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Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants

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Sandia National Laboratories
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Prepared for
U.S. Nuclear Regulatory Commission

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Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants

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Abstract

This report examines effects of aging on cables, connections, and containment electrical penetration assemblies (EPAs). Aging is defined as the cumulative effects that occur to a component with the passage of time. If unchecked, these effects can lead to a loss of function and a potential impairment of plant safety. This study includes a review of component usage in nuclear power plants; a review of some commonly used components and their materials of construction; a review of the stressors that the components might be exposed to in both normal and accident environments; a compilation and evaluation of industry failure data; a discussion of component failure modes and causes; and a brief description of current industry testing and maintenance practices.

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EXECUTIVE SUMMARY

This report examines effects of aging on cables, connections, and containment electrical penetration assemblies (EPAs). In this report, aging is defined as the cumulative effects that occur to a component with the passage of time. If unchecked, these effects can lead to a loss of function and a potential impairment of plant safety.

Cables, connections, and electrical penetration assemblies are used extensively throughout all nuclear power plants. Cables and connections are used in every electrical circuit in the plant; EPAs are included in every circuit that is inside containment.

This NRC-sponsored aging assessment of cables, connections, and penetrations is broken into two phases, defined by the standard Nuclear Plant Aging Research (NPAR) approach. The first phase consists of evaluation of usage, operating experience, current inspection and surveillance methods, and a review of applicable literature. This report details the results of Phase I. The second phase, currently planned only for cables, includes development of improved methods for inspection, surveillance, and monitoring; application of monitoring methods to naturally aged and in-situ cables; and recommendations for utilizing the research in the regulatory process.

Included in this study is a review of component usage in nuclear power plants; a review of some commonly used components and their materials of construction; a review of the stressors that the components might be exposed to in both normal and accident environments; a compilation and evaluation of industry failure data; a discussion of component failure modes and causes; a description of current industry testing and maintenance practices; and a review of some monitoring techniques that might be useful for monitoring the condition of these components.

The conclusions of the study are as follows:

a. Cables, connections, and EPAs are highly reliable devices under normal plant operating conditions, with no evidence of significant failure rate increases with aging. Consequently, they receive little or no preventative maintenance. Under accident conditions, however, the reliability of these components is relatively unknown.

b. The most safety significant aging effects are those that have the potential to lead to common cause failures during accident conditions.

c. Many of the causes of failures in accident conditions for cables, connections, and EPAs would not be detected during normal operation because of the absence of high temperatures and humidities. The most important failure mode is expected to be shorting (or reduced electrical isolation). Several different causes may result in this failure mode.

d. Plant operational experience is useful to the extent that it may indicate some possible accelerated degradation mechanisms for cables, connections, and EPAs that could lead to common cause failures under off-normal environmental conditions. However, current LER data provides a very limited database for this purpose.

e. A significant number of manufacturers have produced cables, connections, and EPAs, resulting in many different materials and construction methods. Consequently, generic assessments of aging effects and vulnerabilities become much more difficult, particularly where failure modes relate to interfacing stresses.

An NRC-sponsored experimental assessment for cables is currently under way at Sandia National Laboratories and will be documented in a future report. A Phase II assessment of cables is planned, but has not yet begun. At this time, the NRC has no plans for a Phase II effort for connections and EPAs.

1.0 INTRODUCTION

For purposes of this report, aging is defined as the cumulative effects that occur with the passage of time to a component. If unchecked, these effects can lead to a loss of function and a potential impairment of plant safety. Not all aging effects will necessarily lead to functional failure, however; the actual results of aging effects will be application dependent.

Cables, connections, and containment electrical penetration assemblies (EPAs) are used extensively throughout all nuclear power plants. Cables and connections are used in every electrical circuit in the plant; EPAs are included in every circuit that is inside containment. Thus, these components are obviously important to overall plant safety.

Because of their safety significance, all of these components have been the subject of extensive research and industry tests. Many of these tests have been equipment qualification (EQ) tests, or are closely related to EQ, such as severe accident research testing. In fact, aging is closely related to EQ,[1] although the emphasis is slightly different. The fundamental EQ concern is that of <u>common</u> <u>cause</u> failure of equipment, with an emphasis on exposure to adverse environmental conditions (e.g. steam, high dose radiation, pressure, temperature, and chemical spray). Reliability of equipment is not considered a part of EQ. Aging is further concerned with random failures (i.e. reliability) and how to predict and prevent increased <u>age-related</u> random and common cause failures through maintenance and surveillance programs.

Cables, connections, and EPAs are much more reliable in normal service than the components that they are normally connected to (perhaps by several orders of magnitude). Thus, slight increases (several hundred percent) in random failure rates of this equipment will have little impact on overall plant risk. It is thus evident that under the current level of operating experience, the only possible aging threat is when increased component vulnerability (resulting from age-related degradation) is combined with a harsh environment exposure. These are the only conditions where the failure rate could become significant enough to impact overall plant risk. Consequently, this report emphasizes common cause failures that might occur during exposure to accident environments, particularly any involving failure mechanisms that could be aggravated by prior age-related degradation. With this emphasis, most equipment that is located outside containment will not be subjected to accident conditions nearly as severe as corresponding equipment inside containment, and thus we will focus largely on equipment inside containment. However, for connections and cables that are typically used only outside containment, some consideration will be given to the harsh environments outside containment.

The aging assessment of cables, connections, and penetrations is broken into two phases, defined by the standard NPAR approach.[1] The first phase consists of evaluation of usage, operating experience, current inspection and surveillance methods, and applicable literature. This report details the results of Phase I. Concurrent with the Phase I effort, an NRC-sponsored experimental assessment of cables commonly used in safety applications in nuclear power plants is being performed at Sandia.[2,3] One objective of the experimental program is to assess whether results of condition monitoring techniques applied during normal conditions correlate with cable performance in off-normal conditions. This is being assessed through performance of various measurements during aging prior to subjecting the cables to simulated accident conditions.

Surveillance and condition monitoring techniques have been reviewed and discussed in work by others[4,5] and a number of them are being assessed in the experimental program. Section 8.0 of this report provides a description of some condition monitoring methods that might be applicable to cables, connections, and EPAs.

1.1 Scope

The scope of the NPAR Phase I study is to assess cables, connections, and EPAs. We will limit most discussions to safety related equipment that is required to be environmentally qualified. As noted in the introduction, particular emphasis will be placed on inside containment applications since these are exposed to the most severe environmental conditions in most accident situations. However, outside containment applications will be considered where a particular type of component is only used there.

2.0 APPLICATIONS AND FEATURES OF EQUIPMENT IN NUCLEAR POWER PLANTS

2.1 Cables

For purposes of the following discussions, cable will categorized as low voltage power, medium and high voltage power, control, and instrumentation. Medium and high voltage power cables are almost non-existent where the circuits must operate under harsh environmental conditions. Thus, they will not be included further in the discussions. Typical low voltage power circuits that might be exposed to harsh environments are those used to power 480 V and smaller motors, such as on motor-operated valves (MOVs). Control circuits that might be exposed to harsh environments typically include solenoid valves, motor-operator control circuitry, and various types of switches. Instrumentation circuitry that might be exposed to harsh environments includes pressure, level, and flow transmitters, resistive temperature detectors (RTDs), thermocouples, and radiation monitors.

Typical cable insulations are ethylene propylene rubber (EPR), cross-linked polyethylene (XLPE), and silicone rubber (SR). Some plants have cables insulated with polyvinyl chloride (PVC), polyethylene (PE), butyl rubber (BR), chlorosulfonated polyethylene (CSPE or Hypalon), or Kapton. Typical jackets are neoprene and hypalon, with some plants having PVC, chlorinated polyethylene (CPE), or fiberglass braid for jackets.

Cables may be either single conductor (with or without a jacket) or multiconductor with a jacket. Jackets are intended for cable protection during installation in trays and conduit, for keeping moisture out, for keeping the shield of shielded cable intact, and sometimes for protecting the underlying insulation from beta radiation during accident conditions.

Table 1 is a list of the cables being used in the NPAR experimental assessment of cables. These represent a reasonable cross section of cables (in terms of materials and construction) used for safety-related applications in nuclear plants. Although a "generic cable" is difficult to define, a 3 conductor, 12 AWG power and control cable or a 2 conductor, twisted shielded pair, 16 AWG instrumentation cable are two constructions that are perhaps the most common in the industry based on information obtained through NRC EQ inspections that Sandia has participated in. The most common insulations are XLPE and EPR and the most common jackets are CSPE and Neoprene.[6]

2.2 Connections

The most common types of connections used in nuclear safety-related applications are splices (butt or bolted), crimp-type ring lugs, and terminal blocks. Splices and lugs may be insulated or uninsulated. Some splices are covered with tape (often Okonite or Scotch) or heat shrink tubing (usually Raychem) when used in potentially harsh environments. Construction of butt splice connectors is quite simple, consisting of a metal barrel slightly larger than the conductor to be connected with an optional insulation that might be composed of Nylon or Kynar. Bolted splices are similarly simple.

Terminal blocks are used throughout plants in many low voltage power (less than 480 V), control, and instrumentation applications. In response to EQ concerns such as those outlined in Information Notice 84-47, a number of plants have removed either all inside containment terminal blocks in safety circuits or all inside containment terminal blocks in instrumentation circuits. Terminal blocks provide a convenient, low-cost method of connecting cables. They are especially convenient where access to equipment leads is necessary for maintenance or calibration.

Another type of connection that has become more common in recent years (as EQ concerns have heightened) is conduit seals. They are used (primarily inside containment) as a moisture barrier between the inside of a conduit and the inside of a component (since the conduits are normally vented to the environment through a junction box). These seals are essentially very small electrical penetrations; hence, the discussions for EPAs are generally applicable throughout this report.

Coaxial connectors are in limited use in safety-related circuits in harsh environment areas; the most critical application (in terms of required function) is for radiation monitoring circuits, where very high insulation resistance may be required during accident conditions.

Other types of connections are used in nuclear plants, such as thermocouple connectors, but they are less common and are generally specialized connections. They will not be specifically considered in this report.

2.3 Electrical Penetrations

EPAs provide access to the reactor containment interior for all electrical power, control, and instrumentation required for normal reactor operation. Further, the EPA must maintain a hermetic barrier to the elevated temperature and pressure of release products resulting from accident conditions.

EPA designs have evolved with the growth of commercial nuclear electric power generating stations. As a consequence, there is a large variety of EPAs, fabricated by a number of companies, currently installed in existing power plants.[7] EPA design concepts include field manufactured units, factory assembled multiple conductor canister designs, and single or multiple conductor modular units that are then assembled into a retaining fixture or header plate to complete the EPA unit.

Table 1 Cable Products Included in the NPAR Experimental Program

Supplier	Description
Brand Rex	XLPE Insulation, CSPE Jacket, 12 AWG, 3/C, 600 V
Rockbestos	Firewall III, Irradiation XLPE, Neoprene Jacket, 12 AWG, 3/C, 600 V
Raychem	Flamtrol, XLPE Insulation, 12 AWG, 1/C, 600 V
Samuel Moore	Dekoron Polyset, XLPO Insulation, CSPE Jacket, 12 AWG, 3/C and Shield
Anaconda	Anaconda Y Flame-Guard FR-EP EPR Insulation, CPE Jacket, 12 AWG, 3/C, 600 V
Okonite	Okonite Okolon, EPR Insulation, Hypalon Jacket, 12 AWG, 1/C, 600 V
Samuel Moore	Dekoron Dekorad Type 1952, EPDM Insulation, Hypalon Jacket, 16 AWG, 2/C TSP, 600 V
Kerite	Kerite 1977, FR Insulation, FR Jacket, 12 AWG 1/C, 600 V
Rockbestos	RSS-6-104/LE Coaxial Cable, 22 AWG, 1/C Shielded
Rockbestos	Firewall-SR, Silicone Rubber Insulation, Fiberglass Jacket, 16 AWG, 1/C, 600 V
Champlain	Polyimide Insulation, Unjacketed, 12 AWG, 1/C
BIW	Bostrad 7E, EPR Insulation, CSPE Jacket, 16 AWG, 2/C TSP, 600 V

Abbreviations used in table:

XLPE - Cross-linked polyethylene
CSPE - Chlorosulfonated polyethylene
AWG - American Wire Gauge
/C - number of conductors
XLPO - Cross-linked polyolefin
FR-EP - Flame retardant ethylene propylene
CPE - Chlorinated polyethylene
EPR - Ethylene propylene rubber
EPDM - Ethylene propylene diene monomer
TSP - Twisted shielded pair
FR - Flame retardant--Kerite FR insulation is similar to Hypalon
BIW - Boston Insulated Wire

3.0 DESCRIPTIONS OF COMMONLY USED COMPONENTS

3.1 Introduction

In this section, the design of the various components will be reviewed. Because of the number of different manufacturers and types of equipment, only certain equipment will be described here. The equipment selected for description is based on the following criteria:

a. Equipment that tends to be most common as judged by previous surveys and NRC EQ inspections that Sandia has participated in.

b. Equipment that tends to be representative of other equipment that is not described.

The equipment chosen for description here does not reflect any views as to the suitability of components for use in nuclear power plants.

3.2 Cables

Based on Sandia experience with NRC EQ inspections and the Equipment Qualification Data Bank (EQDB), over 30 different manufacturers have been identified that have supplied cable to the nuclear industry for safety-related applications. A complete list of cable manufacturers supplying in-containment cables may be found in Reference 6. Based on Reference 6, the most common in-containment cables, as determined by the number of entries in the EQDB (i.e. not based on installed footage), are given in Table 2. It should be noted that Anaconda and Continental and that Rockbestos and Cerro represent the same manufacturers at different points in time.

3.2.1 Rockbestos Multiconductor Firewall III XLPE Cable

Rockbestos Firewall III XLPE is a XLPE-insulated cable that is normally supplied with a flame-retardant Neoprene or Hypalon jacket. The XLPE compound may be either irradiation cross-linked or chemically cross-linked. This power and control cable is available in standard sizes from 9 AWG to 18 AWG and from 2 to 19 conductors. The voltage ratings are 600 or 1000 V. Standard insulation thickness is 25 or 30 mils with jackets from 45-80 mils. Continuous conductor rated temperature is 90° C. The cable is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

3.2.2 Rockbestos Firewall Coaxial Cable

Rockbestos Firewall Coaxial cable is available in coaxial, triaxial, or twinaxial configurations. A thin insulation made of a hard polymer designated "LE" is applied to the conductor. A radiation cross-linked modified polyolefin forms the primary insulation. The jacket is radiation cross-linked, flame-retardant, non-corrosive modified polyolefin. The different configurations are rated for at least 1000 V and different size conductors and different insulation thicknesses. The cable is rated at 90° C and is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

Table 2 Most Common In-Containment Cable Manufacturers[6]

1. Rockbestos
2. Okonite
3. Boston Insulated Wire
4. Kerite
5. Anaconda
6. Brand Rex
7. Raychem
8. Samuel Moore
9. Cerro
10. Continental

3.2.3 Okonite FMR Multiconductor Control Cable

Okonite FMR control cable is an EPR-insulated cable that is supplied with a vulcanized CSPE jacket. This control cable is available in standard sizes from 9 AWG to 18 AWG (also suitable for low power applications) and from 2 to 19 conductors. The voltage ratings are 600 or 2000 V. Standard insulation thickness is 30 or 45 mils with jackets from 45-80 mils. Continuous conductor rated temperature is 90°C. The cable is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

3.2.4 Okonite Okolon Single Conductor Power and Control Cable

Okonite Okolon single conductor control cable uses a composite insulation of EPR and CSPE. This cable is available in standard sizes from 14 AWG to 1000 kcmil (thousand circular mils). The voltage ratings is 600 V. Composite insulation thickness is 45 to 145 mils. Continuous conductor rated temperature is 90°C. The cable is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

3.2.5 Anaconda Flame-Guard FR-EP Multiconductor Control Cable

Anaconda Flame-Guard FR-EP control cable is an EPR-insulated cable that is supplied with a chlorinated polyethylene (CPE) jacket. This control cable is available in standard sizes from 10 AWG to 14 AWG (also suitable for low power applications) and from 2 to 19 conductors. The voltage ratings is 600 V. Standard insulation thickness is 30 mils with jackets from 45-80 mils. Continuous conductor rated temperature is 90°C. The cable is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

3.2.6 Samuel Moore Dekoron Dekorad Instrument Cable

Dekoron Dekorad instrument cable Type 1952/1962 is an ethylene propylene diene monomer (EPDM)-insulated cable that is supplied with a CSPE jacket on each conductor and an overall CSPE jacket. The standard size cable is 16 AWG twisted, shielded pair rated at 600 V. Standard insulation thickness is 20 mils with a primary insulation jacket of 10 mils and an overall jacket of 45 mils. Continuous conductor rated temperature is 90°C. The cable is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

3.2.7 Brand Rex Ultrol Power and Control Cable

Brand Rex Ultrol Power and Control Cable is an irradiation XLPE-insulated cable that is supplied with a CSPE or Neoprene jacket. This cable is available in standard sizes from 9 AWG to 20 AWG and from 2 to 37 conductors. The voltage rating is 600 V. Standard insulation thickness is 25 or 30 mils with jackets from 45-110 mils. Continuous conductor rated temperature is 90°C. The cable is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974.

3.2.8 Older Cable Types

Older and/or less used cable types include those employing silicone rubber, butyl rubber, or polyethylene insulation. Silicone rubber is used for high temperature service (usually where radiation doses are relatively low). A few plants have silicone rubber manufactured by Continental (Anaconda), Rockbestos, AIW, and Lewis Engineering. Rockbestos is apparently the only manufacturer currently producing silicone rubber for safety-related inside containment applications. The soft insulation is vulnerable to local damage and some silicone rubber is prone to radiation damage. These reasons have limited the application of silicone rubber in nuclear plants.

Very little butyl rubber and polyethylene, if any, is still used in containment EQ applications because they are both vulnerable to radiation damage at the levels postulated for accident conditions in typical reactors containments. However, they are still used for a few outside containment applications.

3.2.9 Other Cable Types

Many cable products in addition to those mentioned above are used in nuclear power plants. A few of the more common ones include Rockbestos Pyrotrol; Okonite Okoprene and VFR; Anaconda Durasheath; Samuel Moore Elastoset and Polyset; Kerite FR, FR3, and HTK; Raychem Flamtrol; General Electric Vulkene and Vulkene Supreme; ITT Exane II; and BIW Bostrad 7E.

3.3 Connections

Since the major types of connections used in nuclear power plants are terminal blocks and splices, the discussion here will be limited to these items. Many conduit seals are constructed very much like an electrical penetration and will therefore not be discussed further. Connectors such as the Namco EC210 series will also not be discussed because they are used somewhat less than terminal blocks and splices.

3.3.1 Terminal Blocks

An extensive terminal block evaluation program was conducted at Sandia.[8,9] Included in the report is a review of terminal block usage in the nuclear power industry; terminal block design, manufacture, selection, procurement, installation, inspection and maintenance; and terminal block quality assurance practices.

Based on the usage review,[9] Table 3 lists the most common terminal block manufacturers based on the number of plants identified as having the given manufacturer's terminal blocks. The data is not complete, but it does give some indication of relative usage. A total of 16 different manufacturers is identified in Reference 9.

