending of wire and manipulation, etc.) was also frequently cited as a cause for failure. As evidenced from discussions with host utilities (and, to some degree, the empirical data, for which no formal analysis of failure location was conducted), these aging mechanisms occur predominantly near the end devices or connected loads. Thermal aging results largely from localized hotspots; aging due to ambient environment or ohmic heating may also be present.

3. As evidenced in all of the data sources examined, localized radiolytic degradation affects low-voltage cables and terminations (as a whole) to a lesser degree. This is consistent with (a) the comparatively low percentage of the total circuit population that is installed in high-dose spaces and (b) the high radiation damage thresholds of most component materials in comparison to typical plant TIDs (see Section 4.1). Degradation resulting from exposure to external chemical substances appears to occur very infrequently.

4. Localized thermal, radiolytic, and incidental mechanical damage appear to be the most significant aging mechanisms for cables located near the reactor pressure vessel, especially neutron monitor circuits.

5. Connector failures constitute a large percentage of all failures noted for low-voltage (30% for NPRDS, 58% for LERs) and neutron monitoring systems (83% for NPRDS, 24% for LERs). A large percentage of these failures can be attributed to oxidized, corroded, or dirty contact surfaces.

6. Failures of hookup or panel wire constitute a substantial percentage (36% for NPRDS, and 14% for LERs) of the total number of low-voltage circuit component failures. A large fraction of these failures are not the result of aging influences, but rather stem from design, installation, maintenance, modification, or testing activities.

[21] Only 18% of the NPRDS reports for low-voltage cable were attributable to thermal stress; however, this was the single most significant cause, and nearly half (49%) of the total number of reports did not identify a cause. Assuming that the same proportion (18/51) of these unidentified failures is due to thermal stressors, about 36% of all NPRDS low-voltage cable failure reports can be attributed to thermal degradation. In addition, even severely embrittled and cracked low-voltage cable may operate without failure in certain environments; introduction of other stressors after such degradation has occurred (such as moisture during operations or LOCA) may ultimately induce the failure.

7. Wetting concurrent with operating voltage stress appears to produce significant aging effects on medium-voltage power cable.

8. Loosening and breakage of lugs are the most significant compression fitting failures by a wide margin, based on both NPRDS and LER data.

9. Damage to cable insulation during or prior to installation may be crucial to a cable's longevity, particularly for medium-voltage systems.

3.8 References

3.1 IEEE Standard 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," The Institute of Electrical and Electronics Engineers, Inc., corrected copy June 1976.

3.2 NRC IE Bulletin 79-01B, "Guidelines for Evaluating Environmental Qualification of Class 1E Electrical Equipment in Operating Reactors," Enclosure 4 to "Environmental Qualification of Class 1E Equipment," Nuclear Regulatory Commission, January 14, 1980 (in practice, referred to as the DOR Guidelines).

3.3 NUREG-0588, "Interim Staff Position on Environmental Qualification of Safety-Related Equipment Including Staff Responses of Public Comments, Resolution of Generic Technical Activity A-24," Nuclear Regulatory Commission, Rev. 1, July 1981.

3.4 Title 10, U.S. Code of Federal Regulations, Part 50.49, "Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants," (10CFR50.49), published in the Federal Register, Vol. 48, No. 15, January 21, 1983 (pages 2730 to 2734).

3.5 Title 10, U.S. Code of Federal Regulations, Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," published in the Federal Register, Vol. 60, May 8, 1995 (page 22461).

3.6 EPRI EL-5036, "Wire and Cable," Power Plant Electrical Reference Series, Vol. 4, Electric Power Research Institute, 1987.

3.7 EPRI NP-7485, "Power Plant Practices to Ensure Cable Operability," Nuclear Maintenance Applications Center, Electric Power Research Institute, July 1992.

3.8 NRC Information Notice 87-52, "Insulation Breakdown of Silicone Rubber-Insulated Single Conductor Cables During High Potential Testing," Nuclear Regulatory Commission, October 1987.

3.9 NRC Information Notice 86-71, "Recent Identified Problems with Limitorque Motor Operators," Nuclear Regulatory Commission, August 1986.

3.10 NRC Information Notice 93-33, "Potential Deficiency of Certain Class 1E Instrumentation and Control Cables," Nuclear Regulatory Commission, April 28, 1993.

3.11 NRC Information Notice 92-81, "Potential Deficiency of Electrical Cables with Bonded Hypalon Jackets," Nuclear Regulatory Commission, December 11, 1992.

3.12 NUREG/CR-5772, "Aging, Condition Monitoring, and Loss-of Coolant Accident (LOCA) Tests of Class 1E Electrical Cables" (in three volumes: Vol. 1, "Crosslinked Polyolefin Cables;" Vol. 2, "Ethylene Propylene Rubber Cables;" Vol. 3, "Miscellaneous Cable Types"), Sandia National Laboratories, August 1992, November 1992, and November 1992.

3.13 NUREG/CR-6095, SAND93-1803, "Aging, Loss-of-Coolant Accident

(LOCA), and High Potential Testing of Damaged Cables," prepared by SEA Inc., and Sandia National Laboratories, April 1994.

3.14 EPRI NP-7189, "Review of Polyimide Insulated Wire in Nuclear Power Plants," Electric Power Research Institute, February 1991.

3.15 NRC Information Notice 88-89, "Degradation of Kapton Electrical Insulation," Nuclear Regulatory Commission, November 1988.

3.16 NUREG/CR-2157, "Occurrence and Implications of Radiation Dose-Rate Effects for Material Aging Studies," prepared by Sandia National Laboratories, June 1981.

3.17 NUREG/CR-4301, SAND85-1309, "Status Report on Equipment Qualification Issues Research and Resolution," prepared by Sandia National Laboratories, November 1986.

3.18 NRC Information Notice 92-01, "Cable Damage Caused by Inadequate Cable Installation Procedures and Controls," Nuclear Regulatory Commission, January 1992.

3.19 NRC Information Notice 89-30, "Excessive Drywell Temperatures," Nuclear Regulatory Commission, March 1989.

3.20 NRC Information Notice 86-49, "Age/Environment Induced Electrical Cable Failure," Nuclear Regulatory Commission, June 1986.

3.21 NRC Information Notice 82-03, "Environmental Tests of Electrical Terminal Blocks," Nuclear Regulatory Commission, March 4, 1982.

3.22 NRC Information Notice 80-08, "The States Company Sliding Link Electrical Terminal Block," Nuclear Regulatory Commission, March 7, 1980.

3.23 NRC IE Circular 77-06, "Effects of Hydraulic Fluid on Electrical Cables," Nuclear Regulatory Commission, April 1977.

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

3.25 EPRI NP-5002, "LWR Plant Life Extension," Interim Report, Electric Power Research Institute, January 1987.

3.26 NUREG/CR-3122, ORNL/NSIC-213, "Potentially Damaging Failure Modes of High- and Medium-Voltage Electrical Equipment," prepared by Oak Ridge National Laboratory, August 1983.

3.27 EPRI TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report," prepared by Sandia National Laboratories and Strategic Technologies and Resources, Inc., Revision 1, July 1994.

3.28 NUREG/CR-5461, SAND89-2369, "Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants," prepared by Sandia National Laboratories, July 1990.

3.29 EPRI EL-3501, "Characterization of Failed Solid-Dielectric Cables: Phase I," Electric Power Research Institute, August 1984.

3.30 EPRI EL-5387, "Characterization of Failed Solid-Dielectric Cables: Phase II," Electric Power Research Institute, September 1987.

3.31 NUREG/CR-5643, "Insights Gained from Aging Research," prepared by Brookhaven National Laboratory, March 1992.

4. STRESSORS AND AGING MECHANISMS

This section describes applicable stressors and aging mechanisms, and assesses the potential significance of these mechanisms for low- and medium-voltage cables and terminations. These stressors and aging mechanisms were determined by considering the design, applications, and operating experience of the cables, along with relevant industry research, information, and reports. Guidelines or criteria are also developed to aid plant personnel in evaluating the severity of a given stressor or aging mechanism and its effects on aging of cables and termination components. If the relevant criteria are met (or, in the case of a quantitative threshold, exceeded), then the effects of the associated aging mechanism may be substantial for that component; these are referred to as "if-then" criteria. Note that the development of these criteria is separate from the determination of the significance of a given aging mechanism (Section 4.2 below); "if-then" criteria merely assist a plant operator in determining whether the environmental and operational stressors present at his/her plant are of a sufficient type and/or magnitude to result in substantial aging effects on the plant's cable systems. As discussed in Section 4.2, the significance of an aging mechanism (for the purposes of this document) centers more around whether loss of component functionality may result, and whether the loss of functionality has been observed to occur at a comparatively high frequency in relation to other aging mechanisms.