Table 3 Most Common Terminal Block Manufacturers[9]

1. General Electric
2. Weidmuller
3. Buchanan
4. Marathon
5. States
6. Westinghouse
7. Square D

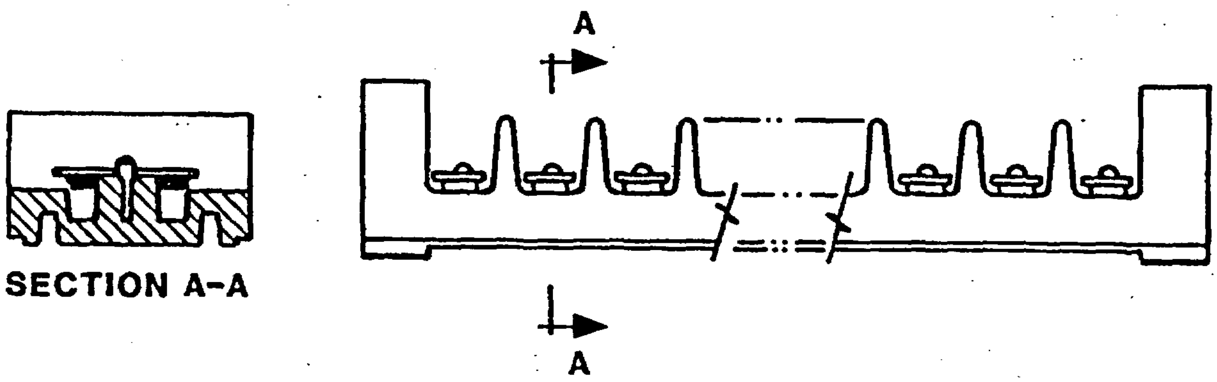
The most common terminal block material identified in Reference 9 was phenolic with either a glass or cellulose filler, with lesser usage of alkyd, melamine, diallyl phthalate, and nylon. Terminal block design is relatively simple and is generally one of two types, either one-piece or sectional. In a one-piece design, the base structure is the insulating material and it is molded as a single piece that includes the barriers between terminals. Terminals are attached to the block, with the number of terminals governed by the one-piece design. A sectional design is only slightly more complicated. Each terminal is an individually molded insulator (with metal terminal added) that is mounted to a common metal rail, thus allowing the block to have a variable number of terminals up to the limit of the rail. Figure 1 shows generic one-piece and sectional constructions.

Terminal blocks are normally installed in junction boxes for physical and environmental protection. Most junction boxes contain a "weephole" to allow condensed moisture to drain from the enclosure and to allow pressure equalization in the event of an environmental pressure excursion.

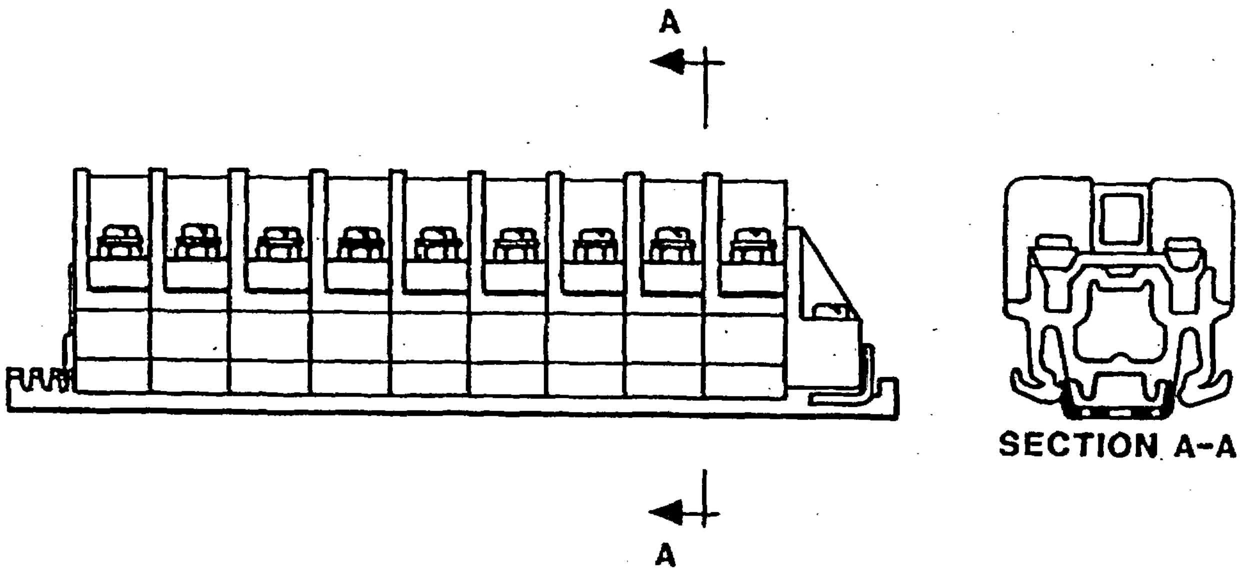
Individual terminal block characteristics differ primarily in size, detailed shape, material, and design (sectional or one-piece). However, they also tend to be much alike because of their simple functional requirements and design. Because of these similarities and the generic discussions here and in References 8 and 9, detailed descriptions of individual blocks will not be given.

3.3.2 Splices

The fundamental designs of butt splices, crimp-type ring lugs, and bolt splices are even simpler than that of a terminal block. Butt splices are simply a circular piece of metal whose ends may be crimped to a conductor. Crimp-type ring lugs are the same as a butt splice on one end, but they have a ring connector at the other end, which might be used to connect to a terminal block. Bolted splices normally consist of two crimp-type ring lugs that are bolted together. An example of a bolted connection using two ring lugs that each have two rings is shown in Figure 2(b). The connection is shown covered with Raychem heat shrink tubing. Butt splices and ring lugs may be covered by some type of insulation, typically nylon or Kynar. In many cases, splices are covered by a heat shrinkable covering or tape. For qualified applications, the major current supplier of heat shrink tubing is Raychem. Okonite and Scotch produce tapes that have been qualified for certain applications.

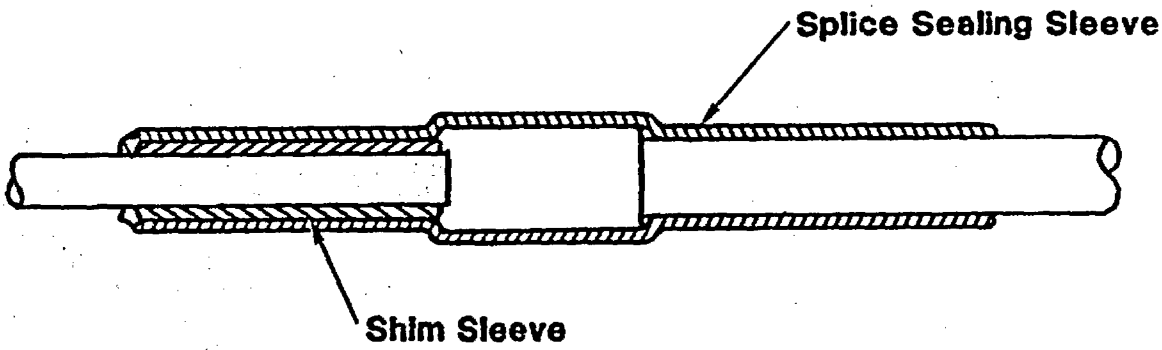


(a) One-Piece

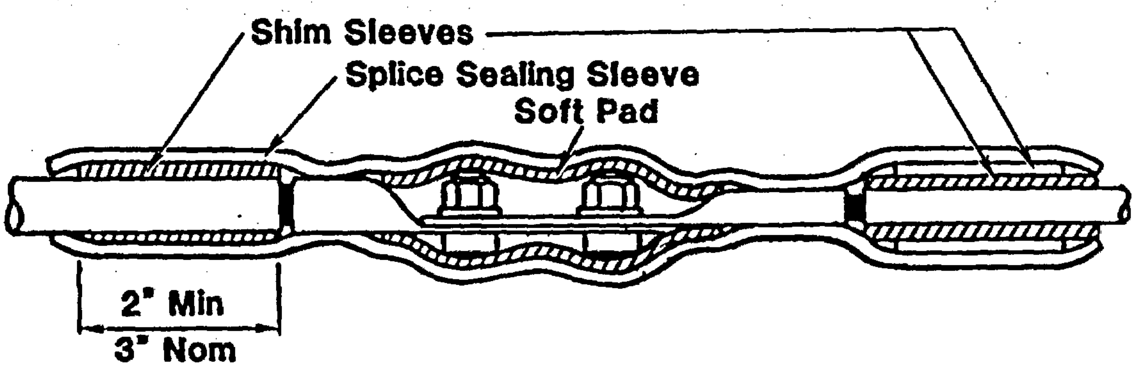


(b) Sectional

Figure 1 Generic One-Piece and Sectional Terminal Blocks[9]



(a) Over Crimped Connection



(b) Over Bolted Connection

Figure 2 Sample Raychem Installations Over a Crimped Connection and a Bolted Connection

Raychem heat shrink tubing, type WCSF(N), is used by most plants in the country. It is composed of a flame retardant, heat shrinkable polyolefin insulation that is coated on the interior with an adhesive designed to form an environmental seal under postulated accident conditions. Another version of the tubing, without the adhesive coating, is available and is designated WCSF(U). This latter version is not qualified to design basis accident conditions, but may be used in areas where no harsh accident environments will exist. Various sizes and configurations are available for making many different types of connections, but all use the same basic materials and method of application. For connection of two different sizes of wire, a special "shim" may be added to the smaller wire. Figure 2 shows two example Raychem installations. Note the use of shims in both installations. Raychem heat shrink tubing is certified to applicable standards that include the aging, accident, and flame spread requirements of IEEE 323-1974 and IEEE 383-1974. The material was tested for 40 year operation at 90°C and is rated at 1000 V. Installation of Raychem heat shrink is governed by a thorough procedure for selection, cable preparation, shrinking, and inspection.

Okonite insulating tape, model T-95, is intended for splicing and terminations in nuclear environments. It is an ethylene-propylene based thermosetting compound, rated at 90° C. It has been tested to IEEE 383-1974 requirements for nuclear applications. Installation practices are important when using a tape splice and detailed procedures are available for this purpose.

3.4 Electrical Penetrations

There is a large variety of EPA's, fabricated by a number of companies, currently installed in existing power plants. EPA design concepts include field-manufactured units, factory assembled multiple conductor canister designs, and single or multiple conductor modular units that are then assembled into a retaining fixture or header plate to complete the EPA unit. Of the considerable number of EPA fabricators, only three, CONAX, D. G. O'Brien, and Westinghouse, currently supply EPAs. A measure of the diversity of installed EPAs and manufacturers may be obtained from Table 4, which is a fairly recent compilation of both active and former EPA suppliers.[7] Column 2 of the table (EPA's installed) was obtained from the Southwest Research Institute Equipment Reliability Data Bank (circa 1982). The seal material column refers to the insulating barrier material through which the electrical conductors penetrate the EPA. The exact composition of any particular sealant/insulation compound is often proprietary information. Those EPA's without seal material information probably were field-fabricated units with very limited information available.

Table 4 EPA Suppliers

Supplier	EPAs Installed	Seal Material
CONAX	213	Polysulfone
O'Brien	268	Metal-Glass
Westinghouse	178	Epoxy
The following are no longer in production:		
Amphenol	360	Epoxy
Chi. Br. & Iron	744	-----
Crouse-Hinds	104	Epoxy
EBASCO	50	-----
General Electric	301	Epoxy
Physical Sciences	64	Metal-Glass
VIKING	404	Metal-Glass

The EPAs manufactured off-site are mounted in nozzles (steel tubes) fabricated into the containment wall. Depending on the EPA/nozzle design, the EPA and nozzle may be mated by one of two methods--either by bolts or by a continuous weld. In the case of attachment with bolts, gasket or O-ring seals are used to insure an impervious seal at the mating flange surfaces. Seal materials include metals, plated metals, and ethylene propylene and other polymer base rubbers. In general, provision is made to allow monitoring of the seal integrity by observing the gas pressure in the region between the adjacent gaskets/O-rings in the mating flanges. Weldable EPA's are attached to containment structure nozzles by means of a continuous weld between the containment nozzle and EPA (integral) weld ring. EPAs may be attached to the containment at either the inboard (reactor) or outboard side. Attachment at the outboard location offers some additional EPA protection in the event of an accident and may also facilitate installation and maintenance/surveillance activities.

All EPAs - field fabricated, canister, and modular - are designed to hermetically seal and electrically isolate all of the electrical conductors on both the inner (reactor side) and outer sides of the penetration. Depending on the manufacturer and EPA design, the EPA may provide for monitoring the internal pressure of a nonreactive gas in the region between the two sealing bulkheads as a measure of seal integrity. For canister and field fabricated units, there are no additional mating surfaces requiring seals. In the case of modular design EPAs, those EPAs with removable modules have double (inner and outer) seals with pressure integrity monitoring capability for each removable unit. For modular EPA's with non-removable modules, the modules are usually welded to the EPA header plate. Finally leakage along the conductors of cables must be considered for those EPA designs that are constructed with continuous, insulated conductors spanning the EPA pressure boundary.

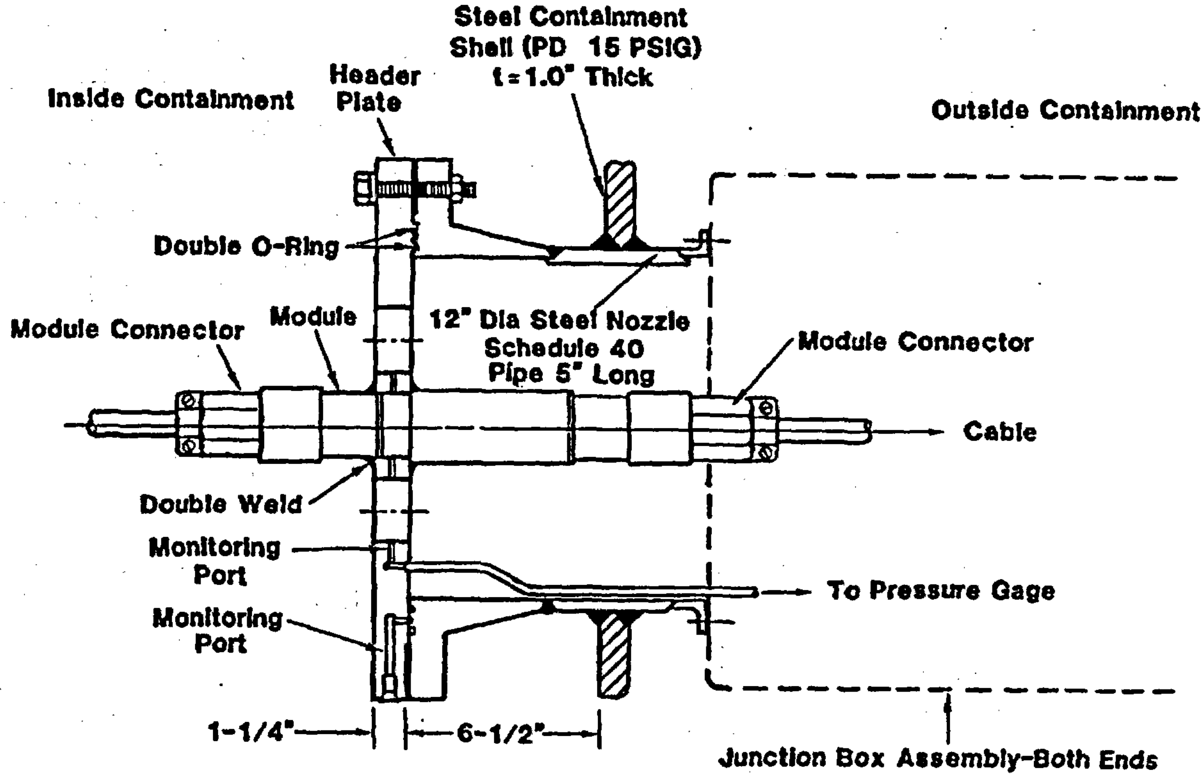


Figure 3 Typical Mounting of D. G. O'Brien EPA[7]

3.4.1 D. G. O'Brien

The D. G. O'Brien EPA is one of the three penetrations currently in production. Figure 3 is a schematic of the O'Brien EPA shown in a typical containment wall mounting configuration. As may be observed from the figure, the EPA consists of three components -- the header plate and module assembly, mating module connectors (i.e. mating plugs), and junction box units. It is also noted that the usual attachment of the EPA to the containment nozzle is with bolts (as opposed to welding). Containment integrity is assured by the double "o"-ring sealing configuration. The "o"-ring sealing status may be ascertained via the monitoring port in the header plate. Because the modules are welded to the EPA header plate, individual modules cannot be removed from the header plate assembly in the event of some sort of module related failure, such as seal integrity failure, electrical shorts or open circuits, etc. A provision for monitoring module seal integrity is provided by a header plate manifold interconnecting the module sockets to a pressure gauge. Insertion of modules in the header plate automatically couples the module interior to the pressure manifold. The header plate-module assembly is evacuated through the manifold-pressure gauge tubing and then backfilled with sulfur hexafluoride gas. Manifold gas pressure is then used as a measure of the module seal integrity.

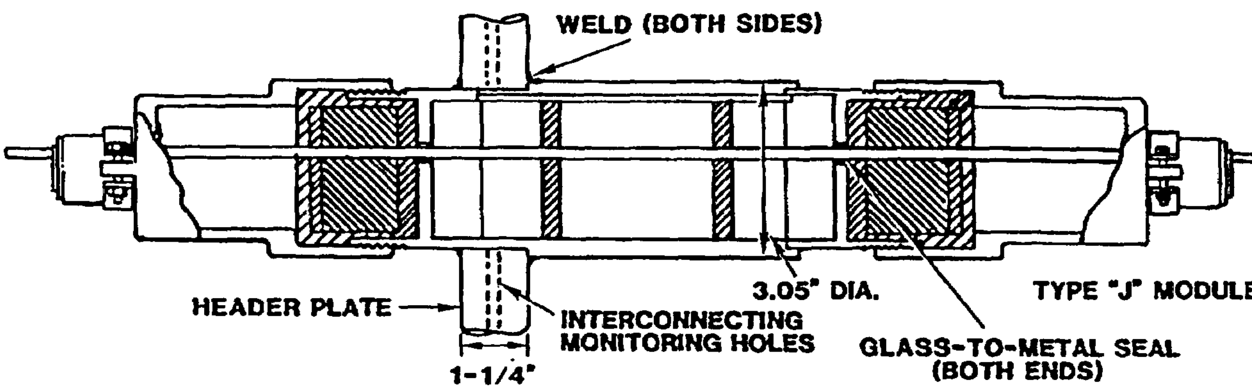


Figure 4 Schematic of Typical D. G. O'Brien Module[7]

A schematic of a typical D. G. O'Brien module with mating connectors is presented in Figure 4. Several design features may be observed from the schematic. First, the (electrical) conductors in the module are terminated at both the inner and outer ends of the module. Termination is into male metal to glass headers that are welded into the module body. Thus individual conductors are insulated from the module housing and one another with an inorganic, relatively inert insulation material. Second, since the electrical cables are terminated at the module (i.e., are not continuous through the module), air leakage through and around individual cables cannot contribute to loss of containment integrity across/through the EPA modules. Thus aging should not be a factor affecting the module electrical or sealing performance.

Drawings of the inboard (containment side) and outboard mating plugs (connectors) are presented in Figures 5 and 6, respectively. Since the inboard plug evolved from the outboard design, we consider the outboard design first. Figure 6 is a telescope presentation of the outboard plug in that the various elements "nest" inside the coupling ring in the order shown in the figure. The assembled plug is secured to the module by means of mating threads on the coupling ring and module. Although not obvious from the drawing, the insulator, contact, and washer assembly combine to form a mating female connector for the module male connector formed by the module metal to glass header. All elements of the plug assembly are rigid with the exception of the cable grommet, which is a pliable polymer base rubber.

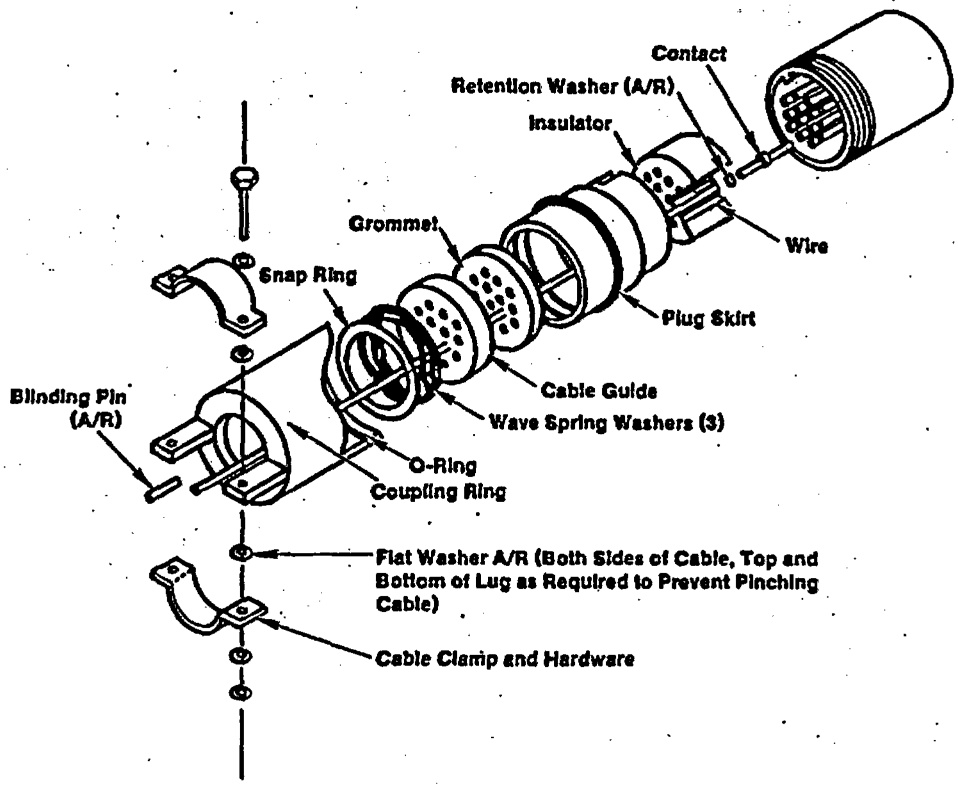


Figure 5 Inboard Mating Plug of D. G. O'Brien Connector[12]

To assure a hermetic seal at the plug-module interface, a gasket of design and composition comparable to the cable grommet is inserted at the junction of the two components (plug and module). Since the grommet/gasket polymer is incompressible (although it is flexible), a torque applied to the coupling ring translates into a compressive loading of the two elements that will then flow into any voids at four (plug sleeve-cable grommet, cable grommet-insulator, insulator-interface gasket, and interface gasket-module header) interfaces and result in a hermetic seal of the plug-module assembly. In earlier design EPAs, the polymer used to fabricate grommet/interface seals had an unusually high coefficient of thermal expansion.[10,11] Because of this high expansion coefficient and the incompressible mechanical properties of the polymer, heating of the EPA (e.g., during accident conditions) resulted in insulation damage to the cables in the plug and the loss of seal integrity at the plug. Insulation damage and sealing loss was sufficient to cause electrical shorting between adjacent conductors. It should be noted that the exterior plug assemblies incurred no damage.

As a result of this elevated temperature behavior, the inboard (containment side) plug was redesigned in an effort to eliminate the destructive effects resulting from close confinement of the grommet/gasket polymer. The redesigned plug is shown in Figure 5. As may be observed from the figure, a major redesign of the plug skirt has resulted. The closed end of the skirt plug has been removed and replaced with a floating polysulfone cable guide. The cable guide rides in the modified end of the plug skirt and restrains the cable grommet. The cable guide is in turn restrained and retained by a snap ring-wave spring washer assembly. When the assembled plug is secured to the mating module by torquing the coupling ring, the compressive force generated is transmitted through the wave spring and cable guide to the grommet. The stressed grommet then flows into any nearby voids and completes the sealing process. During large temperature excursions, the heated grommet expansion is accommodated by compression of the wave spring washers; during cool down and grommet shrinkage, the wave spring expansion maintains a compressive force on the cable grommet. Thus this plug redesign is intended to assure that grommet behavior will be reversible during large temperature excursions. In contrast, temperature excursions caused irreversible grommet extrusion and sealing loss in the original design EPA plugs.[10,11] The redesigned module/plug assembly has been qualified and replacements have apparently been made, where required, in all operating plants.

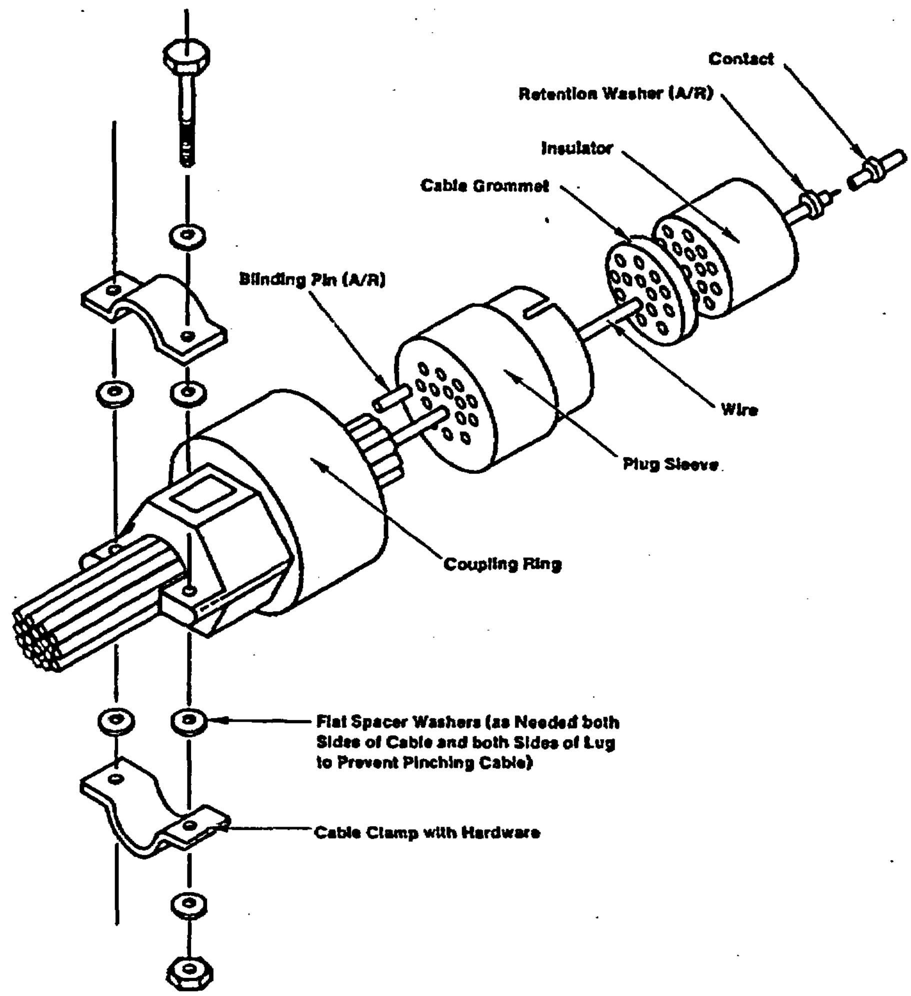


Figure 6 Outboard Mating Plug of D. G. O'Brien Connector[12]

3.4.2 Conax

The Conax EPA is also one of the three penetrations currently being manufactured. A schematic of the EPA, showing the header plate and a single module, is depicted in a typical mounting configuration in Figure 7. Both the header plate and module are stainless steel. Conductors traversing the module are sealed in a polysulfone polymer at both the inboard and outboard ends of the module. The modules are secured to the header plate by means of a threaded fastening device (a "Midlock Cap"), which allows for removal/replacement of individual modules. Finally, the EPA may be welded (as shown in Figure 8) or bolted to the containment vessel nozzle. Details of the EPA features are expanded in Figures 8 and 9. Figure 8 shows the EPA secured to a containment nozzle. The EPA may be attached to the containment nozzle with bolts or by welding. If bolts are used, dual, concentric "O"-rings assure a hermetic aperture seal at the EPA header plate-nozzle flange interface. In order to assure aperture sealing integrity, the gas pressure in the volume defined by the two "O"-rings is monitored with a conventional (bourdon tube) pressure gage. The method for securing individual modules to the EPA header plate is shown in Figure 9. When an individual module is secured to the header plate, it is automatically tied into a module (internal) pressure monitoring system via a manifold machined in the header plate. During the securing sequence, the module is hermetically sealed to the header plate on either side of the module pressure monitoring manifold. Thus all EPA interfaces through containment contain double barriers. Modules are individually secured and hermetically sealed to the EPA header plate with "Midlock Caps". The caps are analogous to a jam nut and a pair of metal wedge seals. By threading the jam nut into the EPA header plate, the pair of metal seals are forced down on the module body and out into the inside diameter of the header plate hole forming hermetic, metal to metal seals between the module and header plate.

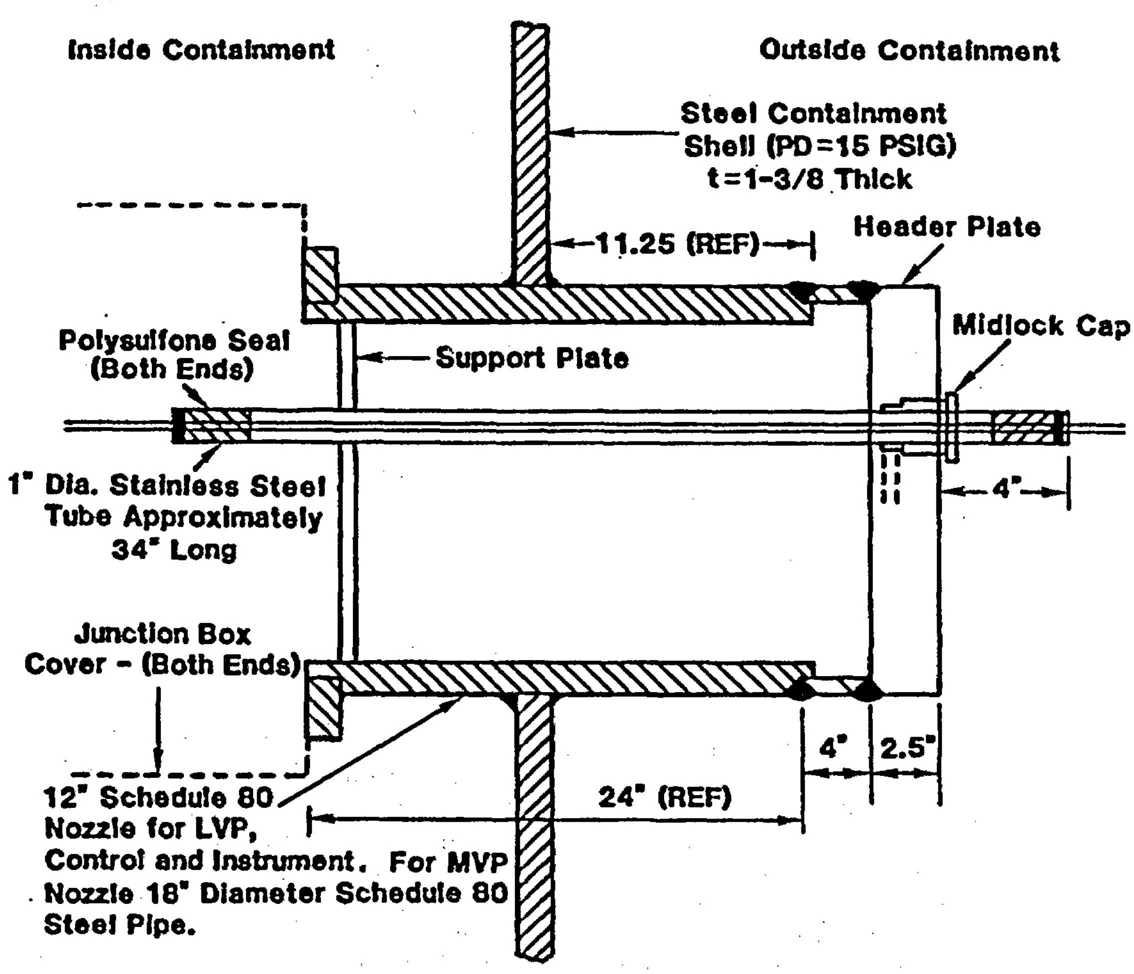


Figure 7 Schematic Diagram of Conax EPA and One Module[7]

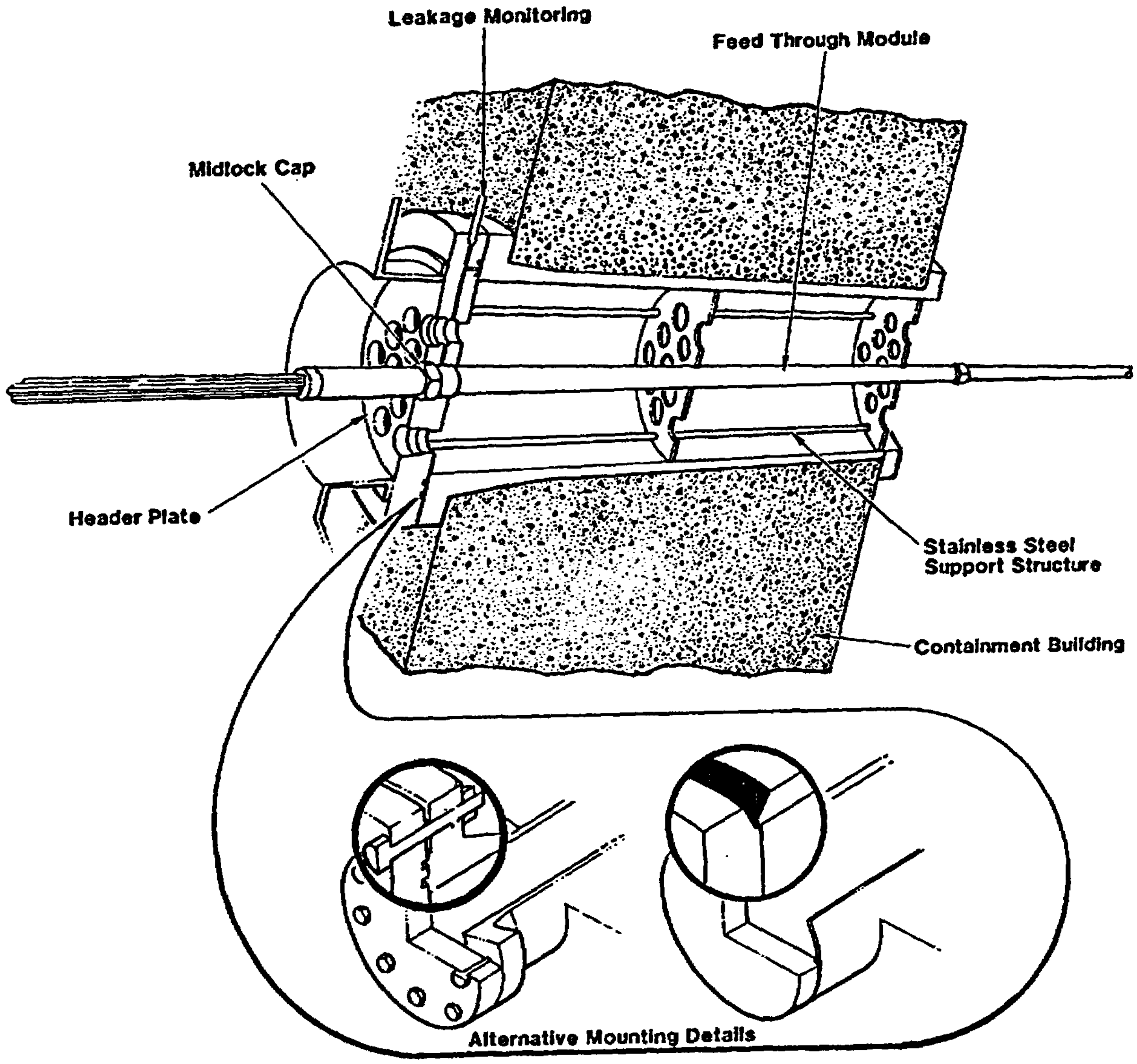


Figure 8 Conax EPA Mounting Methods

Module-conductor sealing is now considered. Figure 9 shows the assembly sequence. There are no cable splices or interconnections in the module; rather all cables--fully insulated--make a continuous run through the module. The cable insulation for this application is polyimide (KAPTON). Each end of the cable run is cast into a polysulfone insulating plug. The cable-plug combination is then assembled into a stainless steel sleeve. The cable-sleeve combination is secured to the stainless sleeve at each end by means of a rolled double crimp operation. This operation compresses, and retains, the polysulfone plug-cable assembly at each end of the stainless steel sleeve. Sufficient force is applied to the the polysulfone plugs to assure hermetic seals between the polysulfone and cables and the polysulfone and stainless steel sleeve. The completed assembly constitutes a module. Each module contains an (internal pressure) monitoring port that is automatically connected to the EPA pressure manifold when the module is assembled to the header plate.

The completed EPA is evacuated and backfilled with an inert gas so that fidelity of the hermetic seals may be monitored. Termination of the individual conductors--with pigtails, lugs, etc--is a customer option. The penetrations are certified to applicable standards that include the aging and accident test requirements of IEEE 323-1974 and IEEE 317-1972.

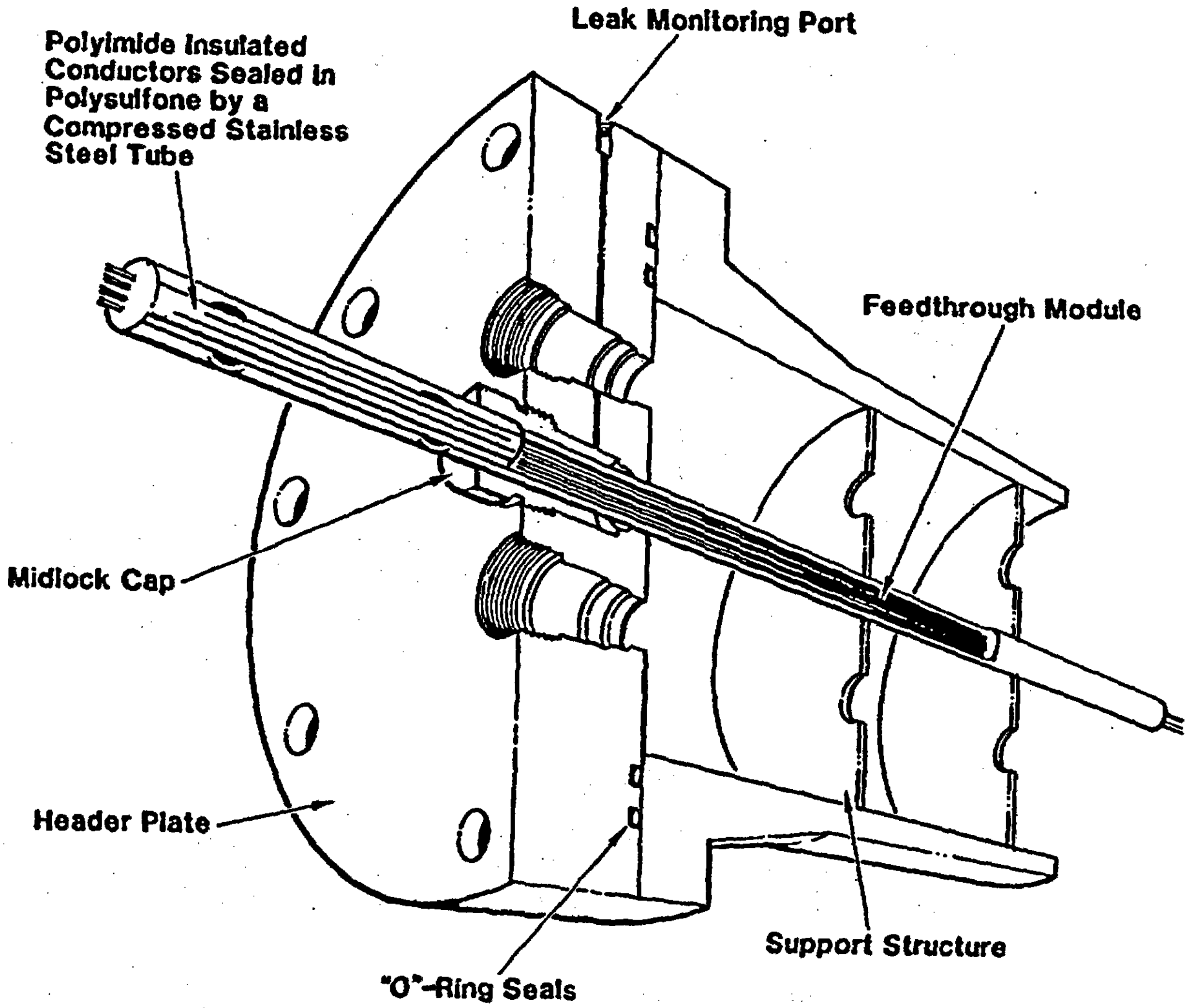


Figure 9 Details of Conax EPA Construction

3.4.3 Westinghouse

The Westinghouse electrical penetrations are available in both canister and modular designs. The penetrations are assembled and tested at the factory. Field mounting uses either a single weld or bolted flange. A modular series penetration is shown in Figure 10, with detail of an individual module shown in Figure 11. The modules are held against the header plant with three mounting clamps with dual silicone o-rings forming the header plate to module seal. Connecting a module into the header plate automatically connects it to an integral leak monitoring system. Blank modules may be installed where necessary to maintain monitoring capability and containment integrity. An epoxy sealing material is used to seal the wires inside the module. Individual modules can be field-replaced by removing three clamps.

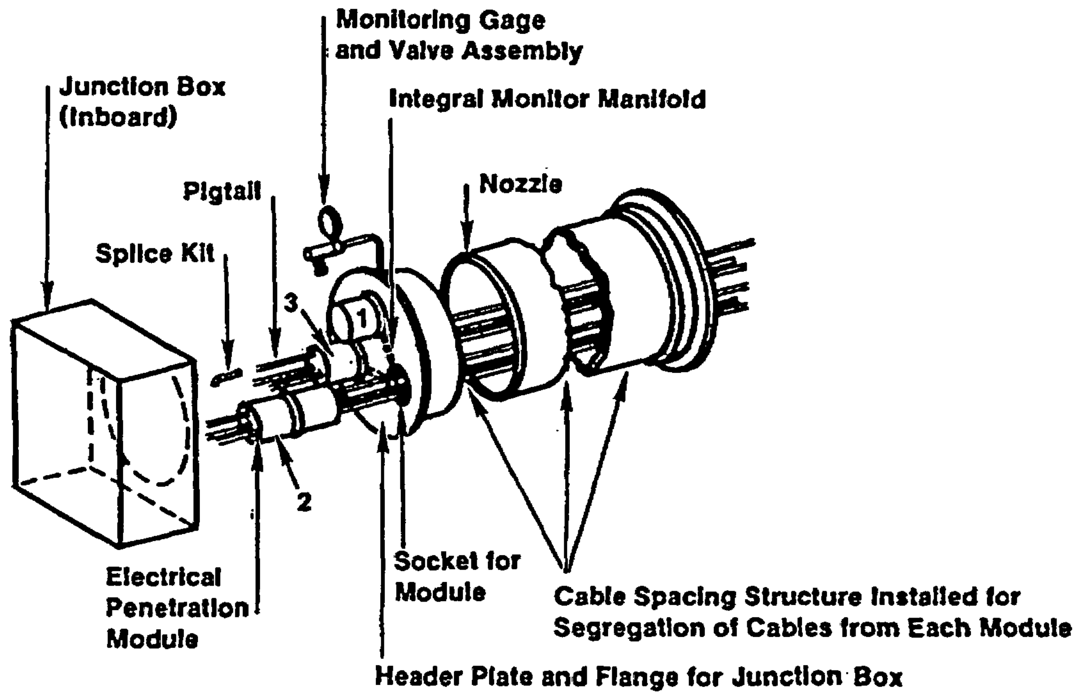


Figure 10 Westinghouse Modular EPA[12]

Figure 12 shows a typical installation of a canister series penetration. A single field weld or bolted flange completes the installation. A canister penetration is somewhat similar to a large single module of the modular penetrations, except that it is installed as a single unit into the containment wall.

Either type of penetration may be supplied with different types of cable, terminations, and junction boxes. The penetrations are certified to applicable standards that include the aging and accident test requirements of IEEE 323-1974 and IEEE 317-1972.

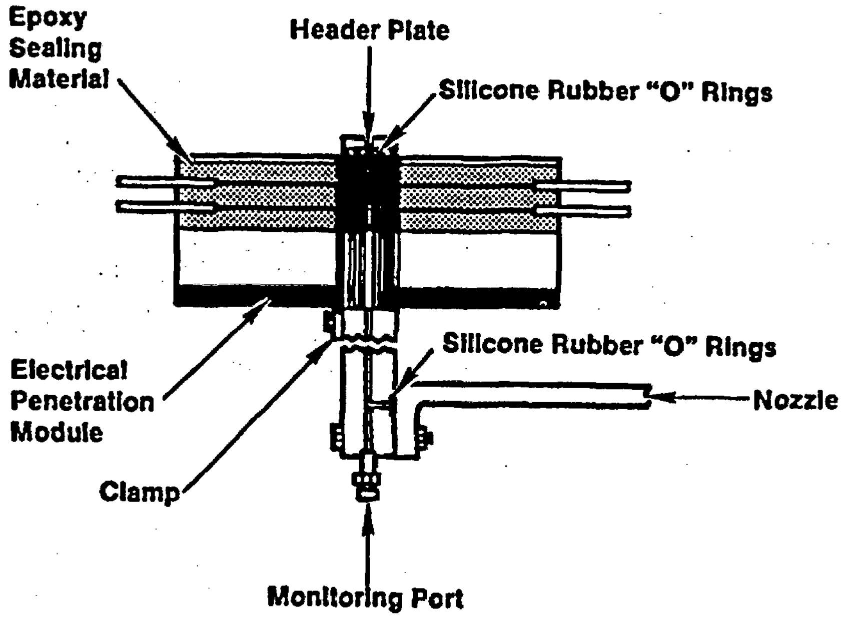


Figure 11 Typical Module for a Westinghouse Modular EPA[12]

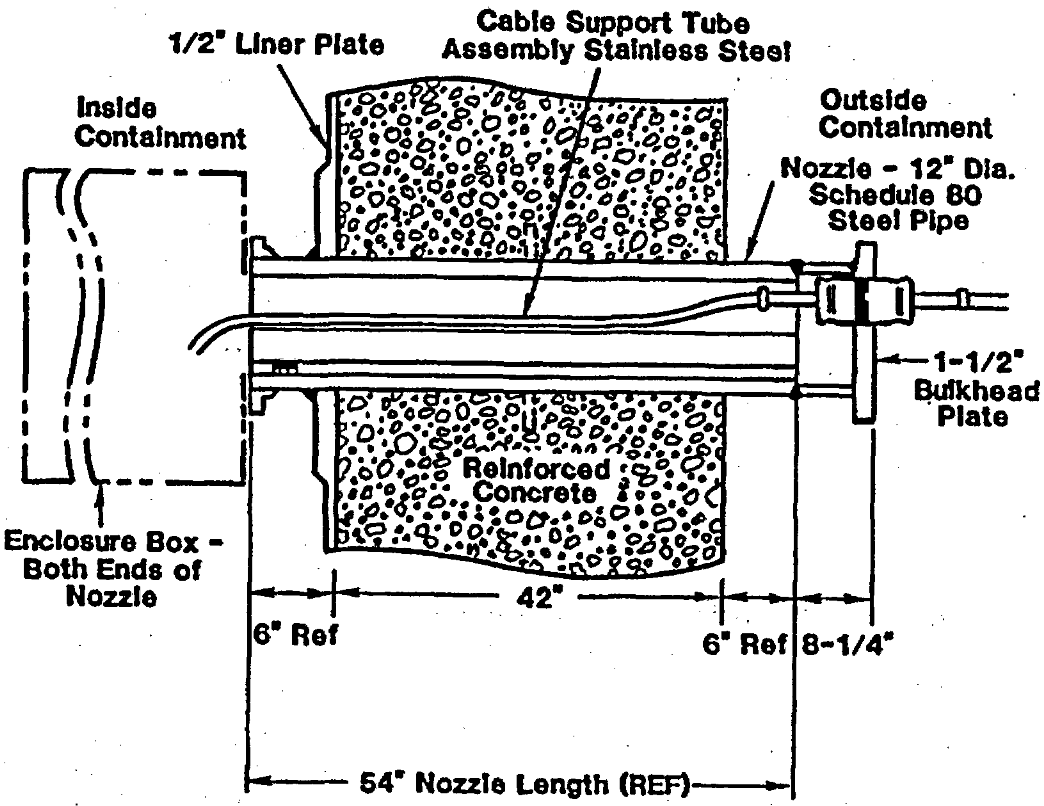


Figure 12 Typical Westinghouse EPA Installation[7]

4.0 STRESSORS AND AGING MECHANISMS

4.1 Normal Environments Aging

The possible aging stressors for the equipment under consideration are thermal, radiation, mechanical (vibration), dust, humidity, electrical load cycling, chemical attack, and maintenance damage. Dust is not likely to be a problem except possibly for some connections. Electrical load cycling will not generally contribute to aging of cable, connections, and EPAs used in typical applications because of the low voltage levels. Increased thermal aging resulting from cable self-heating will be a problem for only a limited number of safety-related cables. Humidity aging is not currently considered part of the scope of qualification aging, but it may be important for some equipment. Humidity resistance of cables is part of the design basis accident steam exposure in the qualification standards, and long-term moisture absorption tests are performed by manufacturers.

All the components considered here can be classified as passive electrical equipment, similar in many respects to piping, connections, and piping penetrations in a mechanical system. Thus, it is expected that the normal random failure rates for these types of equipment are very low. However, when the equipment is exposed to accident conditions following aging, the failure rate has the potential to be much higher than the normal environment failure rate. Part of the reason for this observation is that the failure causes are different under aging and accident conditions. Extensive research indicates that the primary causes of failure for most equipment under accident conditions are moisture-related and result from the steam environments in an accident.[13] Similar steam environments are not present during normal operation. Accident chemical spray environments inside containment may make some failures even more likely.

4.1.1 Cables

Extensive industry testing and NRC aging research testing has been conducted on cables. Much of the NRC work has been directed toward determining appropriate preaging and accident methodologies for qualification testing, while industry testing is directed toward cable qualification itself. The aging stressors considered in most (both research and industry) testing have been limited to thermal and radiation aging, those considered to be of most significance. Humidity, dust, operational cycling, and chemical attack are usually neglected. Humidity is specifically excluded from consideration by section 4.8 of NUREG-0588 requirements. Dust is not considered important in cable aging. Operational cycling is not significant at the voltage levels employed for most nuclear plant safety cable. Chemical attack is generally not included as part of testing programs; cable is assumed to be normally installed where significant chemical attack is not a problem. Mechanical aging is addressed largely by performing mandrel bend tests on aged and accident tested cables to demonstrate mechanical durability; seismic testing as such is generally not performed on cables.

Qualification criteria outlined in various well-known standards and regulations (see e.g. References 14-18) typically includes radiation and thermal aging, followed by an accident exposure including high temperatures, pressures, steam, and chemical spray. Thermal aging is normally based on the Arrhenius methodology with radiation aging based on an "equal dose-equal damage" assumption.

Cable thermal aging information is frequently based on elongation at break from a tensile test. Elongation information at several temperatures is used to develop an activation energy, which is then used to determine time and temperature requirements for simulating a given lifetime at a given temperature. Test data for radiation damage may include elongation data, but this data is not necessary to develop artificial aging exposure conditions using the "equal dose-equal damage" assumption.

The components of a cable that are subject to aging effects are primarily the insulation and jacket. Some manufacturers argue that the jacket is only for cable protection during installation and that insulation is the only critical component subject to aging. While this may be true in many cases, Sandia test experience[19,20] has shown that for one particular cable type, multiconductor cables have failed in several cases where a corresponding single conductor cable did not fail; the failure mechanism was postulated to be a jacket interaction effect. Also, some cables use a composite insulation/jacket combination that may enhance any interaction effects.

Cable thermal and radiation aging mechanisms have been studied extensively (see e.g. Reference 21 and its references) and will therefore receive limited attention here. Aging effects generally result from two different types of reactions, scission and crosslinking. Scission is a chemical process where large chain molecules are broken up; it typically results in decreased tensile strength. Crosslinking is a chemical process where short chain molecules combine; it typically results in increased tensile strength and decreased elongation at break.

Cable functional failure is essentially limited to the loss of dielectric isolation sufficient to cause functional failure of the circuit it is used in. For the cable itself (i.e. not including connections), loss of current carrying capability is very unlikely as a result of aging effects, particularly for the low voltage (and generally low current) applications of primary interest here. Loss of dielectric isolation may be caused by complete electrical breakdown or by reduced isolation sufficient to disrupt an electrical circuit. Changes in capacitance or other dielectric properties are rarely significant in the circuits of interest.

A significant data base of aged cable properties exists within the industry, primarily from artificial aging studies. A limited amount of data from naturally aged materials also exists. However, much of the data is proprietary in both cases. The data is also insufficient to thoroughly validate the Arrhenius technique for thermal aging and the "equal-dose-equal-damage" assumption for radiation aging. In fact, some materials have been shown to possess mild or strong dose rate effects,[22,23] indicating that the equal-dose-equal-damage assumption breaks down. Fortunately, the most common materials currently used in the nuclear industry for in-containment safety-related applications tend to be among those that do not have severe dose rate effects.

Despite the inherent ruggedness of typical cable insulations, several degradation mechanisms that have relevance to aging have been identified, primarily from normal operational environments. A major source of this type of information is NRC Information Notices, Bulletins, and Circulars. Some of the incidents discussed in the following NRC Information Notices, Bulletins, and Circulars resulted from improper application, poor installation practices, lack of proper equipment qualification, or poor maintenance. However, they fall within the perspective of aging as discussed in

Section 1.0. For example, aging might affect cables damaged during installation differently (and perhaps more adversely) than correctly installed cables, with the ability to survive off-normal environments also possibly reduced for the cable damaged during installation.

Circular 80-10 described two cases where improper insulation had been used on environmentally qualified equipment. While neither case resulted in any failures, similar events could result in more rapid aging of insulation resulting from usage of incorrect insulation materials.

Information Notice 84-68 discussed improperly rated field wires connected to solenoid valves. The notice states that a utility was using field cable rated at 90°C (194° F) inside a solenoid valve housing that could have a continuously energized solenoid causing temperatures from 250-280° F. While this is a clear case of misapplication of cables rather than an explicit aging problem, it is actually an aging problem that limits the cable temperature rating. This notice serves as a reminder that aging can be accelerated at a local "hot spot."

Information Notices 86-49 and 86-71 were two other examples of local "hot spots" causing cable ratings to be exceeded. IE Information Notice 86-49 described insulation damage to cable used in a Class 1E 4160-V bus. The accelerated insulation degradation was apparently caused by a nearby hot (400°F) feedwater line. The feedwater line insulation had been removed for maintenance, but was never replaced. Information Notice 86-71 discusses burnt internal wiring that was discovered inside Limitorque motor operator limit switch compartments. The burnt wiring was caused by heaters inside the compartment. The heaters were only intended to be energized during storage to prevent moisture accumulation.

Information Notice 86-52 described insulation damage to cable used on Foxboro Model E Controllers. Cables in the control room RPS logic cabinet at a nuclear plant were found embrittled after more than 10 years of service. Handling the cables had the potential to disintegrate the insulation, resulting in the possibility of short circuits. As a result of this event, the NRC learned that the life expectancy of the cables under mild service conditions is 10 years. Further, the manufacturer recommended a yearly inspection of the cables. It should be noted that no actual failures resulted from the cable degradation. The insulation material was not mentioned in the notice.

Information Notice 87-08 discusses degraded motor leads in Limitorque motor operators. The leads were Nomex-Kapton insulated and several in-service failures were reported. NRC investigation showed that the leads were never environmentally qualified. The reported failures resulted from insulation degradation that allowed leads to short together. It must be emphasized that these failures occurred during normal service.

Information Notice 87-52 discusses high potential withstand testing of silicone rubber insulated cables at a nuclear plant. Cables were tested at a voltage of 80 V/mil. The testing was performed in response to concerns about installation damage to the cables. Although some of the cables failed this test, no conclusions regarding aging are appropriate because of the severity of the dielectric tests.

Information Notice 88-89 discusses degraded Kapton electrical insulation. Kapton's vulnerability to moisture, chemical attack, and nicking (or localized damage) are indicated in the notice. From an aging standpoint, nicking is not a direct environmental aging effect, but rather occurs as a result of installation or maintenance activities. It may contribute to enhanced degradation by other aging effects, such as chemical attack.

A number of cable test programs have been performed at Sandia.[19-31] The intent of these tests was to evaluate the methodology used to qualify cables. The tests were largely concerned with evaluation of sequencing and synergistic effects under both aging and accident conditions and evaluation of dose rate effects during aging.

4.1.2 Connections

The simplicity of typical connections limits the number of age vulnerable materials they contain. Terminal blocks are often constructed of phenolic materials that are very age resistant. Butt and bolt splices may have insulation that could be vulnerable to aging, usually nylon or Kynar. Raychem heat shrink tubing and the tape discussed in Section 3.2.2 are polymeric materials that could be subject to aging. The possible failure modes of connections are either loss of dielectric isolation sufficient to disrupt a circuit or loose connections. Loose connections can cause open circuits, or in some cases, electrical fires. However, the large number of terminations in a nuclear plant and the relatively few reports of loose connections indicate that loose connections are not a significant aging effect. Loss of dielectric isolation is most likely during accident conditions and is rarely reported during normal operation (see section 5.3).

Coaxial connectors are typically constructed of metal with an organic insulator that might be Teflon. In a coaxial connector, the insulator is in a confined location and is for mechanical separation, which provides electrical separation. Thus, although Teflon is known to be age sensitive, its application in coaxial connectors appears to render the aging effect harmless.

Most NRC information that has been disseminated regarding connections resulted from design, selection, installation, and quality assurance inadequacies, not from any aging effects.

Information Notice 80-08 describes a defect on certain States sliding link terminal blocks. The defect involved a crack in the terminal block that could result in connection problems. The defect does not appear to be directly related to aging, but aging effects such as vibration could enhance any cracking in the block. A Sandia test verified that LOCA conditions would not propagate the "crack" and lead to terminal block failure.[32]

Information Notice 82-03 discussed the requirements for maintaining cleanliness of equipment, particularly terminal blocks. Dust and chemical attack are the two major possibilities for terminal block contamination. Sandia's testing[8,9] shows no evidence that small amounts of dust might cause problems. Chemical attack during aging was not addressed in the Sandia tests.

Information Notice 84-78 discusses underrated terminal blocks used in some Limitorque motor operators. This condition resulted from improper terminal block selection and is therefore not directly related to aging. However, an underrated block may have an inherently higher failure probability under accident conditions. This might occur, for example, because of different geometries and dimensions.

Information Notice 85-83 discusses fracture failures of terminal posts on General Electric PK-2 test blocks. The root cause of the failures was not known at the time the notice was issued. The failures may have been aging-related; no additional information is known.

Information Notice 88-27 is mostly concerned with deficient termination practices. These included improperly stripped wires, improperly crimped connectors, and improperly sized connectors. None of the conditions appeared to result from aging effects, although vibration, handling, and/or chemical attack could further degrade a poor connection.

The heat shrink tubing and tapes are made from materials similar to cable materials and their degradation can be expected to be similar to cable materials to a significant extent. One advantage that these materials have over cable insulation is that they normally have significantly thicker insulation. However, their big disadvantage as compared to cable is that they must bond to existing insulation to form a moisture tight seal.

4.1.3 Electrical Penetrations

EPAs must perform two passive functions. First they must provide for the transmission of electrical signals and power to and from the reactor containment structure and second they must maintain a hermetic seal between the containment interior and the exterior environment under both normal and accident conditions. Based on required EPA functions, electrical shorts and open circuits and leaks around and through the EPA are the possible EPA failures.

From the discussion in section 3.3, it is obvious that three general EPA elements may be susceptible to aging degradation--the sealing material, the cable insulation, and, depending on mounting method, the header plate "O"-rings. The degradation of cable aging is the same as that discussed in section 4.1.1, except that the possibility of interaction between cable insulation and sealing material might become important. The sealing materials used are typically inorganics and are thus very resistant to aging effects. The header plate "O"-rings can be vulnerable to aging and could allow the EPA to leak if they degrade significantly.

Bulletin 82-04 identified deficiencies with Bunker Ramo electrical penetrations. While many of the deficiencies reported involved improperly selected or improperly crimped connectors, one problem was identified that may be aging related to some extent. The deficiency involved cracked cable insulation where the cables emerge from penetration modules. Contributing causes to the deficiency may have included aging, the bonding of epoxy from the penetration module to the cable insulation, and mechanical damage from movement or vibration of the cables combined with the previous factors. Aging does not appear to be the major factor in the above events (largely a design weakness), but embrittlement of insulations could be a factor. Licensees were required to remedy any deficient penetrations.

Recent data[33,34] indicates that maintenance problems involving polyimide (Kapton) insulated wiring have been observed to be increasing. This wiring is used in Conax EPAs. In aircraft electrical applications, the polyimide insulation was observed to be developing cracks and frayed surfaces. The degradation mechanism was identified as a hydrolytic chain splitting reaction; it was determined that the degradation rate could be enhanced by elevated temperatures and high humidity conditions. Although the Conax module interior is maintained under controlled conditions, the polyimide extends into the containment from the EPA pigtails. Thus, high humidity aging (particularly at elevated temperatures) may affect polyimide's functional capability. It should be noted that thermal aging for EQ is normally performed at high temperatures with very low humidity.

4.2 Abnormal Environments Stressors

As discussed in section 1.0, the stresses imposed by accident conditions, when combined with the effects of normal aging, are the most important consideration for cables, connections, and EPAs. This observation is indicated by several NRC Information Notices describing failures that have occurred during qualification testing where the failures would never have been detected during normal operation. The major cause of accident condition failures of most equipment is moisture related and occurs when high temperature, high pressure steam causes reduced electrical isolation in circuits. Similar severe environments do not exist under normal operating conditions. The effects of reduced electrical isolation were studied in Reference 9 for various types of circuits and in Reference 35 for radiation monitoring circuits. Although Reference 9 refers specifically to terminal blocks, the same type of analyses apply to any interconnecting device.

4.2.1 Cables

The major causes of cable functional failure under accident conditions result from high temperatures and/or moisture penetration. These conditions allow leakage currents to flow to adjacent conductors or to ground, eventually causing functional failure of the circuit. Insulation resistance decreases with increasing temperature. A rule of thumb is that a factor of 2 decrease in insulation resistance results from each 10°C temperature increase. Open circuits (not including connections) appear to be extremely rare. They would require significant corrosion of the cable conductor and would generally be detected during normal operation or periodic testing. Further, few such open circuit failures have been observed in normal service or in qualification testing. Two information notices and one circular deal with harsh environment degradation, with none directly related to aging.

Circular 79-05 discusses the potential for moisture leakage in stranded wire conductors. The phenomenon of moisture leakage through a stranded wire conductor when a differential pressure exists between the two ends of a cable is well known in equipment qualification testing. The moisture might enter a piece of equipment and cause failure. Although any such failure is not directly attributable to aging effects, it does reinforce the concept that environmentally-induced accident failures can occur with no prior indication during normal service.

Information Notice 84-44 discussed inadequate qualification testing and documentation for Rockbestos cables. This notice is no longer a concern since Rockbestos performed verification testing to ensure qualification of the subject cables.

Information Notice 86-03 described environmental qualification deficiencies in the internal wiring of Limitorque motor operators (also suggested by Information Notice 83-72). The wiring could not be qualified because it could not be identified and/or no qualification documentation was available for some cable that was identified. Even though the cables did not have full certification, they would not necessarily have failed had they been exposed to accident conditions.

Extensive accident testing has been conducted at Sandia as well as in industry. The Sandia testing has focused on questions such as simultaneous versus sequential accident testing; single versus multiconductor qualification testing; and material formulation effects. Industry tests are usually intended for actual qualification. Representative reports that discuss accident testing performed at Sandia include References 19, 20, 30 and 31. A summary report that includes information from these references reports is Reference 13.

4.2.2 Connections

The major cause of failure of connections under accident conditions is moisture-induced leakage currents to other electrical equipment or to ground. A second possible failure cause is loosening of connections resulting in open circuits. In a harsh environment, temperature effects could cause a loose connection or make an already loose connection worse.

A test program was performed at Sandia to evaluate terminal blocks exposed to accident conditions. The tested blocks were unaged since (radiation and thermal) aging are not generally considered important for terminal blocks. The test profile followed was that suggested for generic qualification in IEEE 323-1974. The test was limited to 120 V and below. Many of the terminal blocks showed leakage currents (reduced insulation resistance) sufficient to adversely affect operation of some instrumentation circuits. Transient insulation resistances (e.g. soon after the introduction of steam or soon after changing the applied voltage) were even lower, possibly low enough to affect other types of circuits. The cause of the reduced insulation resistances of the terminal blocks was moisture film formation on the terminal blocks allowing leakage between terminals and from terminals to ground. This is an example of where a dominant failure cause for a piece of equipment is never seen in normal service environments.

In the testing described in Reference 8, the only failure associated with terminal block connections was attributed to excessive tension on a cable caused by extrusion of the lead wires at electrical penetrations (a testing artifact). Otherwise, tight connections remained tight. One additional observation in Reference 8 was that voltages were induced on the terminal blocks with nothing connected to them. This was presumably a result of galvanic reactions due to dissimilar metals on the terminal blocks, combined with the steam environment. The terminal blocks acted as fairly strong batteries (0.5 V at about 1 mA) in some instances. The possible effects of these stray voltages on low level circuits has never been thoroughly investigated.

As a result of the above testing, NRC issued Information Notice 84-47. Many utilities chose to remove terminal blocks from selected circuits, based on circuit type and potential for terminal block exposure to harsh environments.

Coaxial connectors, while relatively immune to aging effects (see section 4.1.2) by themselves, might be vulnerable to accident environments as a result of aging effects on coaxial cable jackets. This situation could arise, for example, if coaxial cable jacket integrity were lost before or during an accident and moisture were to travel along the cable shield into the connector. This could result in decreased insulation resistance or induced voltages, with possible failure of the circuit.

Information Notice 84-57 discusses moisture intrusion in safety-related electrical equipment. While most of the events that formed a basis for the notice involved moisture intrusion into end devices through unsealed conduit or mechanical seals of the device, three events involved connections and one event involved cables. The cable event (LER 327/81-113) is included in the LER tabulation in Section 5, but the connection events (LERs 324/82-86, 331/82-26, and 282/81-23) did not fall within the scope of the connection LERs reviewed in Section 5. Although these failures occurred during normal operation, they were a result of exposure to local off-normal environments. Without locally harsh environments, these degraded connections (poor sealing) would not typically be detected during normal operation, but they could cause failures during accident conditions. Recent equipment qualification emphasis on proper termination procedures should help reduce the number of incidents involving moisture intrusion into connections of critical circuits.

Information Notice 86-104 discusses unqualified butt splice connectors used in qualified EPAs. The connectors used nylon insulation. During testing under harsh environments, four of four samples exhibited excessive leakage currents. The affected utilities performed repairs on the splices by covering them with qualified tapes. This is another example where normal operation would not have detected the possible failure of the connections in a harsh environment.

Information Notice 86-53 discusses improper installation of Raychem heat shrinkable tubing. The generic problems discussed include: a) improper diameters, b) improper overlap onto wire insulation, c) use of the tubing over fabric cover of a wire, d) improper (excessive) bending of tubing/wires, e) insulation damage caused by manipulation of the splice before it had cooled, and f) improper heat shrinking. The major concern was whether the above effects (sometimes severe enough to expose bare wires) could lead to failures during accidents. For almost all cases where no bare wire is exposed, recent industry testing has indicated acceptability of the splices. The testing included artificial aging of the splices. The author is also unaware of any actual field failures (in normal operating environments) of improperly installed splices.

Information Notice 88-81 discusses qualification test failures of AMP window indent KYNAR electrical butt splices and Thomas and Betts nylon wire caps during environmental qualification. Several specimens failed during the accident portion of the test due to excessive leakage/shorting to ground. This type of failure only occurs under accident conditions and would not be detected during normal operation.

4.2.3 Electrical Penetrations

All three of the penetrations discussed in section 3.3 have been qualified for LOCA conditions. These three penetrations were selected by the NRC to undergo severe accident condition (SAC) evaluation.[12] SAC environments exceed LOCA temperature and pressure conditions. Since severe accident conditions are most likely to cause failures, the SAC tests will be discussed in this section. The intent of the SAC testing was to evaluate the sealing integrity of typical Conax, O'Brien, and Westinghouse modular design EPA's with the units exposed to the temperatures and pressures postulated for both BWR and PWR severe accident conditions. Although not a requirement of the test program, electrical performance of the EPA's was monitored throughout the severe accident exposures. Prior to the severe accident sequence, all three of the units were thermal and radiation aged to an end of life (40 year) condition.

In testing of the D. G. O'Brien penetrations, no evidence of environmental leakage either through the modules or the header plate/nozzle flange "O"-ring seals was detected over the duration of the SAC phase. The major portion of the SAC exposure consisted of an initial quick temperature rise to 293°F, followed by a slow rise over 12 hours to a temperature of 361°F at saturation pressure (155 psia). The peak conditions were then held for 9.5 days. The unit was powered throughout the SAC phase and insulation resistance and electrical leakage measurements were obtained periodically over the duration of the test. The electrical measurements results were quite similar to those obtained during the (somewhat milder) LOCA test performed at Sandia on the original design EPA (electrical shorts and moisture intrusion in the plug-module interface as well as evidence of grommet/gasket irreversible flow). One module (coaxial) had insulation resistances below 100 KΩ several hours into the test. By two days into the test, all circuits had insulation resistances to ground of less than 1 MΩ at 50 Vdc. With the exception of one module whose insulation resistance remained above 100 KΩ throughout the test, the other module's insulation resistances fell below 100 KΩ at times ranging from 2 to 6 days into the test. Five of the eight modules were passing 0.5 A currents to ground by the end of the test. Posttest inspection revealed that all except one module were electrically faulty. It should be noted that the EPA was designed for 65 psig/330°F peak accident conditions for periods much shorter than those used in the SAC exposure.

The Conax EPA that was exposed to SAC conditions also maintained seal integrity. The EPA electrical performance was monitored throughout the severe accident exposure. The SAC consisted of an initial rise to 640°F/85 psia steam in 25 minutes followed by a rise to 700°F/135 psia 20 minutes later. These final conditions were then maintained for almost nine days. During the test, one half ampere at 28 VDC was maintained on all low voltage conductors. Sometime during the severe accident exposure, the inner (containment side) polysulfone seal melted as was anticipated at the elevated SAC temperatures. Insulation resistances of the cables degraded significantly from about 5 hours into the test until 11 hours into the test when high leakage currents to ground required removal of the cables from the load bank. EPA thermocouples agreed quite well with reference thermocouples throughout the SAC test. Obviously, the SAC conditions greatly exceeded the EPA design criteria.

A Westinghouse EPA was also tested to SAC environments that exceeded LOCA temperature and pressure conditions somewhat, but included a duration at the high temperature conditions far exceeding typical qualification conditions. The peak conditions were 75 psia steam at 400°F for 10 days. No evidence of environmental leakage either through the modules or the header plate/nozzle flange "O"-ring seals was detected over the duration of the SAC phase. Thus the unit successfully survived the primary requirements of the SAC program for EPAs. The unit was powered throughout the SAC phase and insulation resistance and electrical leakage measurements were obtained periodically over the duration of the test. The electrical measurements were largely a function of the cable type used in the EPA. With the exception of one conductor to conductor insualtion resistance, all insulation resistances remained above 100 KΩ for the first two days of the test. Some conductors maintained good insulation resistance throughout the test, while others had insulation resistance falling into the low KΩ and below region.

Other information on harsh environment degradation of penetrations is discussed in NRC Information Notices. Information Notices 81-20 and 81-29 described failures noted during testing of D. G. O'Brien electrical penetrations by D. G. O'Brien and Sandia National Laboratories. After aging, some circuits in the penetration failed under LOCA test conditions. The grommet used in the connector expanded as a result of the aging and LOCA environments. Extrusion of the grommet sealing material stripped insulation from the cables and resulted in electrical grounding during the LOCA exposure. Retightening of the connector prior to and subsequent to thermal aging contributed to the failure. However, this is an example of a failure that would not have been evident during normal aging but would require the moisture environment associated with accident conditions before a failure would occur.

Information Notice 88-29 described a deficiency in qualification of Bunker Ramo EPAs. The deficiency was that insulation resistance readings on the EPA were not taken at frequent enough intervals to demonstrate that the EPA would function properly for instrumentation circuits during accident conditions. Additional testing of these penetrations has been conducted, but the results are not publicly available.

5.0 EVALUATION OF FAILURE DATA

5.1 Introduction

This section reviews failure data that has been reported in the form of Licensee Event Reports (LERs) and Nuclear Power Experiences (NPE). Most of these reports provide an abbreviated account of the failure/abnormal event. As a result, data on the equipment manufacturer, equipment type/model, or cause of failure may be lacking in the report. It is not unreasonable to view some isolated failure events with skepticism.

Criteria for generating LERs are provided in 10CFR50.73, some of which are based on violation of Plant Technical Specifications. If Technical Specifications and other regulations are not violated, some single failures may simply be repaired with no LER filed. The regulations also tend to be vague and subject to utility interpretation. Thus, few LERs on a certain topic does not necessarily indicate that a plant never has problems in the given area. Similarly, many LERs from a given plant does not necessarily indicate that the plant has a disproportionate number of failures compared to other plants. All LER analyses must therefore be performed and interpreted with the above in mind.

5.2 Cables

An LER search was conducted to find LERs that might be related to aging. Three different computer searches formed the basis for individual LER review. The manual LER review identified events that appeared to be related in any way to aging or the ability of aged cables to survive accident conditions. Appendix A gives a description of the searches and lists LERs from the period of mid-1980 to 1988 that resulted from these searches. Both inside and outside containment cables are included in the listing. Where both locations were affected, the location is listed as inside. Also, where the location was highly uncertain, the location was generally assumed to be inside.

Based on the objectives of the manual search, there are several categories of LERs that are generally not included in the Appendix A listing:

a. Events involving reactor trips caused by maintenance on or near flux monitor cables where a redundant cable was bumped or had noise spikes.

b. Events involving ribbon cables that are primarily used in benign environmental locations, such as the control room.

c. Events involving transmission lines or other high voltage cable.

d. Events involving pinched or locally damaged cable that were clearly discovered when they happened.

e. Events involving temporary jumper wires.

f. Events involving wiring that is completely internal to a piece of equipment. However, events involving instrument lead wires that connect to field wiring is generally included.

Table 5 gives a breakdown on the location and category of the LERs. Because of the low number of LERs and the limited amount of information in some of them, only four categories were used. More than 70% of the LERs involved some type of functional (electrical) failure, either shorting or grounding (electrical faults) or open circuits.

Table 5 Analysis of Cable LER Events (mid-1980 to 1988)

Location	Number	Percent
Inside Containment (I)	63	42%
Outside Containment (O)	88	58%
Total	151	
Category		
Electrical Fault (EF)	79	52%
Design (DE)	38	25%
Open Circuit (OC)	20	13%
Other (OT)	14	9%
Total	151	

The category "design" includes those LERs associated with improperly sized cables, incorrect assumptions about environmental exposure, installation problems, or lack of documentation to support environmental qualification. Most of the events in this category have the potential to cause aging effects and/or failures during abnormal environmental exposure. Many of them could have been eliminated during the design, qualification, and installation processes. The category "other" includes such events as cable wear, deterioration, or damage that was discovered prior to a functional failure occurring but did not appear to result from exposure to higher than postulated environments.

The results shown in Table 5 yield few surprises. The number of events is very small relative to the amount of cable in a typical nuclear plant. This is consistent with the general feeling that cables are a highly reliable device under normal operational conditions.

With due recognition of the limitations inherent in LER analyses, we will attempt to give a very rough, but hopefully conservative analysis of a failure rate indicated by the LERs.

The number of plants currently in operation will be taken as 70. The LERs cover a period of about 8 years, but we will assume an average of 5 years coverage to account for down time and for plants that came on line during the period. We make the further assumption that 1000 circuits in each plant are involved in systems covered by Technical Specifications and that each circuit is operated an average of once per month. Both of these estimates are believed to be reasonably conservative. All 151 failures will be counted in the calculation, even though many of the events could be legitimately eliminated. In some sense, this will compensate for those failures that are not reported. The resulting calculation is given in Table 6, and yields a value of 4×10^{-5}/circuit demand, considerably better than typical active components.

Table 6 Estimate of Cable Failure Rate

# of circuits = 1000
plants = 70
plant age = 5
demands/month = 1
total failures = 151

circuit failure rate per demand due to cables:

151 failures/(1000 circuits/plant x 70 plants x 5 years/plant x 12 months/year x 1 demand/month) = 4×10^{-5} failures/circuit demand

Table 7 gives a tabulation of the number of LERs for all the plants as a function of calendar year. With the small number of events, it is fairly clear that any attempt to analyze the data on a plant age basis or any attempt to look at an individual plant performance would be a statistical nightmare. Further complication arises because of changing LER reporting requirements over the years.

Table 7 Number of LERs per Calendar Year

Year	Number of LERs
1980	22
1981	18
1982	22
1983	23
1984	10
1985	8
1986	29
1987	13
1988	6 (Through ≈ 3/88)

5.3 Connections

The same searches that were used for cables were also used as the basis for a manual search for connection events. The related connection events are tabulated in Appendix B with reference to which of the searches contained each event.