4.1 Stressors Acting on Cables and Terminations

A stressor is an "agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation of a system, structure, or component" [4.1]. Stressors result in aging mechanisms, which are "specific processes that gradually change the characteristics of a system or component with time or use" [4.1]. Stressors caused by normal operation and environmental conditions have a direct effect on the existence and progression of aging mechanisms. It is therefore important to understand the behavior of materials when subject to these various stressors in order to design and operate the component satisfactorily and to develop methods for detecting and mitigating component degradation.

The stressors that are relevant to cables, splices, connectors, compression/fusion fittings, and terminal blocks, either individually or in combination, include the following:

- Thermal
- Electrical
- Mechanical
- Radiation
- Chemical and electrochemical[1]
    - Oxygen
    - Ozone
    - Moisture/humidity
- Dirt, dust, and other contaminants

[1] Oxygen, ozone and moisture/humidity are all chemical stressors. They are listed individually because they are the most significant chemical stressors for polymers.

Although not directly producing stress, oxygen, humidity, dust, dirt, and other types of contamination may intensify the effects of other stressors acting on cable systems and related components and may result in more rapid deterioration.

It should also be noted that certain types of degradation may result only from the combination of two or more stressors. For example, voltage stress and moisture may combine to produce degradation of dielectric materials that would otherwise not occur in the presence of one stressor alone. Similarly, some stressors act to accelerate the degradation that would otherwise be experienced from another stressor; the effect of oxygen on thermal- or radiation-induced degradation is such a case. Hence, both individual stressors and their potential interactions with other stressors must be considered when evaluating the degradation potential of cable system components.

Cables are unique compared with other plant equipment in that they are distributed components, and traverse multiple plant locations and environments. Accordingly, individual sections of a given cable may age or degrade at different rates based primarily on the severity of their respective environments.

The following sections discuss the effects on cables and terminations of each stressor listed above and provide insight into the aging mechanisms applicable to each of the cable and termination components listed in Section 3 of this AMG.

4.1.1 Thermal Stressors and Aging Mechanisms

Thermal stress results from exposure of cable system components to normal and abnormal environments. Environmental influences that may induce thermal stress on a cable or associated termination may result from general area ambient temperatures, localized high temperatures (hot spots), or electrical heating resulting from current flow within the components. Elevated temperature produces some degree of aging in most organic materials. The effects of thermally induced degradation of organics may include embrittlement, cracking or crazing, discoloration, melting, and a change in the mechanical and electrical properties of the material(s) that are essential for the cable or connection to perform its design function. Thermoxidative reactions (i.e., those occurring in the presence of oxygen) are considered in Section 4.1.5.5.

4.1.1.1 Thermal Degradation of Organic Materials

Thermal energy absorbed by polymers initiates various types of chemical reactions within a polymer. Direct effects of this energy absorption include increased molecular excitation. Because organic materials are characteristically covalently bonded (electron sharing), damage to these bonds readily results from such excitation. In solid polymers, free radicals may be formed which help induce other chemical reactions, the predominant types which have important effects on mechanical properties are crosslinking and chain scission. Crosslinking refers to that process where long chain molecules typically present in polymers are covalently bonded together. Chain scission, on the contrary, is the breaking of these chains into smaller pieces. In fact, both scission and crosslinking usually occur during polymer degradation.

Each of these processes will result in some sort of effect on the macroscopic properties of the material, depending on their relative importance and the degree of reaction. Crosslinking will generally result in increased tensile strength and hardening of the material, with some loss of flexibility and eventual decrease in elongation-at-break. Note that crosslinking may be induced during the manufacturing process (chemically or via irradiation) to produce desired properties in certain materials. Scission generally produces reduced tensile strength; however, elongation may increase, decrease, or remain essentially constant, depending on the type of polymer and the level of degradation.