Table 8 gives a breakdown on the location and category of the LERs. Because of the low number of LERs and the limited amount of information in some of them, only five categories were used. Almost 80% of the LERs involved some type of functional (electrical) failure, either shorted, grounded, loose, or open connections.

Table 8 Analysis of Connection LER Events (mid-1980 to 1988)

Location	Number	Percent
Inside Containment	68	35%
Outside Containment	128	65%
Total	196	
Category		
Loose Connection (LC)	62	32%
Bad Connection (BC)	55	28%
Design (DE)	44	22%
Other (OT)	20	10%
Shorted Connection (SC)	15	8%
Total	196	

The category "design" includes those LERs associated with improperly selected connections, incorrect assumptions about environmental exposure, installation problems, or lack of documentation to support environmental qualification. Most of the events in this category have the potential to cause aging effects and/or failures during abnormal environmental exposure. Many of them could have been eliminated during the design, qualification, and installation processes. A significant number of the reported events in this category in the 1986-1987 time frame resulted from qualification deficiencies, sometimes identified during NRC EQ inspections.

The "loose connection" category includes those events where a loose connection was clearly the cause of a bad connection. The "shorted connection" category includes those events where the bad connection was stated to result in a short. Where the type of bad connection was not specified, the more general term "bad connection" was used. We expect that a number of those classified as "bad connections" were actually loose and/or shorted connections. The category "other" consists largely of moisture and corrosion related failures.

Almost all connection events involved functional failure. This is consistent with the low-maintenance philosophy for cables, connections, and EPAs in that little preventative maintenance is performed. Even with most events resulting in failures, the number of events is very small relative to the number of connections in a typical nuclear plant, indicating that connections are a relatively reliable device.

Table 9 gives a tabulation of the number of LER for all the plants as a function of calendar year. As for cables, no attempts at detailed analysis of this data will be performed because of the small number of events. The larger number of events in the 1986 and later time frame is a direct result of two factors. First, complete LER analysis was only performed for 1986-1988, with the earlier data gathered from a search that was only intended to identify cable-related LERs (see Appendix B). In order to determine whether the overall number of LERs is increasing, the second column of Table 9 tabulates only the LERs from search 1, which was consistent throughout the whole period. Second, the number of LERs falling into the "design" category was 15 in 1986 and 13 in 1987, largely because of increased awareness and emphasis on EQ. After adjusting for these two factors, no indication of a year-to-year increase is noted. A faiulre rate analysis would yield a number with the same order of magnitude as for cables.

Table 9 Number of LERs per Calendar Year

Year	Number of LERs	Number in Search 1
1980	13	12
1981	16	16
1982	13	12
1983	14	14
1984	6	5
1985	18	12
1986	45	25
1987	61	25
1988	10	3
Total	196	124

5.4 Electrical Penetrations

A single LER search was used as the basis for tabulating EPA LERs from 1980-1988. The search produced 160 LERs and was based on all LERs that mentioned EPAs. Of these, 26 were identified as relevant to this study. Because of the small number of EPA LERs, Nuclear Power Experiences (NPE) was used as a source of additional information, from the period 1972-1980. This source gave an additional 13 events, for a total of 39 events.

When reviewing the LERs and NPEs, those EPA failures deemed to be primarily the result of personnel errors were not considered equipment failures. Failures reported here were considered to be primarily the result of equipment malfunction. A design defect in one model EPA was only included once in the above. The defect was with connectors used to interface electrical conductors to the EPA. Misapplication of an insulating sealing polymer in highly confining locations (in the connector body) can result in damage to mating cables during temperature excursions. Apparently these specific connectors have all been replaced in operating plants.

Table 10 divides the EPA events into four categories. Electrical failure includes those events where in-service failures were noted. Design events involve EQ, but not in-service failures. The same event occurring at the same plant, but with multiple LERs, was only counted once.

Table 10 indicates that pressure leakage (41%) and electrical failure (26%) caused the most events. However, compared with the number of EPAs and number of conductors per EPA, the number of events is very small. In an accident situation, the leakage events would only be important if they involved significant breach of both EPA seals together with fission product release from the containment.

Several of the LERs, particularly those in the design category, had the potential to impact many EPAs simultaneously under accident conditions. Based on the event data in Table 10, it is evident that these are potentially the most serious of the EPA events. Similar to cables and connections, EPA experience demonstrates extremely high reliability during normal operation. Hence, emphasis should be placed on aging effects that have the potential for common cause failures under abnormal conditions.

To demonstrate the high normal reliability of EPAs based on the number of failures listed in Table 10, Table 11 gives a very crude, but hopefully conservative estimate of EPA failure rates during normal operation. Such factors as multiple modules in an EPA and multiple conductors within a module have been neglected, as has the fact that some events in Table 10 may have affected multiple EPAs.

Table 10 Analysis of EPA Events

Category	Number	Percent
Pressure Leakage (LE)	16	41%
Electrical Failure (EF)	10	26%
Design (DE)	8	21%
Other (OT)	5	13%
Total	39	

Table 11 Estimated Failure Rate of EPAs in Normal Service

Assume about 4000 installed EPAs
Assume 1 demand/month
Average plant age covered by data is about 10 years = 90000 hours
EPA hours = $4000 \times 90000 = 3.6 \times 10^8$
total # failures = 39
EPA failures/hr = 1×10^{-7}/hr
EPA failures/demand = $1 \times 10^{-7} \times 720$ hr/demand = 7×10^{-5}/demand

6.0 FAILURE MODE AND CAUSE ANALYSIS

With the exception of EPA pressure leakage and EPA conductor/seal interface failures, the failure modes are the same for cables, connections, and EPAs. "Short" or open circuits are the major failure modes. In addition, spurious emf generation is a possible failure mode. "Short circuits" is used here to indicate any reduced electrical isolation (i.e. leakage current) that is sufficient to cause malfunction of a given circuit. The only differences that exist among cable, connections, and EPAs are in some of the failure causes. Open circuits are extremely rare in cables and EPAs and therefore will only be considered for connections. Spurious emf generation has been noted for terminal blocks in References 8.

6.1 Cables

The information contained in the LERs discussed in Section 5.2 is of limited use for indicating failure modes and causes. Descriptions in the LERs are normally limited to such details as "shorted conductor," "faulty conductor," or "degraded insulation." In addition, based on the discussions in section 5.1, we feel that aging effects that might lead to common cause failures during off-normal conditions are the key factor in cable aging assessment. Thus, normal operational failure causes are generally not applicable for this discussion. The only significant data for cables subjected to off-normal conditions comes from EQ testing.

Data from normal operational conditions is important when assessing how results of EQ tests might be affected by "aging" mechanisms that are not considered in EQ testing. For example, cables that are damaged during installation or maintenance, but not discovered immediately, will have a higher likelihood of failure under off-normal conditions than will undamaged cable (although the amount of increase is very uncertain). The Electric Power Research Institute is currently sponsoring a program at Sandia[36] to assess methods for detection of localized cable damage and to assess the performance of locally damaged cables in off-normal environments. The LER data gives an indication that the number of damaged cables that were not discovered immediately is fairly low. However, the damaged cables that are discovered at a later time are those that are sufficiently damaged that they are detected during normal operation. Also, the damaged cables had to result in reportable condition. Cables that are not sufficiently damaged for detection during normal operation may never be discovered.

Both industry and research EQ testing provide some insight into causes of cable failures during accident conditions. Unfortunately, when cables fail in industry tests, the results are not generally reported in any detail, if they are reported at all. What is reported is often considered proprietary. Thus research tests form the major source of publicly available data.

In two Sandia tests, the same aged multiconductor cable failed as a result of an apparent insulation/jacket interaction effect that was enhanced by dimensional changes that were caused by moisture absorption; single conductors removed from the multiconductor cable did not fail nor did unaged multiconductor cables. No other gross failures have been noted during past Sandia testing. Several additional failures have been noted in current Sandia tests associated with the NPAR program; they will be discussed in future reports.

The following are some failure mechanisms that might occur during accident conditions:

a. The most important failure mechanism is probably mechanical degradation, such as the insulation/jacket interaction effect discussed above or actual cracking of a cable that has been aged. The mechanical damage allows moisture to create electrical paths to adjacent conductors or ground, resulting in electrical failure. This failure mechanism might go undetected during type testing if the aging simulation performed is not adequate or if the type test sample selection is not adequate (such as if single conductors are used to simulate multiconductor cables when an insulation-jacket interaction effect is important).

b. A second possible mechanism of failure under accident conditions is reduced insulation resistance due to cable material that is not effective at resisting the high temperature and pressure effects of the accident steam. In this case, the insulation resistance might decrease below acceptable levels during the accident, but then recover as the accident conditions are reduced. This failure mechanism would be of concern primarily for instrument cables that require high insulation resistances. In contrast to a) above, this failure mechanism is more likely to apply to both unaged and aged cable. This failure mechanism would likely be detected if an adequate IEEE383 type test was performed on the cable product. However, selection of type test specimen (such as single vs. multiconductor) might be important here also.

c. A failure mode closely related to (b) is reduced insulation resistance due to moisture absorption and swelling. In this case, the bulk insulation resistance is reduced because of moisture presence within the insulation. This failure mechanism may act in combination with (b) to produce a failure or it may be a partial cause for failures discussed in (a). This failure mechanism would also likely be detected if an adequate IEEE 383 type test was performed on the cable product.

6.2 Connections

Terminal blocks were studied in an extensive experimental program[8,9] at Sandia. The objective of that program was to determine the failure and degradation modes of terminal blocks. The basic hypothesis of the terminal block tests was that failure modes would be related to electrical leakage paths through moisture films on the terminal block surfaces. Significant reduction in insulation resistances of the terminal blocks was observed when steam was present, resulting in the conclusion that "surface moisture films are the most probable explanation for the observed degradation of terminal block performance." This type of performance degradation is only associated with accident performance and would not be detected during normal operation.

Because of the materials used in terminal block construction, it is unlikely that aging would have a significant impact on accident performance. The one possible exception to this statement is that corrosion and/or dirt accumulation on the blocks might affect their performance. It should be noted that corrosion and dirt accumulation are largely ignored under current qualification requirements; the assumption is that normal maintenance would identify and correct any such degradation mechanisms.

Aside from electrical leakage, other possible failure modes under accident conditions are open circuits or gross electrical breakdown (more severe than just leakage currents). Open circuits are most likely to be associated with the connector attached to the terminal block. Aging effects (e.g. vibration and thermal expansion and contraction) can cause or enhance these loose connections. However, open circuit failures are not likely to be enhanced by an accident. In fact, the enhanced surface conductivity resulting from an accident might reduce the effects of a loose connection. It should be noted that an open circuit failure was observed in the Sandia tests, but its primary cause was cable extrusion through test chamber penetrations that put a significant tensile stress on the cable. Based on the test results, gross electrical breakdown during an accident does not seem likely at voltages typical of most nuclear power plant usage. Two possible exceptions to this statement apply to blocks that may be contaminated with dirt and/or corrosion and to blocks that are used at voltages above 120 V. For a more detailed discussion of failure modes see section 7.0 of Reference 9.

Many of the same comments that apply to terminal blocks also apply to other splices. Open circuit failures (loose connections) of splice connectors (also used for connections to terminal blocks) are most likely on the crimped portion of the connector rather than where connectors are screwed or bolted together. Inadequate crimping is the most likely root cause for this type of failure.

Electrical leakage or shorting is the more likely failure cause under accident conditions. Most safety-related butt splices inside containment are protected by tape or heat shrink tubing. Heat shrink tubing and tape materials are similar to cable materials, but they are normally significantly thicker than cable insulation. Electrical leakage through tape or heat shrink can be caused by all the same mechanisms as for cables, but in addition, correct installation and adhesion of the tape or splice is important. A number of Information Notices related to splices were discussed in Sections 4.1.2 and 4.2.2.

6.3 Electrical Penetrations

Because EPAs basically consist of standard field cables assembled into a hermetically sealed system, electrical failure modes of EPAs include all possible failure modes of cables as discussed in Section 6.1 above. In addition, the sealing system can introduce new failure modes not present in other field cable. An example of a sealing interaction effect is discussed in an Information Notice (see Section 4.2.3). Another possible sealing interaction effect could result if cables swelled or had other dimensional changes near the sealing interface, resulting in damaged insulation. Aging effects can change the way cables interact with the sealing mechanism.

Leakage through both seals of EPAs is rare. Most LERs report leakage through only one seal. In severe accident testing at Sandia, none of the three penetrations tested showed any signs of significant leakage. Thus, leakage failure modes appear to be much less important.

7.0 TESTING AND MAINTENANCE

Cables, connections, and EPAs generally receive minimal testing and maintenance attention. In large part, this is because of high normal reliability of the equipment. Lack of effective testing methods also limits test activities. Most maintenance that is performed is corrective maintenance rather than preventative maintenance. For example, many utilities have inspected and/or reworked many connections as a result of NRC and industry concerns that installations had not been performed in accordance with qualification requirements. Only some plants have requirements for physical inspection and cleanliness of connections and wiring near an end device when maintenance is performed on the end device. Visual examinations and documentation could prove valuable to utilities as plants advance in age and probably warrant more formal adoption by utilities. Monitoring of pressure in EPAs to detect leakage is required in every plant.

Where routine electrical testing is performed, the most common test is insulation resistance. Acceptance criteria are difficult to determine because of the many factors that affect insulation resistance. These include temperature along the cable, humidity, and the state of terminations. Usually the test is used as pass/fail and actual values may or may not be recorded. The insulation resistance test may give some indications of some connection aging effects. However, it is generally thought to be useless for predicting the aged condition of a cable because even a severely cracked cable may indicate good insulation resistance under certain conditions.

8.0 CONDITION MONITORING

Because cables, connections, and EPAs are relatively low maintenance, high reliability components, few utilities perform extensive routine measurements on them. The measurements that are performed are normally go/no-go acceptance tests, rather than for condition monitoring (CM). Thus, detailed test results may not be recorded. Probably the most common measurement that has been used by utilities is insulation resistance. Other measurements that some utilities have used include continuity, polarization index, capacitance, partial discharge, time domain reflectometry, and high potential testing. A number of these measurements may be made automatically using the ECAD system.[37]

8.1 Sandia NPAR Experimental Program

An experimental assessment of cables is currently in progress at Sandia. A number of different CM techniques are being used in the test program. They include both nondestructive *in situ* tests and laboratory tests on small specimens that are periodically removed from the aging portion of test program. Several criteria were used to select the CM techniques for the experimental program. Most of the CM techniques involve "conventional" measurement techniques. The purpose of the experimental program was not to develop new techniques, but to assess the techniques available at the time the study began. However, as the experimental program has progressed, some additional techniques are being incorporated as they become available. The currently planned CM techniques for the experimental program are as follows:

a. Dielectric withstand voltage. Dielectric withstand (breakdown) voltage of cable samples will be performed using a voltage ramp rate of 500 V/s on small samples removed during aging. This dielectric withstand test is one measure of the ultimate electrical capability of the insulation.

b. Ultimate tensile strength and elongation. These measurements, in particular elongation, have historically been used by the cable industry to assess the thermal aging behavior of low-voltage cable materials. They have also been extensively used to characterize the susceptibility of cable materials to dose rate and synergistic aging effects. Elongation at break is used since it typically decreases with increased aging. In contrast, tensile strength may first increase, then decrease with age, and therefore is used less often to characterize aging behavior.

   Our measurements use test specimens about 6 inches long that are removed during aging. We prepare the tensile specimens by disassembling the cables prior to the start of the aging exposure.

c. Modulus profiling. The elastic modulus is a measure of the slope of the stress vs. strain curve in the initial linear portion of the curve. Modulus profiling considers the variation of the modulus over the cross section of a specimen.[24] Changes in insulation modulus have been shown to correlate with thermal aging effects. However, for ethylene propylene rubber (EPR) materials, modulus has not always correlated well with radiation degradation. In certain circumstances, modulus profiling of cable specimens gives an indication of aging uniformity and hence is being used in our test program to help assess whether thermal and radiation acceleration effects have been eliminated by test parameters.

d. Hardness testing. Hardness is a material's resistance to local penetration. It is measured with any of a variety of hardness testers. While the modulus profiling technique yields much more quantitative information, the hardness test will be included since it represents a very simple field measurement technique that has demonstrated some correlation to polymer degradation.[22]

e. Bulk density. Density measurements have demonstrated that insulation density tends to increase with aging by oxidation.[25] Thus, as for modulus, it may be subject to gradients resulting from oxygen diffusion effects. In the experimental program, bulk density is being measured for selected samples and other techniques, such as modulus profiling, are being used to give an indication of the gradients resulting from oxygen diffusion.

f. Insulation resistance measurements as a function of voltage and time. Information that can be deduced from the insulation resistance measurements includes insulation resistance at a specific time (one minute is a time that is typically employed by industry), polarization indices, and step voltage behavior (i.e., insulation resistance as a function of voltage). For our tests, insulation resistance measurements are performed from each conductor to all other conductors. Measurements are taken at 50, 100, and 250 V. Leakage current (or insulation resistance) data is taken at discrete time points from 2 seconds to 1 minute for 50 and 100 V measurements and from 2 seconds to 5 minutes for 250 V measurements. Insulation resistance gives a measure of the resistive component of the dielectric impedance.

g. Transfer function as a function of frequency. Parameters that can be calculated as a function of frequency from the transfer function are real and imaginary components of the complex transfer function, capacitance and dissipation factor, real and imaginary (loss) components of complex capacitance, power factor, loss angle, etc. The transfer function gives an indication of the variation of dielectric impedance (principally due to the bulk cable capacitance and conductance) as a function of frequency. The imaginary component of the transfer function gives an indication of the dielectric charge/voltage characteristics at the given frequency, and the phase angle between the real and imaginary components gives an indication of the dielectric losses as a function of frequency. The tangent of the phase angle δ is commonly referred to as the dissipation factor (DF) and is often measured only at a single discrete frequency. Dissipation factor also gives an indication of the power factor (PF) since the two are related as $PF = DF/(1+DF^2)$. If δ is a small angle, then $PF \approx DF$.

i. Two additional CM techniques planned for the experimental program are indentation testing and step voltage response. Indentation testing will use a Franklin Research Center test apparatus[38] developed under Electric Power Research Institute (EPRI) funding. Step voltage response (Time Domain Spectroscopy, or TDS) of small samples to measure transfer function[39,40] is a technique advanced at the National Institute of Standards and Technology (NIST). It has particular applicability at very low frequencies. Measurements will be performed through a cooperative program with NIST.

Some of the above techniques are also applicable to connections and EPAs. The listed techniques are applied to cables during aging. The cables are then monitored during accident tests to assess correlations of the observed performance during the accident exposure with the condition monitoring measurements during aging.

8.2 Other Condition Monitoring Activities

Several utilities have ongoing cable condition monitoring activities. A program at Oconee[41] has been ongoing since the early 1970s when Oconee began commercial operation in 1973. Six different cable types are included in the study, but five of them have an outer metallic sheath that is not typical of most cable used in the industry. After the first 5 years of operation, the "rate at which the test samples aged in the reactor environment was as expected."[41] A similar program is underway at Perry,[42] which began commercial operation in 1987. Cables more representative of overall industry usage are included in this program, but because of the recent beginning of commercial operation, results from this program will not be available for some time.

The University of Connecticut is performing a study to compare artificial and natural aging of various components, including cables, heat shrink tubing, and feedthroughs.[43] The study is funded by EPRI, Detroit Edison, and Northeast Utilities. Table 12 is a list of plants participating in the study and a list of cables, heat shrink, and feedthroughs included in the study. Not all specimens listed in Table 12 are included in all plants. Specimens were placed in the plants in 1985. In addition to the naturally aged, additional identical test specimens are being naturally aged to allow for comparison between the two groups. The University of Connecticut also has a small program, funded by Northeast Utilities, involving three control cables. The program began in 1980 and developed into the larger, jointly-funded program described above.

San Onofre employs a cable monitoring program based on the ECAD system.[44] A major feature of the ECAD system is the ability to perform time domain reflectometry (TDR). TDR may provide a good diagnostic capability for loose or corroded connections. Although none of the measurements performed by the ECAD system has yet been shown to have a definitive trend with cable condition, the ECAD system is apparently a valuable diagnostic tool. In addition, future research may establish trends for one or more of the parameters measured by the ECAD system. Using TDR to monitor connection condition is the most promising application for the ECAD system.

A number of papers presented at the 1988 EPRI Cable Condition Monitoring Workshop dealt with various possibilities for cable condition monitoring. None of the techniques has yet been shown to have the capability of predicting cable performance in abnormal environments. A study performed by Ontario Hydro[45] tentatively concludes that "dc or ac hipot tests may be the easiest means of gaining some confidence that the insulation can survive many more years of operation." However, additional research is suggested to establish validity of this conclusion and to determine appropriate test voltages. A study at the University of Tennessee[46] examined solvent extraction, differential scanning calorimetry, Fourier Transform

Infrared Spectroscopy, and small angle X-ray scattering for monitoring of thermal degradation of cables. The one application of these methods given in the paper used a thermally aged, thick-walled XLPE cable.

Table 12 Plants and Components Included in University of Connecticut Study

Plants	Components *
D. C. Cook 1	BIW EPR/CSPE Instrument Cable
LaSalle 2	Kerite EPR/CSPE Power Cable
Maine Yankee	Okonite EPR/CSPE/CSPE Power/Control Cable
Millstone 2	Rockbestos XLPE/Neoprene Control Cable
Peach Bottom 3	Kerite FR/FR Control Cable
Point Beach 2	Samuel Moore FR 90°C Instrument Cable
Trojan	Rockbestos Coaxial Instrument Cable
WNP-2	Brand Rex XLPE/CSPE Power/Control Cable
	General Cable EPR/Neoprene Instrument Cable
	Samuel Moore EPR/CSPE Control Cable
	Raychem Coaxial Instrument Cable
	Raychem XLPE Control Cable
	Anaconda FR EPR/Polychem Instrument Cable
	BIW Type T Thermocouple Cable
	Conax 3/8" and 1/2" Feedthroughs
	Raychem WCSF-300 (2818) N3672-2-2 Shrink Tubing

* Abbreviations are defined as for Table 1

Several additional papers[47-51] generally describe possible cable condition monitoring techniques, either for local degradation, global degradation, or both. Of particular interest is Reference 47, which indicates that one cable manufacturer's experience is that about 90% of cable failures resulted from physical damage to cables. Such damage can occur before, during, or after installation.

9.0 CONCLUSIONS

The conclusions from this study are as follows:

a. Cables, connections, and EPAs are highly reliable devices under normal plant operating conditions, with no evidence of significant failure rate increases with aging. Consequently, they receive little or no preventative maintenance.

b. The most safety significant aging effects are those that have the potential to lead to common cause failures during accident conditions.

c. Many of the causes of accident failures for cables, connections, and EPAs would not be detected during normal operation because of the absence of high temperatures and humidities. The most important failure mode is expected to be shorting (or reduced electrical isolation). Several different causes may result in this failure mode.

d. Plant operational experience is useful to the extent that it may indicate some possible accelerated degradation mechanisms for cables, connections, and EPAs that could lead to common cause failures under off-normal environmental conditions. However, current LER data provides a very limited database for this purpose.

e. A significant number of manufacturers have produced cables, connections, and EPAs, resulting in many different materials and construction methods. Consequently, generic assessments of aging effects and vulnerabilities become much more difficult, particularly where failure modes relate to interfacing stresses.

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APPENDIX A Cable Events

The following LERs resulted from three computer searches (indicated by reference under I/O):

1) Select all LERs between 1980 and 1988 involving problems with cables (1458 LERs).

2) From all LERs between 1980 and 1988 involving problems with cables, connections, insulation, and terminal blocks, select those that involve an equipment qualification problem OR fabrication activity (172 LERs).

3) From all LERs between 1980 and 1988 involving problems with cables, connections, insulation, and terminal blocks, select those with event dates between 1986-1988, but exclude any LERs in Group 2 (456 LERs).

In the LERs listed below, every cable event was included in search 1 except for two. Almost all events between 1986 and 1988 were included in either search 2 or search 3, indicating that search 1 essentially provided the same information as searches 2 and 3.

LER #*	I/O**			Description
250/80-17	I	1	EF	Grounded cable on power range nuclear instrument
259/80-35	I	1	EF	Shorted wires in level switch caused low oil level alarm for recirculation pump
260/80-50	I	1	OC	Open circuit in IRM due to bad cable
261/80-14	I	12	DE	No EQ documentation for PVC pigtail wire used on EPAs
265/80-33	O	1	EF	Grounded wire in generator to bus circuit breaker auxiliary contacts
269/80-2	O	1	EF	HPSW pump motor cable shorted from water in conduit
272/80-14	O	1	EF	Ground in underground cable to a power supply caused station power transformer to deenergize
272/80-15	O	1	EF	Ground in field wiring to RHR sump pump alarm
281/80-4	I	1	EF	Pressure transmitter inoperable because of a cable problem
293/80-66	O	1	OC	Broken wire in governor control assembly to Diesel fire pump
296/80-1	O	1	EF	Feeder cable faulted to bus tie board
296/80-11	O	1	OC	Wire to RWCU valve failed due to work hardening near connection
296/80-43	O	1	EF	Water from heat exchanger removal shorted signal lead to radiation monitor

*The first 3 numbers of the LER number are the plant docket number.

**I=Inside Containment O=Outside Containment
Numbers refer to the searches where the LER was found
Two letter code refers to category in Table 5

296/80-56	I	1	OC	Open wire in cable caused Diesel voltage available relay to be deenergized, apparently due to cable damage during modification
316/80-25	I	1	EF	Insulation failure on cable to vent fan caused fan to trip
317/80-67	I	1	OC	Broken temperature element lead wire in reactor protective system
324/80-47	I	2	OT	SOV pigtails with fiberglass tape overwrap found brittle and easily damaged
327/80-18	I	12	DE	Exposed cable not qualified for radiation dose
335/80-13	O	12	DE	DG exciter lead cables hot and burnt-undersized
339/80-3	O	1	EF	Faulty lead on DG monitoring instrumentation
366/80-52	O	12	EF	Heater cable for SGTS undersized
366/80-66	O	1	DE	Ground in cable to HPCI isolation circuit caused isolation during RCIC testing
254/81-7	I	1	EF	Shorted conductors in recirculation pump discharge valves
255/81-45	O	1	EF	Fault in power supply cable to fire protection annunciator caused by broken wire strands from apparent pinching
259/81-49	I	1	EF	Damage to SRMs and IRMs cables during maintenance
261/81-8	O	1	OC	Open control cable to CCW valve
269/81-20	I	1	DE	Cable to hydrogen purge unit frayed and embrittled by heat and vibration
277/81-40	I	1	DE	Inadequate assurance that radiation monitor cable would perform at high temperature
280/81-62	O	1	OC	Broken wire to radiation monitor detector probe
302/81-70	I	1	EF	Grounded cable to neutron flux monitor caused loss of audible counts in containment
302/81-77	O	1	EF	Diesel control circuit grounded due to electrical conduit separating and rubbing cable insulation
315/81-6	O	1	EF	Broken conduit bushing allowed conduit to cut and ground charging pump inlet isolation valve cable
315/81-31	I	1	OC	Containment interlock inoperable-broken wire
324/81-137	O	1	EF	Electrical short to ground of RCIC MOV trip solenoid control power lead
327/81-113	O	1	EF	Short in ice condenser system valve cable-junction box saturated with liquid from the glycol expansion tank
334/81-94	O	1	EF	Electrical short in wiring harness to hydrogen analyzer pinched by cabinet and found smoking
338/81-61	I	1	EF	Damaged T/C cable to hydrogen recombiner heater
364/81-42	O	1	OC	Broken wire in instrumentation drawer for containment particulate radiation monitor
369/81-42	O	1	OC	Broken wire to seismic monitoring remote starter
369/81-161	I	12	DE	Cable to HRRM not qualified for high temp.
255/82-40	O	1	EF	Damaged wires in remote flow switch caused short in fire system alarm panel
271/82-12	O	1	OT	Frayed wire found in breaker for SW pump
272/82-15	O	1	EF	Wire to undervoltage relay shorted to feeder cubicle door
277/82-41	O	1	EF	Frayed wire caused short to RWCU high temp. isolation switch-caused false initiation signal
280/82-13	I	1	OT	Corrosion in CRD cable due to from nick in cable
281/82-08	O	1	EF	Feeder cable to transformer failed apparently due to brackish water spray

296/82-27	I	1	EF	Damaged lead to SOV caused failure to operate
302/82-17	O	1	EF	Water in junction box and cable-fluctuating readings on reactor building pressure indicator
324/82-15	I	1	EF	Tear in cable caused ground in IRM signal cable
325/82-113	I	1	EF	Insulation to SRM was cut, resulting in short
327/82-50	O	1	OC	Broken lead to annunciator horn caused loss of control power to DG
327/82-76	O	1	OC	Power wire to ice bed temperature monitor broken due to pinching when drawer was pulled out
328/82-83	I	1	EF	Condulet cover pinched and grounded wire to isolation valve for steam generator blowdown sample line
332/82-4	O	1	EF	Power to RHR pump lost due to fault in 4 kV cable
336/82-13	O	2	DE	Undersized ground wire to MOV overheated
361/82-148	O	1	EF	Grounded wire in salt water cooling system control circuit
364/82-29	O	1	EF	Ground fault on power cable to river water pump
369/82-10	O	1	DE	Cable to digital rod position indicators susceptible to conductor damage under flexure due to their own weight
369/82-48	I	1	EF	Wire pinched by deformed conduit to PORV limit switch
373/82-1	O	1	OC	Broken speed cable to Diesel fire pump prevented Diesel from running
387/82-59	O	1	EF	Crushed field wire to DG oil pump
416/82-165	O	12	DE	Unqualified cable in DG control circuitry
029/83-24	I	1	DE	High temperature embrittlement of cable to feedwater temperature indicator
219/83-21	O	1	EF	DG power cable failed
237/83-40	I	1	EF	Isolation valve cable shorted between drywell penetration and valve
245/83-26	O	1	EF	Cable to gas turbine speed sensor failed from oil impregnating the cable and heating
254/83-34	I	1	EF	Recirculation pump discharge valve cable shorted
260/83-82	I	1	EF	Cable fault due to previously gouged wire to recirculation pump
263/83-6	O	1	OT	HPI governor coil lead wire insulation degraded
263/83-9	O	1	OT	HPI governor coil lead wire insulation degraded
269/83-12	O	1	EF	Shorted cable to condenser circulating water discharge valve
289/83-2	O	1	EF	Wire failed due to contact with a burr in MCC causing MCC to trip
302/83-51	O	1	EF	Worn insulation to selector switch of DG led to inoperability
312/83-24	O	1	EF	Ground fault to service water pump from apparent cable damage during installation
316/83-24	I	1	EF	Faulty cable caused ground on containment isolation valve cable
325/83-61	O	1	EF	Defective cable to IRM
327/83-152	O	1	EF	Bad cable to containment isolation valve
366/83-79	O	1	OC	Broken wire to HPCI bearing temp. element
368/83-2	O	1	OT	1/2 inch long rupture in fan motor cable-cable showed signs of internal pressure
369/83-2	I	1	EF	Pressurizer heater cable overheated and burned, apparently due to hot resistors
369/83-81	O	1	OT	Insulation of fire detector cable broken
370/83-51	O	1	EF	Failed cable to rod positioning coil
373/83-143	I	1	DE	Two cables in upper drywell damaged by heat from localized "hot spots"

395/83-6	O	1	DE	Wiring to hydrogen analyzer damaged by heat
416/83-185	O	1	EF	Two wires shorted in transformer breaker handswitch causing breaker to trip
213/84-17	O	12	OT	15 conductor reactor control instrumentation cable degraded-dried out and slightly hardened
255/84-10	I	1	DE	Cable damaged by high temp. resulting from enclosure in fire barrier
263/84-13	O	1	EF	Ground fault in underground cabling to station auxiliary transformer
265/84-1	I	1	EF	IRM cable faulty
278/84-10	O	1	EF	Grounded leads on primary side of condensate pump transformer
311/84-18	I	1	OC	Broken wire in valve operator circuit to relief valve resulted in reactor trip
325/84-7	O	1	OC	Broken wire to HPCI turbine speed indication caused HPCI isolation
325/84-34	O	1	EF	Defective cable to intermediate range monitor
373/84-18	I	1	DE	Allegations of improperly installed butt splices and poor jacket removal technique causing cuts in cable insulation-inspections/repairs performed
388/84-2	I	1	EF	Faulty detector cable to SRM
259/85-37	O	1	EF	Isolation valve cables pinched and shorted
278/85-27	O	1	EF	Pinched wire in differential pressure indicating switch caused ground in RHR system logic
295/85-22	O	1	EF	Pinched wires inside SI pump inlet valve
304/85-18	I	12	DE	No EQ documentation for Limitorque wiring
338/85-7	O	1	EF	Defective cable
366/85-12	O	1	EF	Cable to main steam line radiation detector saturated with water and connector to a redundant detector failed
409/85-14	O	1	EF	Grounded wire in CRD mechanism
482/85-54	O	12	EF	Failure of a wire supplying power to a 120V instrument distribution panel
247/86-5	I	12	DE	No EQ documentation for Limitorque wiring
249/86-8	I	13	EF	Drywell RM cable stepped on and shorted
250/86-38	O	13	OT	Burned motor leads on AFW valve actuator
251/86-23	O	13	OT	Nicked insulation in cable to immersion heater coil for lube oil temperature control to DG
254/86-18	I	13	OT	IRM cable worn and cracked
255/86-03	I	12	DE	No EQ documentation for Limitorque wiring
259/86-03	O	13	EF	Cable fault caused short to ground of alternate feeder to shutdown bus
260/86-08	I	13	EF	Electrical arcing from containment ventilation valve limit switch caused by broken conduit connector and cable contact with junction box knock out
272/86-18	I	12	DE	No EQ documentation for Limitorque wiring
276/86-06	I	1	OC	Broken wire to isolation solenoid valve caused by initial improper stripping of wire followed by vibration
278/86-04	O	13	EF	Two grounded wires inside RHR pump breaker
280/86-20	I	12	DE	No EQ documentation for Limitorque wiring
281/86-1	O	13	EF	Failure of stress cone connection on feeder breaker caused cable short to ground

286/86-10	O	13	EF	Moisture in underground conduit caused grounds in generator transmission line disconnect switch cable
289/86-9	O	12	DE	Cable to reactor building cooling fan not included on EQ master list
302/86-7	I	12	DE	No EQ documentation for Limitorque wiring
316/86-16	O	13	EF	Shorted control power wires to power range monitor drawer
322/86-28	I	12	DE	No EQ documentation for Limitorque wiring
324/86-7	O	13	EF	Damage to lead insulation of reactor building exhaust RM caused power lead to ground
331/86-18	I	13	DE	No EQ documentation for Limitorque wiring
335/86-09	O	13	EF	Smoking isophase bus cable jumpers
344/86-01	O	13	OT	Cracked insulation on feedwater control valve motor operator motor shunt field lead wire
370/86-13	I	12	DE	No EQ documentation for Limitorque wiring
397/86-19	I	12	DE	No EQ documentation for Limitorque wiring and connections
397/86-33	O	12	DE	Undersized wires to standby service water pump
414/86-35	I	12	DE	No EQ documentation for Limitorque wiring and connections
440/86-57	I	12	DE	No EQ documentation for Limitorque wiring and connections
456/86-10	O	13	EF	Cable to SRM nicked during maintenance causing control power fuse to blow
458/86-8	I	12	DE	No EQ documentation for Limitorque wiring and connections
155/87-6	I	12	DE	Questionable EQ of butyl rubber and polyethylene cable
219/87-03	O	13	OT	Ribbon cable for area RM nicked and degraded from age and use
261/87-7	I	12	DE	Unidentified cable with unknown EQ status in safety related circuits
261/87-20	I	13	EF	Feedwater regulating valve cable shorted-water in conduit
272/87-16	I	12	DE	Power lead cabling to pressurizer PORV stop valve degraded-actual environment higher than expected
309/87-5	I	12	DE	No EQ documentation for a cable of unexpected brand
312/87-6	I	12	DE	Undersize power cables to motor operators
327/87-48	I	12	DE	Cable pulling practice could damage cables and result in failures
382/87-8	O	13	EF	Shorted wire in feedwater control system
387/87-30	O	13	EF	Nicked wire to reed switch for Target Rock position indication shorted in containment instrument gas isolation valve
454/87-18	O	1	OC	Broken wire to proximity sensor for feedwater pump wear annunciator
461/87-67	O	13	OC	Fatigue failure of T/C lead wire when adjacent wire was moved for maintenance
482/87-19	O	13	OC	Broken shield on coaxial cable caused spike on containment purge RM
213/88-9	I	13	OT	Nuclear instrument detector cable deteriorated
261/88-11	O	1	EF	Degraded insulation on turbine speed probe caused turbine trip
280/88-08	O	13	EF	Phase to phase fault in motor leads to low head SI pump
395/88-01	O	13	EF	Electrical lead pinched in distribution panel cover and shorted to ground
413/88-3	I	12	DE	RTD cables not installed per EQ requirements
498/88-31	I	1	DE	Extended range neutron monitor cable may cause erroneous reading

APPENDIX B Connection Events

The three searches described in Appendix A were also used as the basis for the manual search for connection events. The related connection events are tabulated below with reference to which of the searches contained each event and which category each event was placed in (refer to Table 8). Even though search 1 was only intended to identify cable-related LERs, a significant number of connection events were also included in this search, but not in the other searches (because of their limited scopes). Thus, connection events were also tabulated while performing the cable tabulation, with due recognition that some connection LERs were missed for the 1980-1985 time frame.

LER #	I/O*			Description
155/80-48	I	12	DE	150 splices and 5 terminal blocks of questionable EQ
259/80-34	O	1	LC	Loose connection on jumper wire in Limitorque MOV
260/80-50	I	1	BC	Open circuit in IRM due to bad connections
263/80-15	I	12	DE	Unqualified splices in power cables for MSIVs
324/80-46	I	2	DE	Unqualified splices to SOVs
324/80-64	O	1	OT	Annunciator relay for low reactor level alarm actuated due to excess wire grounded at termination
324/80-68	O	1	SC	HPI governor connector plug cracked and shorted
325/80-11	O	1	LC	Loose wire to control switch for HPI oil pump
331/80-35	O	1	OT	CST low level switch failed from corrosion on probe lead wires caused by moisture-also LER 81-5
335/80-5	O	1	LC	Loose power lead to CRD power supply
336/80-29	O	1	SC	Frayed insulation in connector to DG speed sensor caused ground
346/80-45	O	1	LC	Nuclear instrumentation cable not connected completely in control room
346/80-78	I	1	LC	Loose solder connection to RCS pressure sensor
247/81-27	O	1	BC	Connection to strip heater element was burned and broken off
251/81-09	O	1	LC	Loose crimp on coil wire to transfer inhibit relay for DG
255/81-39	I	1	DE	Splices, terminal blocks, and jumper wires with questionable EQ
259/81-13	O	1	LC	Loose connection to cooling tower transformer relay
275/81-03	O	1	LC	Separated center wire in coax connector to radwaste effluent line RM
285/81-03	O	1	LC	Loose connection to 125 Vdc bus feeder switch caused cable to burn loose
304/81-04	O	1	BC	Broken wire on Diesel tachometer caused DG to trip
304/81-28	O	1	BC	Wire to RM flow switch relay vibrated opened
312/81-8	O	12	LC	Loose connection on pigtail to trip coil for reactor building spray pump breaker would not allow breaker to trip
317/81-51	O	1	BC	Lead to high flow trip for RM system broke and tripped pump
318/81-18	O	1	SC	Worn and abraded tape connection caused short to ground and charging pump to trip
321/81-122	O	1	BC	SBGT connection defective

321/81-140	O	1	LC	Loose connection in rod sequence control panel caused overheating of jumper and fuse block
324/81-91	O	1	SC	Ambient room humidity caused short in RHR valve logic because of failure to seal electrical leads
366/81-82	O	1	BC	Separated wire to HPCI oil pump motor-appeared to have been cut and degraded from normal use
369/81-49	O	1	BC	Power cable to waste processing panel not properly terminated

265/82-8	I	1	BC	Broken sensor wires and dirty contact to relief valve position monitoring systems
272/82-25	O	12	SC	Piece of solid wire shorted SG level transmitter-wire left in from maintenance
281/82-41	I	1	BC	Broken wire at a splice to SG level transmitter
317/82-75	I	1	SC	Containment cooling unit tripped as a result of taped connection fraying and shorting to ground
318/82-29	O	1	BC	Bent detector cable to particulate RM caused five wires crimped to a connector to pull free
320/82-38	O	1	LC	Loose cable plug-loss of meteorological data
325/82-102	O	1	OT	SRMs inoperable-broken wire and moisture in connector
333/82-19	O	1	BC	Broken wire at control rod selector switch
334/82-23	I	1	OT	Water in cable and connector of excore detector from inleakage through refueling cavity seal
334/82-42	O	1	BC	Connection at fan motor lead burned off
335/82-27	I	2	SC	Shorted terminal lugs to caused bad position indication of isolation SOV
346/82-2	I	12	DE	Short wires to RM strained and broke-bad installation
346/82-13	I	1	DE	Broken wire to RM at penetration connector-improper installation

250/83-05	O	1	OT	Momentary short in coil lead due to water getting into control rod power cabinet
251/83-18	O	1	OT	Water in motor lead connection box-RHR pump inoperable
259/83-17	O	1	SC	Breakdown of insulation tape at connections to DG lube oil circulating pump
293/83-13	O	1	LC	Loose wires at contact of SBGT heater-burnt wire
302/83-5	O	1	LC	Loose connection-loss of wind speed sensing
302/83-60	O	1	BC	Cold solder joint on indicator wires-failure of decay heat cooler discharge temperature monitor
315/83-74	O	12	DE	4 cables with badly damaged and burned insulation at auxiliary transformer-due to copper connectors on aluminum conductors
317/83-31	O	1	DE	Broken lead to T_{hot} signal power supply due to stress at termination point
325/83-31	I	1	BC	Defective signal connectors to IRMs
327/83-19	I	1	LC	Loose connection at reactor head for rod position indicator
328/83-50	I	1	BC	Open connection to CRD lift coil
369/83-96	O	1	BC	Bad solder joint in coaxial cable to steam line RM
395/83-34	O	1	SC	Insulation failure to RHR pump caused by terminal lug forced against termination box cover by its own weight
395/83-39	O	1	SC	Power loss to RM system-power lead short to ground

244/84-09	O	1	LC	Loose connection to DG control logic
250/84-11	O	1	OT	Water in EPA canister caused inner to outer shield short in power range detector cable

259/84-23	O	1 LC	Loose terminal due to installation of 3 wires on 1 terminal
275/84-30	O	1 LC	Loose connection in turbine control system caused turbine and reactor trip
280/84-02	O	1 LC	Loose cable to semi-vital bus
281/84-8	O	2 DE	RHR pump 4160 V motor leads had 1000 V heat shrinkable material
029/85-7	O	2 LC	Loose solder terminals to power range monitor
251/85-21	O	1 BC	Bad electrical at CRD mechanism caused rod drop
259/85-51	O	1 LC	Heat from loose connection caused cable insulation to be dry and cracked in RPS panel
277/85-28	O	1 SC	Stray strands of wire at connection in contact with dc voltage caused fuse to blow
302/85-28	O	1 LC	Loose connection on motor breaker caused 6900 V bus fault
311/85-9	O	2 LC	High resistance connection in CRD cable
315/85-46	O	1 BC	Instrument bus circuit breaker tripped as a result of inadequately terminated lead
316/85-4	I	2 DE	RCS RTD connection not qualified
327/85-34	O	2 LC	DG connector loose from controls to governor hydraulic actuator
362/85-34	O	1 LC	Loose connection to fuel storage pool RM
366/85-34	O	1 BC	Power feeder to RPS breakers burned in two at connection
370/85-17	O	1 BC	Doghouse level switch control circuitry connection and relays corroded-reactor trip
374/85-22	I	1 LC	Very loose penetration cable to IRM
388/85-18	O	1 LC	Loose connections to RPS breakers caused trip
416/85-30	O	1 BC	Faulty instrument plug connector to generator cooling water flow transmitter
454/85-86	I	2 DE	Unqualified terminal strips to MSIVs
482/85-54	O	12 BC	Faulty crimped connection to 120 V instrument distribution panel
483/85-7	I	2 DE	Unqualified TBs in MOVs
247/86-35	O	13 LC	Loose connections in circuitry to RPS relays
251/86-18	O	3 BC	Corroded connection in current to pressure conversion module for AFW valve
254/86-37	I	2 DE	Butt splices used at EPA failed EQ test
260/86-12	O	13 LC	Loose internal wire in breaker
261/86-02	O	3 LC	Loose connection on test jack for SG level transmitter
272/86-06	I	13 BC	Broken wire associated with a series solenoid isolation valve for SG feedwater
272/86-7	I	2 DE	Unqualified connectors to SOV in post accident sampling system
272/86-15	I	3 DE	Raychem splices not installed as required for EQ-analysis indicated acceptability
275/86-10	O	3 LC	Loose connections in reactor trip switchgear
278/86-20	O	3 BC	Corrosion caused poor electrical connection in feedwater control system, resulting in scram
278/86-24	O	13 LC	Loose connection for RCIC temperature switch caused closure of RCIC steam supply valves
280/86-35	I	12 DE	Improper installation of Raychem heat shrink tubing
281/86-01	O	13 DE	Improper installation of stress cone connection on transformer feeder breaker
281/86-18	I	13 DE	Improper installation of Raychem heat shrink tubing

282/86-07	I	13	DE	Improper installation of Raychem heat shrink tubing
286/86-08	I	13	DE	Improper installation of Raychem heat shrink tubing
293/86-10	O	2	LC	Loose wires to Primary Containment Isolation/RPS
295/86-26	I	13	DE	Improper installation of Raychem heat shrink tubing
295/86-40	I	12	DE	Terminal blocks found where only splices permitted for harsh environment EQ
309/86-07	O	13	LC	Loose connection on control oil pump to main turbine caused trip
312/86-11	O	2	LC	Loose terminations inside Bailey cabinets
316/86-08	O	13	SC	Faulty connector caused shorting in power range monitor drawer
324/86-04	O	3	SC	Shorting of solder connection penetrating the backplate of a control room panel
324/86-07	O	13	SC	Damage to lead insulation sheathing caused shorting and RM trip
324/86-12	O	3	LC	Loose connection to RWCU temperature switch
324/86-14	I	13	BC	Oxidized coaxial connections on five signal cables to IRMs
324/86-23	O	3	BC	Loss of continuity at T/C connections for HPI isolation instruments
325/86-30	O	13	BC	Motor generator set breaker trips from high resistance connection at breakers
328/86-03	O	13	LC	Loose connection in junction box between alarm and iodine low sample flow switch
333/86-17	I	3	OT	RM connectors dirty or wet-also broken connector
344/86-11	O	13	LC	Loose connection on main turbine vibration sensor caused trip
346/86-21	I	13	DE	Improper installation of cable splices
362/86-08	I	13	BC	Faulty wire on detector/preamp assembly connector to containment airborne gas monitor
374/86-02	O	3	LC	Loose torque switch connection on RCIC steam line isolation valve
374/86-13	I	2	DE	SOV terminations not installed as required for EQ
374/86-14	I	2	DE	Okonite tape terminations not analyzed for use over Kapton insulated wire
387/86-11	I	13	BC	Broken shield on SRM cable at detector connection
388/86-13	I	13	BC	Faulty connectors at EPA to IRM
395/86-11	O	3	BC	Oxidation inside SOV connector-caused feedwater isolation valve to close and reactor trip
397/86-37	I	12	DE	Connector to acoustic monitor not qualified
410/86-24	O	3	BC	Corrosion on battery bus bars and terminals
414/86-4	O	13	BC	Wire to solid state protection system switch insufficiently connected
458/86-39	O	3	OT	Inadvertent fire protection system actuation caused water accumulation in bearing vibration probe for main turbine, resulting in scram
461/86-19	O	2	BC	Bad connection and ground problem at control room RM detector interface box
482/86-43	I	12	DE	No EQ documentation for wiring and terminals in MOVs
155/87-8	I	12	DE	23 unqualified splices to valve position indicating circuits
206/87-6	I	2	DE	Butt splices of non-qualified configuration
206/87-18	O	3	OT	Moisture at solenoid connections caused ground indication on DC bus

219/87-11	O	13	OT	Maintenance personnel inadvertently disconnected termination that were improperly installed
219/87-13	O	2	BC	Connector fell off recently installed power supply
219/87-22	I	3	BC	Failure of a cable splice from coaxial cable to twisted shielded pair on relief valve position indicator
219/87-35	O	3	LC	Loose ground connection on IRM
244/87-05	I	12	OT	Frayed middle conductor on BNC connector to input of particulate RM
247/87-28	O	1	OT	Moisture found on the electrical leads to gas and particulate monitor sample pump motor
251/87-15	I	3	SC	Shorted wire at solenoid from deteriorated insulating tape
251/87-19	O	2	LC	Loose solder joint to RPI caused spurious indication
254/87-3	O	2	LC	Loose solder joint in RCIC flow controller
254/87-6	O	3	LC	Loose soldered connection on HPI reset solenoid
255/87-02	I	3	OT	Highly corroded connector pin at nuclear instrumentation detector element
259/87-05	O	3	OT	Burned electrical connection between power boost current transformer and voltage regulator of DG
259/87-07	O	3	LC	Broken terminal lug and loose connection to control room inlet RM
261/87-3	I	12	DE	Questionable splice to power lead of SI valve
277/87-19	O	13	LC	RHR pump trip caused by loose connection at fuse
298/87-03	O	13	LC	Connections to feedwater flow recorder loose
309/87-3	I	2	DE	Unqualified splices to TCs and RTDs
309/87-5	I	12	DE	Terminal block found where a splice was required
312/87-42	O	3	BC	Electrical contact problems with Amphenol blue ribbon connectors
316/87-15	I	3	BC	Power range detector high voltage cable connector separated from cable after routine calibration
317/87-7	I	2	DE	Unqualified taped splices to SOVs
317/87-13	O	3	LC	Trip caused by loose connection on breaker which controls reactor coolant pump starts
321/87-02	O	13	LC	Trip caused by loose wire and conductive film on cable to main generator ground fault detector
322/87-05	O	13	BC	Worn cable and connection to meteorological delta temperature sensors-also LER 87-28
322/87-35	O	13	BC	Grounding problem in primary containment monitoring panel
328/87-08	I	13	BC	Poor ground on air RM detector cable
331/87-27	O	1	LC	Loose connection to RCIC isolation valve power supply caused valve to close
341/87-31	O	3	BC	Faulty connection to shaft rider vibration sensor on main turbine generator
341/87-46	I	2	DE	7 improperly installed heat shrink terminations
344/87-9	I	2	DE	Excessive bending radius of Raychem splices to PORV SOVs
344/87-37	O	3	LC	Loose connection in auto-start circuitry for turbine driven AFW pump
352/87-15	O	13	LC	HPCI turbine shutdown-loose flow controller lead
352/87-40	O	3	BC	Faulty connection to electro hydraulic control logic board
352/87-41	O	13	LC	Loose connection to RM
354/87-51	O	13	BC	Bad connection and degraded cable in main steam line RM drawer
361/87-28	I	3	BC	High impedance connection in RM from deposits

361/87-31	O	3	OT	Corrosion of power leads and terminal block to main feedwater isolation valve
362/87-11	O	3	LC	Loose bolt connection from instrument bus to main bus of non-1E uninterruptible power supply-intermittent loss of continuity
368/87-7	O	12	BC	Poor electrical contact at aluminum setscrew-type terminal lug to instrumentation distribution transformer
370/87-16	O	3	OT	Grounded motor lead connector on instrument air compressor due to insulating tape wear
373/87-26	O	2	DE	RHR motor terminations not installed as required for EQ
395/87-25	I	12	DE	Possibly unqualified tape splices
400/87-1	O	12	LC	Loose connections on digital CRD position indication
412/87-22	O	13	BC	Faulty connection to DG
413/87-15	O	3	OT	Trip caused by moisture in a terminal box caused fuse to blow for main feedwater isolation
423/87-10	I	13	LC	Loose plug connecting loose parts monitoring sensor coaxial cable to preamplifier
440/87-25	I	13	LC	Loose signal common connection to vessel pressure sensor
455/87-01	I	3	BC	Poor splice connection to reactor coolant RTD
456/87-32	O	3	LC	Loose connections in disconnect switch in rod control system power cabinet
461/87-07	I	13	BC	10 KΩ short in control circuitry caused actuation of SRV
461/87-43	O	3	LC	Loose connection on the turbine trip vibration detection circuitry caused scram
461/87-66	I	3	DE	156 electrical junction boxes and panels found without drain holes as required for EQ
482/87-19	O	13	BC	Broken shield on coaxial cable connector to containment purge exhaust RM
482/87-22	O	3	LC	Trip caused by loose connection at breaker for turbine building fan
482/87-37	O	13	BC	High resistance and heating at bolted T-pad connection
482/87-52	I	2	DE	Terminations on instrument circuits not installed as required for EQ
482/87-54	O	3	OT	Moisture induced corrosion of a connector to containment atmosphere RM
482/87-58	I	3	DE	Containment area RM connections not installed as required for EQ
244/88-01	I	3	BC	Faulty connections at SRM
259/88-01	I	3	LC	Loose solder connection in temperature switch
265/88-09	O	1	BC	Five high resistance connections in station battery connections reduced capacity to 58%
395/88-02	O	3	DE	Poor design allowed loosening of test board terminal posts for power range monitor-plant trip
413/88-5	I	2	DE	Buchanan terminal blocks potentially not qualified for use in MOVs inside containment
416/88-10	O	13	LC	Trip caused by loose connection which deenergized scram pilot solenoids
458/88-06	O	3	OT	Flashover from phase to ground due to moisture intrusion from a leaking service water valve resulted in recirculation pump motor trip
483/88-03	I	3	DE	Containment area RM connections at EPA not installed as required for EQ
498/88-4	O	2	LC	Loose connection to control room toxic gas monitor
498/88-8	I	12	DE	Improper installation of cable splices

APPENDIX C EPA Events

In the following tabulation, the two character codes refer the categorization of Table 10.

LER #		Description
255/80-8	LE	Leaking EPA--cause not determined-also LER 83-66
261/80-14	DE	EPA's with PVC insulation-no EQ data on PVC
285/80-7	DE	No LOCA qualification for splices to EPA
285/80-11	LE	Excessive EPA leakage
409/80-1	LE	Cracked EPA glands-leak rate exceeded
029/81-13	LE	Excessive leakage due to loose flanges on Chicago Bridge and Iron EPA
270/81-2	LE	MV EPA cracked inboard insulation bushing SF_6 loss-also LER 81-14.
328/81-138	OT	Defective EPA cable conductor to reactor coolant pump thrust bearing temperature monitor
280/82-92	EF	Faulty rod position indication due to EPA exposure to excessive moisture
346/82-35	OT	Degradation on insulation to SRM in EPA module
409/82-11	LE	3 cracked EPA glands-leak rate exceeded
348/83-7	LE	Excessive leakage due to cracked metal "O"-ring-probably occurred during repair during previous outage
362/83-65	OT	Faulty EPA to high range radiation monitor
409/83-2	LE	Cracked EPA glands-leak rate exceeded
281/84-05	EF	Water in electrical penetration to motor leads of reactor coolant pump caused pump to trip
285/84-9	DE	EPAs failed qualification test
271/85-10	EF	6 GE EPAs-potential shorting due to sharp edges on EPA assembly, reported shorts
348/85-12	EF	Short in EPA to control rod grippers caused supply fuse to blow and reactor trip-also LER 86-4
348/85-16	EF	Shorts in GE EPA's, 14 of 55 modules had shorts between adjacent pairs
247/86-13	DE	Discovered a circuit that could become submerged during LOCA conditions-not qualified to function-rerouted circuit in another EPA
249/86-24	DE	EPA's with butt splices failed EQ tests because of excessive leakage
254/86-37	DE	EPA's with butt splices failed EQ tests because of excessive leakage
348/86-8	EF	Electrical shorts in GE penetrations
206/87-10	OT	Installation damage to pigtails of penetration
344/87-11	LE	Excessive leakage past conductor seals--permanent compression set of seals
213/88-6	DE	Flooding could cause submergence of terminal blocks connected to EPA

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Date	Plant		Description
11-74	DRES 2	LE	Cracks in inner epoxy seal GE
5-74	HATCH1	LE	Failed seals around conductors (GE 100 series)
10-77	MILL 2	EF	Electrical faults between adjacent conductors (GE 100 series EPA)
9-77	MILL 2	EF	Low IR's adjacent conductors-moisture intrusion
10-79	COOK 1	EF	Faulty Westinghouse containment cable penetration
10-80	SEQ 1	EF	RTD lead resistance excessive-faulty penetration with defective lead
7-72	SURRY1	LE	Heat generation in EPA connector-degradation and failure with loss of pressure seal at interface
10-75	OCON 2	LE	Cracked insulation bushing-exterior side SF_6 loss
10-76	OCON 2	LE	Cracked insulation bushing-reactor side SF_6 loss
'73-'75	OCON	LE	Units 1-3 EPAs leaking flange-seal corrosion; MV EPA's stress on bushings caused cracking of in & out board insulating seals
'60-'65	YAN RO	LE	Leaking inner seal-defective inner seal moisture intrusion field manufactured unit
11-75	YAN RO	OT	Cracked glands on MI cable excessive outward pressure-General Cable Corp. seal
7-81	Various	DE	Catawba 1&2, McGuire 1&2, and Yankee Rowe-EQ test shows potential for connector insulation on D. G. O'Brien EPA to expand and strip cable insulation, causing electrical shorts-connectors have been redesigned

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This report examines effects of aging on cables, connections, and containment electrical penetration assemblies (EPAs). Aging is defined as the cumulative effects that occur to a component with the passage of time. If unchecked, these effects can lead to a loss of function and a potential impairment of plant safety. This study includes a review of component usage in nuclear power plants; a review of some commonly used components and their materials of construction; a review of the stressors that the components might be exposed to in both normal and accident environments; a compilation and evaluation of industry failure data; a discussion of component failure modes and causes; and a brief description of current industry testing and maintenance practices.

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