Other effects that may occur in polymers include crystallization and chain depolymerization, where molecules "unzip" in sequential fashion due to the free radicals at the ends of the scissioned molecule. Crystallization is often the result of exposure to high temperature or rapid heating/cooling of a material and therefore is generally not considered an aging phenomenon, although in some instances scission processes can result in enhanced crystallinity. Chain depolymerization is basically a subset of the chain scission process that occurs during normal aging to varying degrees based on the material type and aging influences.

Thermal degradation effects on cable system materials can be divided into two categories based on the longevity of exposure and the dominant physical processes: short-term and long-term. Short-term effects will typically result from relative extremes of temperature and can occur over a very brief period of exposure. Long-term effects, on the other hand, occur over a more protracted period and are commonly associated with the concept of component "aging." Each of these types of degradation is discussed in the following sections.

4.1.1.1.1 Short-Term Thermal Degradation

Exposures of organic materials to comparatively high temperatures (e.g., those well in excess of normal ambient aging temperatures or cable service ratings) may produce other types of physical or chemical processes and degradation not normally associated with low-temperature aging. For example, exposure of thermoplastics to high temperatures can result in reduced viscosity or melting, thereby allowing material deformation (flow) under mechanical stress. This situation can ultimately affect the mechanical and electrical properties of the material (including reduced thickness, electrical resistance, etc.) and produce shorts, leakage, or other undesirable effects.[2] For other materials, crystallization resulting from thermal exposure can produce substantial and irreversible changes in physical properties such as tensile strength, compression set, elongation, and viscosity as well as electrical performance [4.2]. In addition, differential thermal expansion of materials at low temperature can create substantial mechanical stress and result in cracking of certain cable or termination components. At high temperatures, thermal expansion of organic components can place significant stress on nearby components.[3]

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[2] Overcurrent testing observed by the authors on small-gauge Tefzel® (ETFE) insulated wire caused the insulation to melt and dissociate from its conductor due to the sustained high conductor temperatures during the test.

[3] For example, thermal expansion of a polymer grommet constrained inside the connector assembly of a D. G. O'Brien electrical penetration assembly caused damage to nearby components, thereby necessitating redesign. The thermal expansion was attributed to the comparatively large temperature swings experienced by the containment-side connector as primary containment temperature changed. See NRC Information Notice 81-20 for additional information.

Note that the susceptibility of each component or material to such short-term effects may depend on several factors, including the type of material, the peak temperature to which it is exposed, the duration of exposure, ambient environmental conditions (humidity, oxygen concentration, etc.), and the rate of heat input/component temperature change. A precise temperature or other criterion that differentiates long-term aging from short-term degradation may be impractical or impossible to determine for many materials. Rather, knowledge of the differences in effects of such exposures (if any) can be useful in identifying short- versus long-term degradation mechanisms. Furthermore, modeling of short-term thermal degradation by use of the Arrhenius equation (described below) is generally not valid, because the fundamental chemical and physical processes induced by the higher temperatures may be significantly different from those which occur under more typical low-temperature thermal aging. Hence, it is often difficult or impossible to assess how much of a material's lifetime has been "lost" as a result of a brief exposure to high temperature.

4.1.1.1.2 Long-Term Thermal Degradation

Long-term thermal degradation of cable system materials is controlled by the mechanisms described in Section 4.1.1.1. Multiple models describing long-term thermal degradation of organic materials have been developed, such as the Arrhenius, Eyring, and inverse power models, which are described in detail in EPRI NP-1558 [4.3]. The Arrhenius model, which provides a relationship between material lifetime and thermal stress (that is, temperature), is by far the most commonly used and recognized, and is described below.

Arrhenius Model

The Arrhenius model relates the rate of degradation (reaction) to temperature through the following exponential function [4.3]:

$$R = Ae^{(-\phi/kT)}$$

where:

R = rate at which the degradation reaction proceeds
A = frequency factor (constant for the material under evaluation)
ϕ = activation energy (eV)
k = Boltzmann's constant (8.617×10^{-5} eV/K)
T = absolute temperature (K)

The activation energy, ϕ, is a measure of the energy required to produce a given type of endothermic reaction within the material. This parameter can be correlated to the rate of degradation; that is, materials with higher activation energies will thermally degrade at a slower rate than those with lower activation energies.

A common form of the Arrhenius equation relates the degradation time for a material at one temperature to that at another temperature as follows: