Electrical Connectors Application Guidelines

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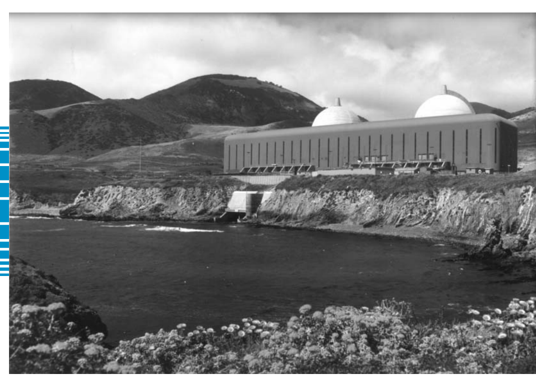

Electrical Connector Application Guidelines

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REPORT SUMMARY

This application guide provides an overview of electrical connectors found in nuclear power plants, summarizes connector failure and aging mechanisms, and provides general guidance and best practices for installing and inspecting specific connector types.

Background

There are hundreds of thousands of electrical connectors and a wide variety of connector types found in a typical nuclear power plant. Electrical connectors in nuclear power plants are an essential part of the systems required for plant startups and daily operation. They also play an essential role in the safe shutdown of the plant and the protection of public health and safety following anticipated operational occurrences and other design-basis events. To date, the performance and reliability of connectors have been good. However, electrical connectors are subject to age-related degradation mechanisms and so may become more prone to failure as nuclear power plants age. In addition, the replacement of existing plant equipment and installation of new equipment, particularly instrumentation, control, and computer equipment, are increasing the number and variety of connectors in nuclear plants.

Objective

- To provide an overview of electrical connectors found in nuclear power plants
- To discuss connector failure and aging mechanisms
- To provide plant personnel with general guidance and best practice for installing and inspecting specific connector types

Approach

A literature search was conducted to identify relevant publications and journal articles. Members of the Technical Advisory Group (TAG) were contacted for information regarding plant connector issues as well as for plant-specific installation procedures. A review was conducted of available failure data and problem reports from the database of the Institute of Nuclear Power Operations (INPO), from the Nuclear Power Reliability Data Systems (NPRDS), and from the Equipment Performance Information Exchange (EPIX), as well as from the United States Nuclear Regulatory Commission (U.S. NRC) Licensee Event Reports (LERs). Relevant U.S. NRC publications (for example, NRC documents [NUREGs]) and information notices were also reviewed. Published vendor information and component catalogs were collected. A summary description of connector types and common connector failure and aging mechanisms was prepared, along with guidance and best practices for specific connector types.

A draft of the guide was submitted to members of the TAG and the EPRI Nuclear Maintenance Applications Center (NMAC) for review and comment. The guide was structured to readily accommodate expansion to include guidance on additional connector types in future revisions.

Results

This document provides an overview of electrical connectors found in nuclear power plants, summarizes connector failure and aging mechanisms, and provides general guidance and best practices for installing and inspecting specific connector types.

EPRI Perspective

Each year NMAC performs an annual review of maintenance issues to identify existing or potential maintenance issues faced by nuclear plants within the United States. In recent years, an evaluation of unplanned capacity loss factor data has indicated a need to investigate the subject of electrical connections. The evaluation has shown that electrical connections within several specific plant systems have directly or indirectly caused plant transients, unit load reductions, or forced outages. The purpose of this effort was to provide an overview of electrical connectors, discuss failure and aging mechanisms, and provide some good practices for installing and inspecting connectors.

Key Words

Electrical connector
Lug
Splice
Termination
Preventive maintenance
Thermography

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ABSTRACT

This report explores types of electrical connectors and splices found in nuclear power plants. Also discussed are connector and hardware materials, as well as failure and aging mechanisms. Available industry guidance on environmental qualification and life extension of electrical connectors is summarized. The report also provides guidance and best practice for installing and inspecting specific connector types. A bibliography listing connector references is included.

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INTRODUCTION

1.1 Background

A typical nuclear power plant contains approximately 50,000–60,000 electrical cables routed in cable trays, conduits, duct banks, and wireways. There are hundreds of thousands of electrical connections in the form of splices and terminations associated with these cables. In addition, power plants have an equally large number of electrical connectors internal to electrical enclosures and electrical, electronic, and computer equipment. These connectors come in a wide variety of types and sizes and are supplied by a large number of different vendors.

Electrical connectors are an integral part of all electrical, electronic, and computer systems. These connectors must function properly to ensure reliable operation of the power plant. Available failure data for connectors show that the number of connector failures is very low in proportion to the large number of connectors found in nuclear power plants.

There are a number of reasons for the low failure rates of cable and connectors in nuclear power plants. Corrective action programs document, track, and trend equipment failures. Programs that implement the requirements of 10CFR Part 50.65 (Maintenance Rule) [1] monitor the performance and condition of certain safety-related and nonsafety-related systems, structures, and components to ensure that they are capable of fulfilling their intended functions. Equipment Qualification programs (10CFR Part 50.49) [2] ensure that systems, structures, and components are designed and installed to be compatible with the environmental conditions associated with normal plant operation, maintenance, and testing, as well as postulated accidents. However, despite low failure rates, when connector failures occur, they can cause equipment shutdowns, plant trips, forced outages, and sometimes fires.

As plants age, degradation mechanisms related to age begin to affect the reliable performance of electrical connections. Especially for those connectors that are not environmentally qualified, these degradation mechanisms become more of a concern to the nuclear power industry as the population of plants advances in age. Figure 1-1 shows that of the 107 licensed reactors currently operating in the United States, 62 reactors have been operating for more than 20 years [3]. Of that number, 10 have been operating for more than 30 years.

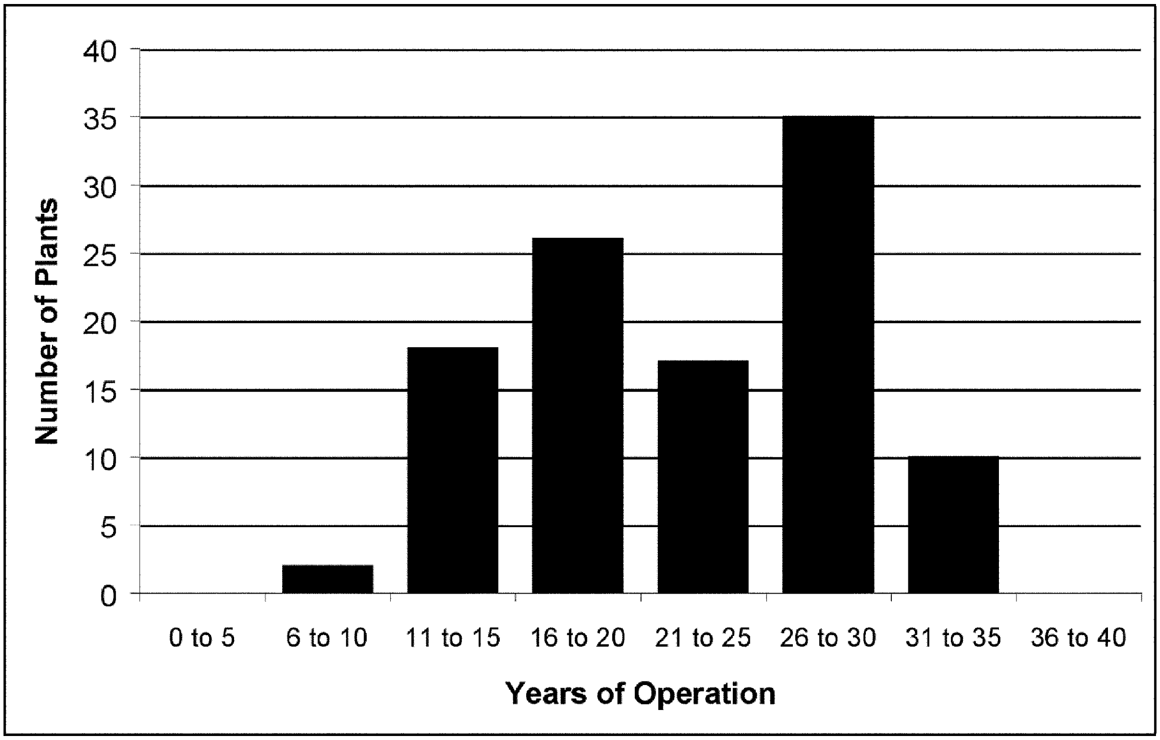


Figure 1-1
Years of Operation for U.S. Nuclear Power Plants as of 2002

1.2 Purpose

The purpose of this guide is to provide an overview of the wide variety of electrical connectors found in power plants and to summarize the types of connector failures that occur and the aging mechanisms for which plant personnel need to be vigilant. This guide also provides general guidance and summarizes best practice for selecting, installing, and inspecting specific connector types.

Initial input from utility personnel indicated that crimped and bolted electrical connectors are of particular interest. Furthermore, these connector types represent the largest number of connectors in power plants. Although crimped and bolted electrical connectors are generally reliable, when failures do occur, they can result in serious consequences.

This guide is intended for plant maintenance personnel, system engineers, and design engineers.

1.3 Approach

For this application guide, the topics covered were determined based on input obtained from plant end users (those individuals who would refer to an application guide on electrical connectors in the future) as well as on the results of failure data (which gives insight into the types of problems readers might experience themselves).

Once the topics were determined, information was gathered from a wide variety of sources, such as:

- Technical literature, including conference proceedings, earlier publications by EPRI, and published documentation available in the public domain
- Guidance from engineering textbooks and handbooks
- Vendor data available on-line as well as in vendor catalogs
- Plant procedures and personal interviews provided by interested utilities and members of the Technical Advisory Group (TAG)
- Failure data, which were obtained by a review of documents publicly available from the United States Nuclear Regulatory Commission (U.S. NRC) and published literature and by study of reported events contained in the Institution of Nuclear Power Operation (INPO) Equipment Performance Information Exchange (EPIX) database.

1.4 Organization

Section 2 of this guide provides an overview of the various connector types found in nuclear power plants. Section 2 also identifies the connector vendors whose equipment is commonly found in nuclear plants in the United States and common hardware and materials used to construct connectors.

General guidance, summaries of industry best practice, and vendor recommendations for selecting, installing, and inspecting specific connector types are detailed in Section 3.

Industry experience and connector degradation mechanisms are discussed in Section 4. This section provides a summary of failure data reported for electrical connectors used in nuclear power plant service based on industry sources and failure event reports.

Finally, this guide includes three appendices. Appendix A provides a comprehensive bibliography of connector references that will be useful to readers who wish to delve further into the subject matter. Appendix B provides a discussion of infrared imaging technology available for performing *in situ* monitoring of the condition of electrical connectors as part of a condition-based maintenance program at a nuclear power plant. Appendix C summarizes electrical connector equipment qualification. This is an essential part of ensuring that equipment important to safety can accommodate the effects of and be compatible with the environmental conditions associated with normal nuclear plant operation, maintenance, and testing, as well as postulated accidents, for the qualified life of the connector. Appendix C also discusses how the qualified life of the connector can be extended as might be necessary for those plants considering license renewal.

1.5 References

1. *Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants.* Title 10, Code of Federal Regulations, Part 50.65.

2. *Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants,* Title 10, Code of Federal Regulations, Part 50.49.

3. *2002 World Nuclear Industry Handbook*. Nuclear Engineering International, 2002.

2
ELECTRICAL CONNECTOR OVERVIEW

In a power plant, electrical connectors and splices are ubiquitous. They are found in the high-voltage systems that provide the electrical interface between the power plant and the electric power transmission system. There are numerous electrical connectors and splices in medium- and low-voltage power systems. Effective plant grounding systems rely heavily on connectors and connection joints. There are a large number and variety of electrical connectors and splices used in plant instrumentation and control systems, plant security and communication systems, plant data and monitoring systems, and plant computer systems.

A typical nuclear power plant contains approximately 50,000–60,000 electrical cables routed in cable trays, conduits, duct banks, and wireways. There are hundreds of thousands of electrical connections in the form of splices and terminations associated with these cables. There are an equally large number of electrical connectors found in high-voltage switchyards, medium- and low-voltage switchgear, motor control centers, segregated and non-segregated bus ducts, equipment and structure grounding systems, control cabinets, and other electrical enclosures. There are also a large number of connectors internal to electronic and computer equipment, many of which were installed at the factory versus at the plant.

Electrical connectors are an integral part of essentially all electrical, electronic, and computer systems. They are a vital part of systems required for power plant startup, power operation, and shutdown. In a nuclear power plant, electrical connectors and splices are also integral parts of Class 1E or safety-related systems and components. As such, they are essential to the safe shutdown of the plant and the protection of the health and safety of the public following anticipated operational occurrences and other design-basis events such as loss-of-coolant accidents and external plant hazards.

2.1 The Essence of an Electrical Connector

The Institute of Electrical and Electronics Engineers (IEEE) Standard 100 [1] defines an electrical connector as “a coupling device employed to connect conductors of one circuit or transmission element with those of another circuit or transmission element.” Fundamentally, electrical connectors are electromechanical systems. They provide an electrical connection or bonding between two or more subsystems or components by various mechanical means.

Functionally, a good connector or splice should not introduce significant power loss, voltage drop, or ohmic heating into the circuit. For instrumentation, control, and communication circuits, a good electrical connector should not introduce unacceptable signal distortion or degradation (that is, the integrity of the signal waveform and amplitude should be preserved). In that regard, digital signals have signal rise-times that are typically much shorter than analog signals. As pulse rise-times approach the nanosecond range, it becomes necessary to consider electrical connectors as electromagnetic transmission lines because of the wavelengths involved. Special design and installation techniques are required for connectors used in circuits transmitting high-speed digital signals.

Some connectors are intended or expected to provide a separable interface between the mated subsystems or components. Separable connectors are necessary to facilitate disassembly, maintenance, or reconfiguration of the associated subsystems or components. Separable connectors include ring-tongue and fork-tongue termination lugs, bolted connectors, and plug and socket connectors. In contrast, some connectors are intended to provide a permanent interface between the mated subsystems or components. Permanent connections are created metallurgically or mechanically. Examples of metallurgical-type permanent connectors include exothermic fusion welds commonly used for grounding system connectors, and solder connections. Crimp and compression connectors and in-line cable splices are examples of mechanical-type permanent connectors.

Most functional connector systems are really a combination of both a separable and a permanent connector. Consider, for example, a simple #12 American wire gauge (AWG) wire landed on a terminal strip in a typical control cabinet with ring-tongue termination. A permanent crimp connection conjoins the wire to the termination ring-lug barrel, and a threaded screw fastener secures the ring-lug tongue to the terminal strip, forming a separable connection. For a reliable connection, both parts of the connector have to be selected and installed properly using compatible materials and the right tools.

Key Technical Point

Most functional connector systems are really a combination of both a separable and a permanent connector. Both parts have to be selected and installed properly using compatible materials and the right tools.

2.2 Power Plant Connector Types and Materials

In a typical power plant, there is a wide variety of connector types and sizes. These connectors are supplied by a number of different vendors. Table 2-1 lists suppliers of connectors and splices commonly found in U.S. nuclear power plants. There has been a substantial amount of consolidation in the electrical equipment industry since the construction of most nuclear power plants in the United States. In addition, a number of foreign suppliers have entered the market. For example, a number of trade names such as Amp, Buchanan, and Raychem have been consolidated under Tyco Electronics. Burndy is now part of Framatome Connector International (FCI). As part of the consolidation in the industry, some product lines have been discontinued or modified significantly since the time of original plant construction. For the most part, even for safety-related Class 1E applications, the products available in today’s market are commercial grade items.

Table 2-1
Common Electrical Connector and Splice Manufacturers

3M	Conax	Marathon
Alpha	Connectron	Namco
AMP	Dosset	Omega
Amphenol	Deutsch Elastimold	Panduit
Anderson	EGS (Grayboot)	Patel
Bendix	General Electric	Raychem
Bishop	ILSCO	Rosemount
Blackburn	ITT Canon	Thomas & Betts
Buchanan	Kerite	Tyco Electronics
Burndy	Kulka	Weidmuller
Cadweld	Litton-Veam	Westinghouse

The ongoing addition of electronic and computer-based equipment to plants today is expanding the type and number of connectors found in power plants. For example, edge-type connectors commonly used for printed circuit boards and other electronic components, D-type connectors often found on various computer and communications cables, and various pin and socket connectors play an increasing role in plant monitoring and control systems. This will continue to occur as new equipment is introduced into plants and as plants address the obsolescence of existing instrumentation and control equipment.

2.2.1 Types of Electrical Connectors

Common power plant connectors include:

- **Bolted connectors -** A variety of types and styles of bolted connectors can be found in power plants. Split bolt connectors, for example, were often used in equipment bonding cables. Bus and terminal connections often employ bolted joints.
- **Coaxial and triaxial connectors -** Coaxial and triaxial connectors are commonly used in instrumentation circuits, especially with high-frequency signals. There is a wide variety of types and styles of coaxial and triaxial connectors. For example, BNC connectors are commonly used for these types of connections.
- **Compression connectors -** Compression connectors provide permanent, high-quality connections. They require specific tools and dies for installation. Crimped connectors are a type of compression fitting.
- **Crimped connectors -** Crimped connectors are probably the most widely used connectors in power plants. They are used in both power and control circuits. A crimped connection

involves inserting a wire or cable into a connector and applying compacting force to the connector. The conductor and connector are deformed in order to form a single body.

- **D-Type connectors -** There is a great variety of sizes and styles of D-type connectors. They are commonly used with multi-conductor computer and telecommunications cables.
- **Edge connectors -** Edge connectors are often used to connect circuit cards to wires. These type of connectors are typically found internal to plant electronic, computer, and telecommunications equipment.
- **Ferrules -** Ferrules are often used to protect wire strands from fraying or breaking. There are insulated and uninsulated ferrules. Insulated ferrules are sometimes used to provide an added insulation barrier when the insulation barrier of a terminal strip is short or narrow.
- **Fusion connectors -** Exothermic welding is a process in which an electrical connection is made by pouring superheated, molten copper alloy on and around the conductors to be joined. The molten copper alloy, contained and controlled within a semi-permanent graphite mold, causes the conductors to melt and fuse together. When installed properly, exothermic fusion connectors exhibit sound electrical properties. Fusion connectors are widely used in grounding systems.
- **Insulation displacement connectors (IDC) -** IDCs are found in a variety of electronic and computer equipment. Unlike a crimped connection, fabricating an IDC does not require the removal of the wire insulation. An IDC pierces and displaces the conductor insulation as the wire or cable is inserted into the terminal or connector housing. IDC connectors are widely used with ribbon cable. They are designed for lower installation costs and sometimes require special tooling to install.
- **Pin and socket connectors –** Pin and socket connectors are available in a variety of types and styles. Amphenol connectors are a common type of pin and socket connector found in radiation monitoring equipment, nuclear instrumentation systems, and other vendor-packaged equipment. Some auxiliary relays use pin and socket connectors to mate the coil and contact unit to the wire terminal base.
- **Soldered connections -** Soldered connections are used in a variety of electrical connections, particularly those included in electrical, electronic, and computer equipment assembled at the factory. The soldering process consists of five key elements: 1) the solder, 2) fluxes to clean the surfaces to be soldered, 3) the conductor type and material, 4) the time and temperature used in the soldering process, and 5) the final cleaning process.
- **Splices -** Electrical splices are used to join two or more similar but noncontinuous conductors into one continuous run. Electrical splices are also used to join two unconnected continuous runs. Electrical splices involve a mechanical connection, such as a bolted joint or crimp connector, and an insulation system. Heat-shrink materials and tape-wrap materials are used for splice insulation systems. Raychem supplies a variety of environmentally qualified heat-shrink kits. 3M and Bishop are common suppliers of taped splice material. Some plants are also using 3M cold-shrink splice kits.
- **Stress cone terminations** - Stress cone terminations are cone-shaped stress relief devices used on high-voltage cable. Cable insulation is increased at the end of a shield termination to reduce the stresses that concentrate at that point. These stresses could otherwise cause a

breakdown of the cable insulation at the end of a shield termination. Newer terminations are tubular rather than conical and now employ high dielectric compounds to reduce stresses.

- **Terminal lugs -** Terminal lugs are used to land a conductor onto a terminal strip, bus pad, bushing, or other such terminal.
- **Wedge type connectors -** Wedge type connectors are a unique category of mechanical connectors. The wedge connector incorporates a wedge component and a tapered, typically C-shaped spring body (or C-body). During installation the wedge is driven between two conductors placed in the C, spreading the C-body, which in turn places high forces on the conductors for a reliable, stable connection. There are two basic means by which the wedge is driven into the C member: 1) a specially designed tool system that fires a cartridge to propel the wedge at high velocity (powder actuated), and 2) a mechanical drive bolt that, when tightened, drives the wedge between the conductors. Wedge connectors are used primarily in tap applications. Wedge connectors can be used to make connections between combinations of aluminum, copper, and aluminum conductors steel reinforced (ACSR) conductors. Wedge connectors are commonly used in overhead high-voltage systems and grounding systems.
- **Wrapped connections -** Wrapped connections, which are frequently referred to by the trade name Wire Wrap, are often used to connect wire to pins or posts inserted into printed circuit boards. Wrapped connections are commonly found in electronic and computer equipment, especially on backplane panels.

2.2.2 Materials Used in Electrical Connectors

2.2.2.1 Materials of Construction

The main types of materials used to construct connectors are metals and plastics. Metals are used to conduct electric current through the connector. Metals are also used as plating added to protect connectors from oxidation. Plastics and other materials (like porcelain and rubber) are typically used as insulators and housings. Table 2-2 lists materials of construction used for connectors.

Table 2-2
Common Materials Used in Electrical Connectors

Category	Material	Application
Metals	Aluminum	Connector body Hardware Splice sleeve Connector housing
	Beryllium copper	Center conductor in coax connectors Female contacts in socket connector
	Brass	Connector housing Terminal body Connector hardware
	Bronze	Grounding clamps Connector body Connector hardware
	Cadmium	Connector housing plating
	Copper	Terminal body Crimp barrel sleeve Splice sleeve
	Gold	Terminal plating
	Nickel	Connector plating Connector housing plating Terminal body
	Phosphor bronze	Terminal body
	Silicon bronze (Durium)	Connector hardware
	Palladium nickel	Socket connector pins
	Silver	Terminal plating
		Connector housing Splice sleeve Connector hardware Belleville washers
	Tin	Terminal plating Housing plating
	Zinc	Terminal plating Housing plating Connector hardware plating

Table 2-2 (cont.)
Common Materials Used in Electrical Connectors

Category	Material	Application
Plastics	Cross-linked polyethylene (XLPE)	Connector insulation
	Cross-linked polyolefin (XLPO)	Heat shrink caps Heat shrink tubing Connector covers
	Delrin	Coax connector dielectric
	Diallyl phthalate	Insulator
	Kynar (polyvinylidene fluoride)	Connector insulator
	Nylon	Crimp barrel insulation Connector housing
	Phenolics	Terminal blocks Connector housing
	Plastisol	Connector covers
	Polyamide	Connector housing, dielectric
	Polycarbonate	Insulator Connector housing
	Polyester	Insulator Connector housing
	Polyethylene (PE) and high-density PE	Connector covers Connector housing
	Polymethylpentene (PM)	Coax connector dielectric
	Polyphenylene sulfide	Connector housing dielectric
	Polypropylene (PP)	Coax connector dielectric Terminal block Connector cover
	Polyvinyl chloride (PVC)	Heat shrink tubing Connector covers Insulator
	Rubber (EPDM)	Cold shrink tubing
	Stanyl	Connector housing Connector cover

Table 2-2 (cont.)
Common Materials Used in Electrical Connectors

Category	Material	Application
	Styrene	Connector housing
	Teflon	Coax connector dielectric
	Tefzel (ethylene tetrafluoroethylene)	Pre-insulated terminals
	TFE fluorocarbon	Coax connector dielectric
	Thermoplastics	Connector housing Connector cover
	Zytel	Insulator Environmental cover
Other Materials	Fluorocarbon	Connector housing gasket
	Neoprene	Connector housing gasket
	Porcelain	Connector housing
	Rubber	Insulator, connector cover

2.2.2.2 Electrical Joint Compounds

Electrical joint compounds prevent the formation of oxides on contact surfaces and prevent moisture from entering the connection. Electrical joint compounds are generally applied after the mating surfaces of the connector are prepared and prior to the assembly of the connector joint. These products are available in many varieties.

In considering the use of a joint compound, it is important to select a product that is suitable for each particular application. Most electrical joint compounds can cause personal safety hazards such as irritation and burns if they come in contact with the eyes or have prolonged contact with the skin.

Key Human Performance Point

Joint compounds can cause irritation to the eyes or burns upon prolonged skin contact. Follow the manufacturer's safety precautions when using these materials.

When selecting a joint compound, consider the connector materials being used and the environmental conditions which the connector will experience. The use of an effective electrical joint compound is especially important with connections involving aluminum conductors. Some of the more common compounds are listed below.

- **Petrolatum -** The use of petrolatum (trade name Vaseline) to prevent oxidation of electrical contacts dates to the late 1800s. It helps prevent oxidation of contact surfaces and keeps moisture away from those surfaces. Petrolatum can be used for copper and plated copper connections.
- **Alcoa Filler Compound (AFC) -** AFC is a light-tan-colored grease with solid grit particles. It is recommended by Alcoa for use as filler for compression connections involving aluminum conductors. As the compression fitting is made, the AFC is forced around the strands and thereby seals out air and moisture. The solid grit particulate present in the compound abrades the sliding interfaces of the connector's mating surfaces. The abrasion of the oxide film and subsequent sealing of the mating surfaces yield an electrical interface with low contact resistance.
- **Alcoa No. 2 Electrical Joint Compound (EJC) -** Alcoa No. 2 EJC is recommended by Alcoa for use on aluminum-to-aluminum and aluminum-to-copper connections involving flat surfaces such as rectangular bus-to-bus or terminal pad-to-bus connections. Alcoa No. 2 EJC is a brown grease that contains a microcrystalline wax made of petroleum oil blended with a proprietary corrosion inhibitor. It also contains a proprietary detergent compound and hydrogen fluoride. These compounds act to dissolve oxide films on contact surfaces and seal the mating surfaces against moisture. The flow point for Alcoa No. 2 EJC is approximately 150°F (65.6°C). Alcoa No. 2 EJC is corrosive to steel and tinned copper and should not be used for applications involving these materials.
- **Alnox EJC -** Alnox EJC is recommended by Alcoa for use with aluminum-to-aluminum and aluminum-to-copper parallel-groove clamp and compression connectors exposed to the weather and elements. Alnox EJC is a gray-colored grease with an aluminum and nickel grit. Alnox is workable at low temperatures. Its melting point is above 500°F (260°C).
- **Alnox-UG -** Alnox-UG electrical joint compound is recommended by Alcoa for use with connectors on aluminum or copper conductors where compatibility with rubber products is required. It is particularly suited for use underground. Alnox-UG is a gray-colored grease with an aluminum and nickel grit, polyglycol fluid, and a lithium hydroxy-based thickener. Alnox-UG is weather resistant and workable at low temperatures. Its melting point is above 375°F (190.6°C).
- **NO-OX-ID A-Special -** NO-OX-ID is recommended by its manufacturer, SANCHEM, Inc., for use on copper-to-copper, bronze-to-bronze, and aluminum-to-aluminum contact surfaces to prevent the formation of oxides, sulfides, and other corrosion deposits. NO-OX-ID is applied as it comes from the container, using a brush or rag. NO-OX-ID is rubbed onto the metal thoroughly to absorb all moisture and to ensure coverage of all surface irregularities. The appropriate coating thickness varies with the severity of the connector service environment.
- **Penetrox -** Penetrox is a synthetic-based anti-oxidant compound manufactured by FCI. It can be used for aluminum-to-aluminum and copper-to-copper connections. There are different formulations of Penetrox, some with suspended particles of copper and some with suspended zinc particles. After they are applied, Penetrox compounds have a high melting temperature of approximately 500°F (260°C).
- **Aluma-Shield -** Aluma-Shield is a Thomas & Betts product that is sometimes referred to by its catalog number, 21059. It is used for aluminum cable connections. Aluma-Shield contains

fine zinc particles that break through the oxide film on cable strands upon compression of the connector. Using the compound seals out air and moisture and helps ensure a low-resistance connection. Aluma-Shield is Underwriters Laboratories Inc. (UL) listed only for use on electrical cables in cable connector assemblies or on bus bars rated for National Electrical Code (NEC) applications up to 8 kV and 194°F (90°C).

2.3 Power Plant Connector Performance

Despite the large number and diversity of connector types, the in-service performance of power plant electrical connectors and splices has been very good. The number of connector failures that occur is very low in proportion to the total number of connectors found in today's nuclear power plants. Connectors in medium-voltage systems and in low-voltage power, control, and instrumentation systems have low failure rates.

There are a number of reasons for the low failure rates of cable and connectors in nuclear power plants. Corrective action programs document, track, and trend equipment failures. Programs that implement the requirements of 10CFR Part 50.65 (Maintenance Rule) [2] monitor the performance and condition of certain safety-related and nonsafety-related systems, structures, and components to ensure that they are capable of fulfilling their intended functions. Equipment Qualification programs (10CFR Part 50.49) [3] ensure that systems, structures, and components are designed and installed to be compatible with the environmental conditions associated with normal plant operation, maintenance, and testing, as well as postulated accidents. Factors that contribute to the low failure rates of cable and connectors in nuclear power plants include:

- Electrical cable and termination systems are ubiquitous throughout the world, and the technology is very mature.
- The electricians and instrumentation and control technicians who install cable connectors and terminations in power plants are skilled craftsmen who receive periodic training.
- Electrical cables and connector installations in nuclear power plants are subject to various quality assurance and quality control checks.
- Electrical cables and connector installations in nuclear power plants fall within the scope of a number of programs (such as in-service testing and functional testing) that are aimed at identifying and correcting problems and ensuring component reliability.
- Periodic test and surveillance efforts, which help to ensure that standby safety systems are operable and capable of performing their intended safety functions, include cables and connector systems.
- The normal operating environments for electrical connectors in a nuclear power plant are generally controlled and mild.
- The reporting of problems and best practices to the industry by the U.S. NRC, EPRI, INPO, Nuclear Energy Institute (NEI), and other organizations helps to eliminate bad actors and prevent the reoccurrence of problems.

Despite having low rates of failure, the integrity and reliability of electrical connectors are important elements to be considered for safe plant operations, continued improvement in plant availability, and aging management. Section 4 of this guide discusses connector failure and connector aging mechanisms.

2.4 References

1. *The IEEE Standard Dictionary of Electrical and Electronic Terms, Standard 100-1996,* 6th Ed. Institute of Electrical and Electronics Engineers, Inc., Piscataway, NJ, 1996.

2. *Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants.* Title 10, Code of Federal Regulations, Part 50.65.

3. *Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants,* Title 10, Code of Federal Regulations, Part 50.49.

3
GOOD PRACTICES FOR CONNECTORS

Review of nuclear power industry procedures and discussions with personnel in the industry show that the selection, design, and installation of terminal lugs on conductors, including bolting these lugs to terminal points, are common activities and key areas of interest. This section summarizes good practices associated with these types of connectors. Specifically addressed are recommended practices to follow when selecting connecting lugs, when crimping lugs onto the ends of conductors, and when completing bolted joints. In addition, the section provides general guidance and recommends good practices for assembling electrical connectors based on industry experience and plant procedures.

3.1 Good Practices for Lug Selection

Manufacturers provide a wide array of choices for connector lugs. The appropriate lug selection to use for a given application varies with the conductor material, size, circuit current capacity, and configuration of the connected conductors. Examples of design parameters to consider when selecting a terminal lug are presented in Table 3-1.

Table 3-1
Terminal Lug Design Considerations

Parameter	Options	Comments
Lug material	Copper vs. aluminum	Choice depends on materials of conductor and terminal contact surface (see Table 3-2).
Connection between conductor and lug	Mechanical vs. compression	Plants commonly use compression connectors (crimped) instead of mechanical connectors for terminal lugs. Mechanical connectors are often used in grounding systems.
Lug tongue shape	Ring vs. rectangular vs. fork	Plants generally permit use of either type. Rectangular lugs are specified where more than one bolt hole is required. Forked lugs are commonly used when a connection is intended to be relanded frequently.
Lug angle	Flat vs. bent	Bending lugs to limited angles is permitted for certain types of lugs per the manufacturer's specifications. Lug bending can facilitate installation in constrained spaces.
Number of lug bolt holes	Single vs. multiple	Use of multiple bolt hole lugs prevents the lug from rotating around the stud. Such rotation can result in degradation of the electrical contact between the lug and the contact surface.
Number of lugs connected to a terminal stud	Single vs. multiple	Nuclear power plants generally limit the number of lugs per stud to no more than two, unless otherwise specified by design drawings. This helps ensure sufficient engagement of the fastener and that adequate dielectric creep distance is achieved.

3.1.1 Lug Material

The lug material used for the termination needs to be compatible with the conductor material to avoid any kind of galvanic action. Conductors are generally made from copper or aluminum materials. Aluminum is anodic relative to copper; therefore, aluminum is subject to galvanic corrosion when connected to copper in the presence of an electrolyte. The materials to be used for electrical connectors are chosen so as to minimize the galvanic attack of aluminum components in the connection. Table 3-2 provides a matrix of connector materials to be used for connection of various types of conductors [1]. This table reflects the experience of equipment manufacturers and utility companies and is based on the following logic:

- For joining like materials (aluminum-to-aluminum or copper-to-copper), use a connector made of the same material. This is appropriate since there will be no dissimilar metals and hence no galvanic attack.

Key Technical Point

When aluminum components are involved in a connection, select connector materials so as to minimize the potential for galvanic corrosion of the aluminum components.

- For joining aluminum-to-copper materials, use an aluminum-bodied connector. This will prevent galvanic corrosion of the aluminum conductor, which is the most vulnerable element to attack in the connection. The surface area of the aluminum connector should be massive in comparison to the surface area of the copper conductor where it emerges from the connection. This will reduce the electrolytic current density over the exposed face of the aluminum connector. Since the galvanic corrosion rate is directly related to the current density on the surface of the anodic aluminum material, the relatively large surface of the aluminum connector will suffer only mild galvanic corrosion.

Other considerations for corrosion protection and material selection are provided in Appendix C of this guide.

Connector materials are often plated to prevent oxidation, which would otherwise form on most metals (with the exception of gold). Several materials are available for plating purposes including tin, lead, nickel, silver, gold, or alloys containing these metals. Plating is typically done by electroplating or in some cases by hot dipping.

Military Standard MIL-T-10727 specifies a minimum plating thickness for the purposes of corrosion protection of 0.001 in. (1 mil) on the visible surfaces [2].

Table 3-2
Connector Material Selection [1]

When Connecting…	To…	Use this Connector Material
Aluminum	Aluminum	Aluminum
Aluminum	Tinned aluminum	Aluminum
Aluminum	Tinned copper	Aluminum
Tinned aluminum	Copper	Silicon bronze
Tinned aluminum	Tinned copper	Aluminum or silicon bronze
Copper	Copper	Copper or silicon bronze
Copper	Tinned copper	Copper or silicon bronze
Silicon bronze	Silicon bronze	Copper or silicon bronze

3.1.2 Lug Design Features

3.1.2.1 Barrels

The barrel is the part of the lug that receives the bare conductor and is crimped around the conductor. During assembly, the conductor is pushed inside the barrel until it reaches appropriate position. The barrel is then squeezed or deformed around the conductor to form the crimp.

In many lug models, dimples (or serrations) on the barrel inner surface are provided to improve the strength of the crimped connection by providing additional contact surface between the conductor and the lug barrel. To facilitate the admission of the conductor into the barrel, lug manufacturers often provide a funnel, bell, or chamfered-type entry path on the open end of the barrel. This is particularly helpful when using multi-strand conductors. These features should be kept in mind when procuring terminal lugs.

Some manufacturers of copper lugs construct lug barrels by rolling the barrel material over a tube and joining it together at a seam. Some seams are then brazed (soldered with copper material), and some are simply butted. Butted seams may fold or split during crimping, which can result in non-uniform contact between the conductor and lug, therefore increasing joint resistance. Some manufacturers offer barrels that are seamless, while some lug models are provided with an additional metal sleeve that fits over the barrel and becomes an integral part of the crimped lug.

Some lug barrels are closed at the tongue end, which stops penetration of the conductor into the barrel. These types of lugs generally include inspection holes in the tongue end of the barrel to ensure that the strands and conductors are well seated.

3.1.2.2 Sleeves

Some manufacturers offer additional conductive sleeves that fit around the conductor insulation as well as the lug barrel itself. The sleeves reduce flexing of the conductor at the point of entry into the barrel, thereby helping to prevent crimp loosening or conductor/strand damage due to conductor flexing.

3.1.2.3 Notches

Some models of lugs offer notches on the end of the lug barrel or the sleeve. These notches are intended to *bite* the conductor insulation. This increases the tensile strength of the connection because it divides the pull-out force between the conductor wire and the insulation.

3.1.2.4 Tongues

The tongue is the part of the lug that comes in contact with either a terminal or piece of equipment. Tongues come in many shapes and dimensions. The tongue is intended to be fastened by one or more bolts, studs, or screws. Tongue types used throughout the electrical industry include:

- Flag ring tongue
- Flanged fork tongue
- Flanged spade tongue
- Fork tongue
- Hook tongue
- Locking fork tongue
- Long spring spade tongue
- Rectangular tongue
- Rectangular tongue bent 45°
- Rectangular tongue bent 90°
- Ring tongue
- Short spring spade tongue
- Slotted ring tongue
- Spade tongue
- Tab tongue

Many of these lug types are no longer used in new applications.

Some manufacturers provide lugs with tongues already bent to specific angles, for use where space constraints preclude the use of straight lugs. Using a lug bent by the manufacturer is preferable to field-bending lugs. If it is necessary to bend a straight lug for an application, bending of plated lug tongues should be done with care to avoid cracking the plating layer and producing a pathway for corrosion to the lug inner material.

Key Technical Point

If lug bending is required, take care to avoid cracking the lug plating layer during bending. Inspect the lug thoroughly after bending for evidence of cracking or excessive plastic deformation.

The type of tongue to be selected is influenced by the device or equipment to which it will be connected. Ring and rectangular lugs are the most secure, while other tongue types (such as forks) provide for convenient lifting and reterminating.

Screws should be sized to fit inside the tongue hole without requiring turning to be fitted. If a screw is turned inside the lug hole for insertion, there is potential for lug plating abrasion, producing a pathway for corrosion of the lug inner material. Often, the lug manufacturer will specify or recommend the correct fastener size to use for a given lug.

3.1.3 Lug Sizes

Most lugs are manufactured to accommodate a range of conductor sizes. When selecting a lug, ensure that the lug size is compatible with the size of the mating conductor as well as the fastener. It is preferable to use the largest size conductor that will fit in a lug since this will minimize the air gap or voids in a crimped lug. These air gaps provide a pathway for moisture and air to enter the connection, leading to potential for corrosion of the conductor or connector. Gaps also reduce the pull-out strength of the crimp and increase electrical resistance.

In most cases, a lug is stamped to identify the sizes of conductors that it can fit. If lugs are not stamped, then the lug packaging may contain this information. It is important to keep any technical information found in the lug packaging on file for later use by technicians and engineers. Labeling or color coding should be considered when procuring terminal lugs.

3.1.4 Lug Testing Prior to Assembly

Test requirements for lugs are presented in UL Standards 486A for copper connectors and 486B for aluminum connectors [3, 4]. The standards provide test requirements for UL approval of lugs. Tests are performed by UL for lug manufacturers. Utilities need not perform these tests for UL-approved lugs. The UL standards require tests on samples of lugs for secureness, static heat, and pull-out strength. Samples are normally tested using maximum current-carrying capacity. UL does not perform secureness tests on lugs for wire sizes AWG 20 to 30 (which may be included in vendor-supplied equipment). Brass parts are subject to an additional stress cracking test. Insulated lugs are further tested for dielectric-withstand voltage, flexing, and moisture absorption.

MIL-T-7928 [5] is a military standard that provides performance requirements covering voltage drop before and after current cycling, corrosion using salt spray, axial load, vibration, and tensile strength. Insulated lugs are also subject to dielectric-withstand voltage testing, immersion testing, heat aging, flammability testing, and low temperature crimp testing. (This standard is no longer active but is sometimes referred to in procurement documents for original equipment.)

The UL 486 standards stipulate that testing be done on connector samples assembled per the manufacturer's requirements as to: 1) the use of specific required tools, 2) required crimping operations, 3) the strip length of the conductor, and 4) the preparation of the conductor. These requirements are to be supplied with the lug. Typically, the requirements are marked on the packaging material. Therefore, it is important for the receiving and stocking personnel to retain any such information and pass it on to the technical personnel.

Key Human Performance Point

Requirements regarding 1) the use of specific required tools, 2) required crimping operations, 3) the strip length of the conductor, and 4) the preparation of the conductor are typically marked on a manufacturer's packaging material. Receiving and stocking personnel should retain such information and pass it on to technical personnel.

3.2 Good Crimping Practices

The purpose of the crimp is to provide a secure connection with maximum contacting surface between the conductor and the lug to allow for maximum current-carrying capacity. The crimp should also minimize voltage drop and minimize the factors that will degrade the connection over the long term.

3.2.1 *Types of Crimp*

Most crimps are named after an alphabet letter because of the impression left after the crimp is complete. The most common are the *C, H, O*, and *W* type, as shown in Figure 3-1. Different types of crimps are achieved using different tools.

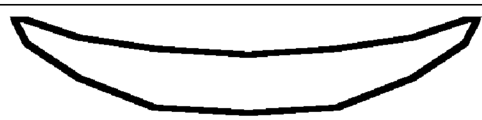
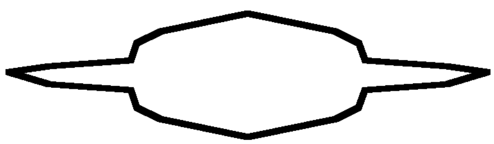
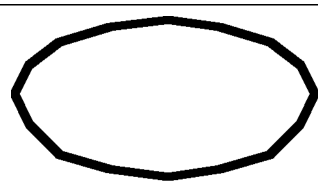
Crimp Type	Comment
 *C* Type Crimp	This type of crimp forms the cable and lug together into a *C* shape. This shape can produce some sharp edges. Sharp edges are not desirable because the electrical field, normal to the current field, propagates in all directions.
 *H* Type Crimp	The *H* crimp finishes with a shape having two wi*ngs.* It often happens that the conductor strands do not enter the wing area of the crimp. Conductor strands generally do not enter the crimp wings, although the presence of strands in the wings may be acceptable.
 *O* Type Crimp	The *O* crimp offers the most compact crimp without substantial deformation. Depending on the type of seam in the barrel and the size of the conductor, a fold could occur.
 *W* Type Crimp	The *W* crimp is similar to the *C* crimp. It also offers the possibility of sharp edges.

Figure 3-1
Types of Crimps

The final shape of the crimp should be such that the current density remains constant throughout the path of the current. If the conductor thickness decreases in the direction of the current, a hot spot may develop. This will cause increased resistance and voltage drop, which may become a problem if the connection carries a high current relative to its rating.

Key Technical Point

If the conductor thickness decreases in the direction of the current, a hot spot may develop. This will cause increased resistance and voltage drop, which may become a problem if the connection carries a high current relative to its rating.

3.2.2 Crimp Quality Characteristics

The optimum crimp connection provides the same or better conductivity as the conductor (that is, no voltage drop or temperature rise due to increased resistivity), the same or better mechanical strength as the conductor, and protection against vibration damage.

3.2.3 Making a Crimped Connection

The basic steps for making a crimped connection are:

1. Inspecting parts and tools
2. Cutting and stripping the conductor
3. Inserting the lug into the crimping tool
4. Inserting the conductor into the lug barrel
5. Applying pressure on the crimping tool to close the lug barrel
6. Inspecting the crimped connection

In addition, as a precursor to work at a nuclear plant, systems and procedures need to be in place to ensure that work is done in a controlled fashion in accordance with quality assurance program requirements.

Each of these steps is described below.

3.2.3.1 Precursor Activities

Precursor activities are intended to ensure that the work is done in accordance with good engineering practice and applicable quality assurance program requirements. These activities include receipt inspection of components and tools used to make connections, proper storage of materials prior to use, and verification that the correct materials are issued and are within their expiration dates.

Precursor activities specific to connector assembly include:

- A continuity test (or in some cases a meggar test) for the conductor to be done while the conductor is still on the spool. This will ensure that the installation does not use conductors with internal breaks. It is difficult to make a visual preexamination of conductors because they usually come shipped on spools and only the outer layer is visible. This is typically done during receipt inspection of the conductor.
- Lug inspections for quality defects, such as plating blisters, sharp edges, peels, or cracks. They should conform to the material purchase order. Personnel should verify that the appropriate lug is issued based on lug markings used to identify their type and size. This is typically done during receipt inspection of the lugs.
- Care of crimping tools. Tools need to be kept in good working order and have up-to-date calibration. They might need some regular lubrication or need to be checked for wear. Generally, manufacturers will offer test-measuring devices, such as go/no-go gauges, by which to calibrate or check the level of wear of tools.
- Personnel training, including preparation and use of clearly written procedures, defining the plant requirements for joint assembly and design selection.

These activities are intended to simplify the work of the connector assembly crew. The expectation should be that methods, materials, and tools are satisfactory, and only a quick visual inspection of the lug and conductor should be done by the installation personnel.

3.2.3.2 Inspecting Parts And Tools Prior to Use

Both lugs and conductors should be visually examined for quality defects before making a crimped connection. The lugs should be clean, free of burrs and sharp edges, and have no plating blisters, pits, cracks, or peels. They should be visually clean and free of defects. The fit of the fastener into the lug should also be verified prior to starting assembly.

The crimping tool and die used should be as specified by the manufacturer for the specific lug. The tool die or shape-forming part should be checked for wear. Manufacturers generally provide guidance or test devices (such as test bores or go/no-go gauges) to determine if the tool needs repair.

The conductor stripping tool should also be examined for wear according to the manufacturer’s guidelines.

3.2.3.3 Cutting and Stripping the Conductor

The cutting of the conductor should be done with a good quality cutter, appropriate for the conductor size. The cut should be clean, should be made in a single pass through the whole of the conductor, and should not upset the lay of the individual strands. If applicable, it is good practice to cut and remove the end of the conductor that was held within a cable-pulling device or exposed to the environment during storage, prior to terminating the conductor.

Conductors should be stripped immediately before the lug is crimped in order to minimize oxidation. When stripping conductors, ensure that the solid conductor or individual strands are not severed, nicked, scraped, or damaged in any way. If plated conductors are used, they should be examined to ensure that the plating has also not been damaged. Any damage to the conductor surface will provide a pathway for corrosion. Cuts also increase resistance, which in turn can cause a temperature rise in service with the concomitant increase in resistance and voltage drop.

Key Technical Point

The end of a conductor may be damaged during cable pulling or by exposure to the environment. Prior to making a crimped connection, cut off the end of the conductor. Strip insulation immediately before crimping to minimize the time the bare conductor is exposed to the environment.

The ideal way to strip a conductor is by using professional stripping tools (see Figure 3-2). They provide for adjustable insulation cutting length and a preset insulation cutting depth. This helps avoid damaging conductors during stripping. These tools are available from major manufacturers and often include specific dies for cutting different insulation thicknesses.

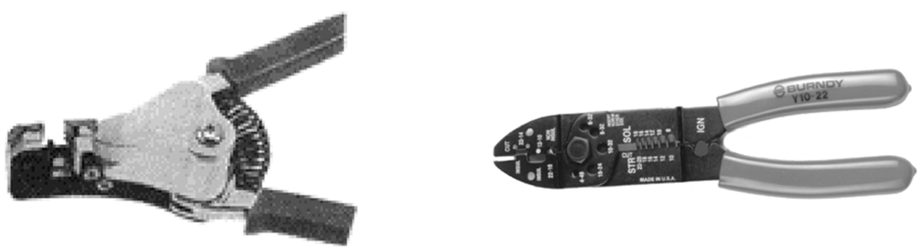


Figure 3-2
Stripping Tools

Courtesy of FCI - BURNDY Products.

Strip the wire to a length suitable for the type of connector. The recommended length of insulation removal depends on the type of lug. The lug manufacturer usually provides guidance in this respect.

Take care to strip the appropriate length of insulation. The length of stripped conductor that protrudes from the end of an open barrel should be long enough to be visible for inspection, but short enough to prevent interference with the fastener and to prevent the strands from fanning out.

If the lay was disturbed by cutting or stripping, the conductor strands should be slightly twisted in the same direction as the lay so as to reseat the strands in their general lay direction. This will reduce the air gap within the conductor strands. If the conductor being used is of the bunched-strand type (normally used for highly-flexible, smaller-gauge wires), the strands will have a tendency to fan out in all directions. In this case, the strands will need to be twisted slightly to keep them together prior to insertion into the lug barrel.

3.2.3.4 Inserting the Lug in the Crimping Tool

Unless otherwise specified by the manufacturer, the lug should be inserted into the crimping tool before the strands are inserted into the lug barrel. The lug must be properly inserted in the crimping tool to ensure that a good crimp is achieved.

3.2.3.5 Inserting the Conductor Into the Lug Barrel

Once the lug is properly seated and held in the crimping tool, the conductor can be inserted into the lug barrel. It should be inserted into the barrel without disturbing the strand lay. If an open-ended barrel is used, the strands should not overshoot the end of the barrel by more than 1/8 in. (3.175 mm). Overshooting the barrel end will cause the strands to fan out when crimped, offering a corrosion path to the interior of the conductor. An excessive overshoot can also interfere with the fastener.

Key Technical Point

Overshooting the barrel end will cause the strands to fan out when crimped, offering a corrosion path to the interior of the conductor. An excessive overshoot can also interfere with the fastener.

If a closed barrel lug with inspection hole is used, then the conductor should be inserted until the strands just touch the end of the barrel. Excessive insertion into a closed barrel will cause the strands to bunch and disturb the lay. This can provide a pathway for moisture and air to infiltrate the connection, leading to corrosion.

If the wire was stripped with the proper length of insulation removed, then the wire inserted in the lug will have a small length of bare wire (approximately 1/16 in. [1.59 mm]) visible from the barrel insertion end. If a lug with a sleeve is used, it is important to have the sleeve overlap the insulation slightly. The required overlap is generally specified by the manufacturer and is typically on the order of 1/8 in. (3.175 mm).

When using stranded wire, it is important to keep the strands aligned in the same geometrical direction. A smooth entry path to the barrel will tend to keep the strands aligned without deformation. This in turn will promote surface contact of the crimp, including inter-strand contact.

3.2.3.6 Use of Joint Compounds

Joint compounds are commonly used inside lugs to improve the seal between the conductor and connector. The compounds prevent oxidation and offer a block to moisture penetration. They are normally applied after the oxide film has been removed from metallic components in the connector. Joint compounds are not often used in smaller caliber wire, such as that used for instrumentation and control connections.

The choice of compound to use should be based on environmental conditions such as temperature and humidity. It is essential to use a compound suitable for the materials being joined because use of the wrong one might degrade the connection instead of protecting it. Section 2 of this guide contains a description of commonly used joint compounds.

Key Technical Point

The choice of compound to use should be based on environmental conditions such as temperature and humidity. It is essential to use a compound suitable for the materials being joined because use of the wrong one might degrade the connection instead of protecting it.

3.2.3.7 Making the Crimp

When the wire is properly inserted into the lug in the crimping tool, it is time to apply crimping pressure. If the crimping tool has only two stages, (a holding stage for the lug and a crimping stage), then the wire needs to be held in place momentarily until it is maintained in place by the increasing crimping pressure. If the tool has three stages, then it will exert a first level of pressure that will deform the barrel in order to hold the connector. At this stage, it is still possible to move the conductor slightly and make some minor final adjustments. The crimping tool should then be fully pressurized to complete the crimp. After the final stage is complete, the tool will automatically release the lug from the tool.

There are many crimping tools available. Generally, each manufacturer specifies the type of crimping tool to use for specific lug and conductor combinations. Depending on the size of the conductor and lug, manufacturers offer handheld tools (see Figure 3-3), ratchet-type tools (see Figure 3-4), and pneumatic and hydraulic pressure tools. The hydraulic tools are used mostly for large conductors or automated connection systems.

Figure 3-3
Simple Handheld Crimping Tool

Courtesy of FCI - BURNDY Products.

Figure 3-4
Ratchet-Type Crimping Tools

Courtesy of FCI - BURNDY Products.

The more advanced tools are equipped with specific dies. Each die is suited for a specific type of lug and will prevent over-crimping of the lug. The use of dies is important not only because of the shape the die induces to the crimp connection, but also because the use of dies provides control over the pressure applied to the crimp.

Using a handheld crimping tool without protective features to prevent over- or under-pressurizing the crimp is not recommended for installations where the longevity of the connection is critical. Pressure control is important because if insufficient pressure is applied, the connection will be loose, and the contact surface may be insufficient for the current-carrying capacity.

Key Technical Point

Using a handheld crimping tool without protective features to prevent over- or under-pressurizing the crimp is not recommended for installations where the longevity of the connection is critical.

If excessive pressure is applied, there is a chance of deforming the lug beyond its specifications, reducing its mechanical strength, and possibly cutting or damaging conductor strands. This will in effect increase the resistance of the connection and lead to the potential for overheating.

Key Technical Point

Under-pressurizing a crimp can lead to a loose connection and reduce the current-carrying capacity of the connector. Over-pressurizing can lead to lug deformation and possible conductor damage, which can increase electrical resistance.

It is usual for the crimping die as well as the lug (insulated type) to be color coded. This facilitates matching of the tool die and the lug.

Note: If an insulated lug is used for the connection, then it is often necessary to make a second crimp onto the insulation. This normally requires the lug to be reseated in a slightly different location on the die, and a second crimp executed. During this second crimp, it is not possible to adjust the seating of the crimp because the insulation crimp position is dictated by the lug crimp location.

3.2.3.8 Inspecting the Crimp

Crimp inspection methods include the following:

- **Visual inspection** - Visual inspection of the crimp is the most common inspection method. This method is primarily based on experience and performed in a routine manner. Visual inspection includes checks for barrel folding, conductor strand position and disturbance, lay disturbance, tightness of the crimp, air gaps, lug distortion or cracking, and insulation damage. If the crimp is of high importance and its failure can be of grave consequence, then additional verifications should be done such as those below. This inspection should be done for all crimps.
- **Pull-out test** - The pull-out test is a simple pull test on the conductor while holding the lug. The test is generally done in a shop or lab. This test is similar to the pull-out test performed during industry standard testing, such as UL 486 and MIL-T-7928 [3–5]. For example, the military standard uses a pull-out force of 50 pounds for a connector with #16 AWG conductor. The pull-out test in the field does not need to apply as much force. Most manufacturers will provide a pull-out lug force upon request. The test is intended to see if conductor or strand movement is apparent under force. The strands as seen through the inspection hole or through the open-ended barrel should not move. In the case of insulated lugs, a slight pull on the insulation can also reveal if it is well crimped. This inspection should be done in the shop or lab to demonstrate that the crimping technique used is acceptable.
- **Flexing test** - The flexing test is similar to the pull-out test and is usually done at the same time. This test is done by moving the conductor from side to side and up and down while looking again to see if the strands are influenced by the movement.
- **Crimp thickness measurement -** Thickness measurement gives an estimate of the quality of the crimp final shape and provides an indication of the long-term survivability of the connection. Using a caliper, thickness is measured at a specific location on the lug after crimping. Some manufacturers will provide the range of the measurement indicating a good crimp. This measurement indicates if the lug has been pressurized to its final shape. It does not indicate if the conductor is properly squeezed. This method, although indicative and representative, is not always efficient when doing installations requiring a large number of connections. This method should be used if there is doubt in the quality of the connections. It can also be used as a sample method.
- **Voltage drop test** - The voltage drop test is performed per standards such as MIL-T-7928 on samples from the manufacturer. These tests are conducted using maximum rated current for the lug, with appropriate conductors. Acceptable voltage drop values can range from 3 to 4 mV depending on the size. These tests are usually performed by puncturing the conductor insulation approximately 1/16 in. (1.59 mm) from the barrel and measuring the

voltage drop at the intersection of the tongue and barrel (joining point). Since puncturing the insulation is not feasible in the field because it would jeopardize the insulation integrity, the field test can use the point closest to the insulation and the barrel and tongue joining point. This test is generally done in a shop or lab to qualify techniques, but it may be performed in the field when troubleshooting problems.

- **Resistance measurement** - This test uses a high-precision ohm meter sensitive enough to register in micro-ohms (μΩ). The resistance measurement is analogous to the voltage drop test but uses a much lower current. This test indicates the acceptability of the crimp resistance. The order of magnitude is more important than the actual value. Resistance measurement will yield a qualitative indication of the acceptability of the connection. This test is generally done in a shop or lab to qualify techniques, but it may be performed in the field when troubleshooting problems.
- **Thermography** - Thermography provides a thermal image of an object that indicates the temperature of the object. This inspection method is commonly used for the examination of power connections. The inspections need to be done while the unit is powered, preferably at nominal current values. Higher than normal temperatures at the connection provide an indication of high resistance at the connector and a possible problem. Thermographic inspection 24 hours after installation can be used to determine if connections are holding. See Appendix B for further information on thermography.
- **Oscilloscope analysis** - In the case of low-power analog signals, the use of an oscilloscope can be helpful in determining if a field connection is introducing any kind of impedance change. The waveform analysis needs to consider the electrical characteristics of the signal, such as frequency and rise times, in relation to the specific application.

3.2.3.9 Soldering Crimped Connections

Soldering the conductors before crimping is not a good practice. While soldering provides an extra coat of oxidizing resistance, it introduces more variables that can affect the quality of the crimp. Specifically, soldering introduces another material between the conductor and the lug. The solder material may break off during crimping and introduce flakes in the crimped joint. Further, the base conductor and lug materials had been previously matched for their compatibility. Soldering could make the connector susceptible to deterioration and contamination. Soldering before crimping also reduces conductor flexibility and malleability. Unless materials are chosen specifically to be compatible with the solder material, application of solder to conductors prior to crimping is not recommended.

Applying solder after crimping is sometimes indicated, particularly in cases where folded-wing type crimps are used. In these connectors, the bare conductor is placed inside the wings, which are then folded on top of the conductor. Crevices formed between the folded wings and bare conductor can be filled with solder. Best practice includes applying heat to the lug rather than the solder material so that the lug heats the solder to its melting temperature. This permits good flow of the molten solder into the crevices in the crimp. Allow solder to air cool rather than quench with water.

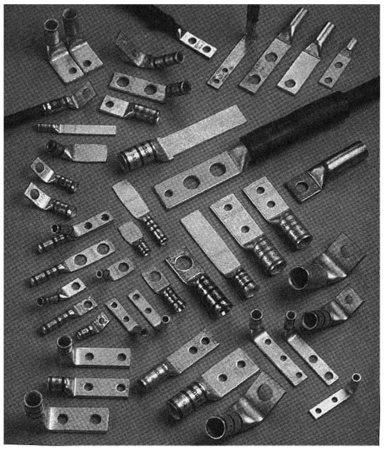
Key Technical Point

Soldering conductors prior to crimping is not recommended. Soldering after crimping of folded-wing type lugs may be advised to enhance current flow through the connector.

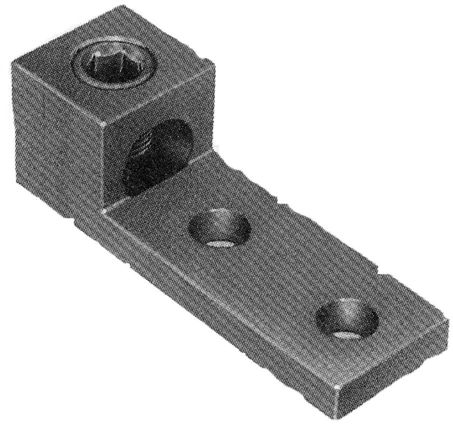
3.3 Good Practices for Bolted Connectors

Many electrical connections used at nuclear power plants are made using bolted joints. These include bonding jumpers for equipment grounding; in-line cable splices; high-voltage, medium-voltage, and low-voltage bus connections; and terminal lugs. Ensuring acceptable long-term performance of bolted joints requires appropriate design, good assembly practices, and periodic maintenance and inspection. In this section, each of these requirements is discussed as they pertain to bolted electrical connectors.

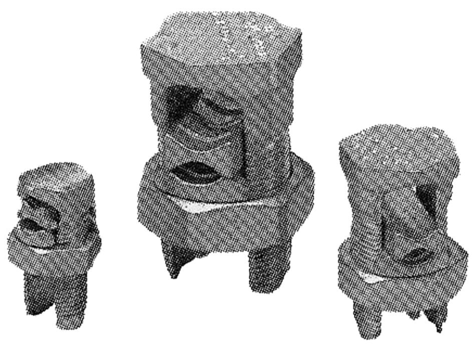
By definition, a bolted electrical connector contains one or more types of threaded fasteners. Types of bolted electrical connections include compression connectors, mechanical connectors, split bolts, and grounding clamps. Examples of each type are shown in Figure 3-5.



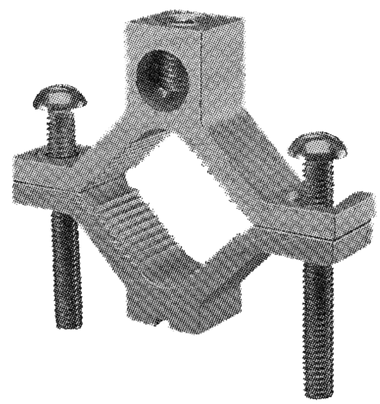
Compression Terminal Lugs



Mechanical Terminal Lug



Split Bolt Connectors



Typical Grounding Clamp

Figure 3-5
Types of Bolted Electrical Connectors

Courtesy of Panduit Corporation, 1999.

Typical applications for bolted electrical connections used at nuclear power plants include connecting:

- An end of a cable to a terminal stud
- An end of a cable to a busbar
- Two or more cables together at a splice
- A generator to outgoing bus bars and transformers
- A cable to ground

3.3.1 Design

Bolted connectors form strong, reliable joints when correctly engineered and assembled. They are relatively simple and economical to install in comparison to other types of joints (such as welded or soldered joints). Bolted connectors are especially preferred where the connector may need to be disassembled periodically for testing or maintenance.

Once the decision has been made to use a bolted electrical connector for a specific application, the following design choices must be made:

- **Connector type** - In general, connections between conductors and terminal boards or busbars are made using bolted terminal lugs, and splices are made using bolted or crimped connections. Nuclear power plants typically prequalify one or more connector manufacturers and identify (in some cases by way of plant procedure) the appropriate type of electrical connector to use for specific applications.
- **Connector hardware** - Connections are generally made using a combination of bolts, nuts, flat washers, lock washers, and, in some cases, Belleville washers. Various manufacturers recommend differing configurations of connection hardware and provide the hardware in kits supplied with the connector. Some nuclear power plants have developed their own bolted connection hardware configurations based on experience. For illustrative purposes, Table 3-3 shows hardware configurations recommended by a large manufacturer for various types of connections.

  General considerations for connection design include the following:

  - Each connection should have one flat washer on each side of the connectors being joined. The purpose of these flat washers (two per bolt) is to protect the surface of the connectors from damage when the nut or bolt is turned during installation.
  - When the temperature of the connection increases due to ambient temperature increase or resistive heating, the metals used in the electrical connector will expand. If the connection contains different types of metals, differences in thermal expansion behavior between the metals may result in some components expanding more than others. For instance, if the bolts have a larger thermal expansion coefficient than the connected metals, the joint will loosen upon heating. To prevent joint loosening, designers often include Belleville washers in the connection hardware. The Belleville washer acts as a spring to keep the load on the connection as the conductors and bolt materials change in length during heatup and cooldown.
  - Belleville washers are usually installed between the bolt head and a flat washer, with the concave side of the Belleville washer in contact with the flat washer. The flat washer outer diameter should be greater than the flattened Belleville washer so that no overhang results under any joint loading conditions.
  - To determine whether a Belleville washer is needed, compare the thermal expansion coefficients for the materials used in the joint. If there is a large difference between coefficients, use of a Belleville washer is advised. Table 3-4 lists thermal expansion coefficients for typical materials used in bolted electrical joints [6]. Note that the thermal expansion coefficient of high-strength steel is about half that of aluminum. Accordingly, for a connection between aluminum components held together with a

high-strength steel bolt, a Belleville washer should be used. Conversely, a connection of copper components held together with a bronze bolt would not require a Belleville washer. Table 3-3 references the correct use of Belleville washers as depicted in Figure 3-6.

Table 3-3
Recommended Connector Hardware From a Typical Manufacturer

Materials Being Joined	Bolt	Nut	Flat Washers	Lock Washer	Belleville Washer	Reference Figure 3-6
(Number per bolt)	--	1	2	0 or 1	0 or 1	
Copper to copper	SB	SB	SB	SB	NR	(a)
	SS	SS	SS	SS	NR	(a)
Copper to aluminum	SB*	SB*	SB*	NR	SS	(b)
	SS	SS	SS	NR	SS	(b)
Aluminum to aluminum	AL	AL	AL	AL	NR	(a)
	SS	SS	SS	NR	SS**	(b)
Copper to steel	SB	SB	SB	SB	SS**	(a) or (b)
	SS	SS	SS	SS	NR	(a)
	GS	GS	GS	GS	NR	(a)
Aluminum to steel	SB*	SB*	SB*	NR	SS	(b)
	SS	SS	SS	NR	SS	(b)
	GS	GS	GS	NR	SS	(b)

Key:

AL Aluminum
GS Galvanized steel
SB Silicon bronze
SS Stainless steel
NR Not required
* Tin Plated
** Alternate recommendation— Belleville washer in place of lock washer

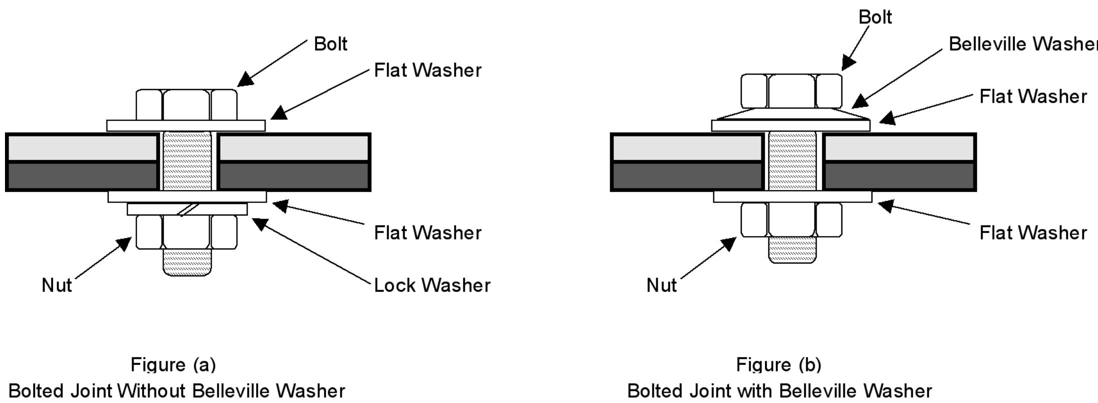


Figure 3-6
Correct Use of Belleville Washers [7]

Table 3-4
Thermal Expansion Coefficients for Typical Materials Used in Electrical Connectors

Material	Thermal Expansion Coefficient (inch/inch-°F at 70°F)
Aluminum	12.1×10^{-6}
Bronze	9.6×10^{-6}
Copper and brass	9.3×10^{-6}
Stainless steel	8.5×10^{-6}
High-strength steel	6.4×10^{-6}

Source: ASME Boiler and Pressure Vessel Code, Section II Part D, 2001.

– Connections should be provided with a means to prevent loosening when exposed to vibration. This is generally achieved by putting one lock washer between the nut and the flat washer. When used in the connection, Belleville washers will prevent loosening due to vibration as well as from thermal expansion. Accordingly, if a Belleville washer is included in the connection, a lock washer is unnecessary.

Key Technical Point

Belleville washers are included in bolted connections when the connector is subject to vibration or when the bolting hardware and materials being connected have widely varying thermal expansion properties.

- Single-bolt electrical connectors are sufficient for many applications. However, these connectors have limited electrical contact area. Connections with two or more bolts are used where additional contact area is required. Single-bolt connections are also subject to possible loosening due to external torque applied to the connection. Where such loads are expected, the use of multiple bolt connections is recommended.
- It is important that personnel assembling electrical connections are trained to verify that the correct hardware is being used. There are numerous cases in industry and military applications where installation of the wrong bolt in a joint led to a failure in service. (For an example, see the case histories at the end of this section.) Bolts can be identified by markings on the bolt head. Tables 3-5, 3-6, and 3-7 show markings used to distinguish steel and non-ferrous bolting materials [8–10].
- Lubrication of connection hardware should be performed in accordance with the manufacturer's specifications. In general, aluminum nuts and bolts require lubrication to prevent galling during assembly. Steel and silicon bronze hardware generally do not require lubrication. In fact, care must be taken to ensure that sealants and joint compounds do not contact steel or bronze hardware since these compounds will act as lubricants and adversely affect the integrity of the bolted joint.

Table 3-5
Markings for Carbon and Low Alloy Steel Bolts and Screws

ASTM AND SAE GRADE MARKINGS FOR STEEL BOLTS AND SCREWS

Grade Marking	Specification	Material
 NO MARK	SAE–Grade 1	Low or Medium Carbon Steel
	ASTM–A307	Low Carbon Steel
	SAE–Grade 2	Low or Medium Carbon Steel
	SAE–Grade 5	Medium Carbon Steel, Quenched and Tempered
	ASTM–A 449	
	SAE–Grade 5.2	Low Carbon Martensite Steel, Quenched and Tempered
	ASTM–A 325 Type 1	Medium Carbon Steel, Quenched and Tempered Radial dashes optional
	ASTM–A 325 Type 2	Low Carbon Martensite Steel, Quenched and Tempered
	ASTM–A 325 Type 3	Atmospheric Corrosion (Weathering) Steel, Quenched and Tempered
	ASTM–A 354 Grade BC	Alloy Steel, Quenched and Tempered
	SAE–Grade 7	Medium Carbon Alloy Steel, Quenched and Tempered, Roll Threaded After Heat Treatment
	SAE–Grade 8	Medium Carbon Alloy Steel, Quenched and Tempered
	ASTM–A 354 Grade BD	Alloy Steel, Quenched and Tempered
	SAE–Grade 8.2	Low Carbon Martensite Steel, Quenched and Tempered
	ASTM–A 490 Type 1	Alloy Steel, Quenched and Tempered
	ASTM–A 490 Type 3	Atmospheric Corrosion (Weathering) Steel, Quenched and Tempered

Reprinted from ASME ANSI B18.2.1-1981, *Square and Hex Bolts and Screws Inch Series* by permission of The American Society of Mechanical Engineers [8].

Table 3-6
Markings for Alloy and Stainless Steel Bolting Materials [9]

Alloy Steels

Marking	Grade	Marking	Grade
B5	B5	B7M	B7M
B6	B6	B7M	B7M
B6X	B6X	B16	B16
B7	B7		

Stainless Steels

Class	Marking	Grade	Class	Marking	Grade
Class 1	B8	B8	Class 1D	B94	B8
	B8C	B8C		B95	B8M
	B8M	B8M		B96	B8P
	B8P	B8P		B97	B8LN
	B8T	B8T		B98	B8MLN
	B8F	B8LN		B99	B8N
	B8G	B8MLN		B100	B8MN
Class 1A	B8A	B8A		B101	B8R
	B8B	B8CA		B102	B8S
	B8D	B8MA	Class 2	B8	B8
	B8H	B8PA		B8C	B8C
	B8J	B8TA		B8P	B8P
	B8L	B8LNA		B8T	B8T
	B8K	B8MLNA		B8N	B8N
	B8V	B8NA		B8M	B8M
	B8W	B8MNA		B8Y	B8MN
	B9K	B9MLCuNA		B9J	B8MLCuN
Class 1B	B8N	B8N	Class 2B	B9G	B8M2
	B8Y	B8MN	Class 2C	B9H	B8M3
	B9J	B9MLCuN			
Class 1C	B9A	B8R			
	B9B	B8RA			
	B9D	B8S			
	B9F	B8SA			

As specified in ASTM Standard F-468 [10]:

> All products shall be marked with a symbol identifying the manufacturer. In addition, they shall be marked with the alloy/mechanical property marking (shown below). The marking shall be raised or depressed at the option of the manufacturer.

Table 3-7
Markings for Nonferrous Bolts, Head Cap Screws, and Studs [10]

Marking	Alloy	Marking	Alloy	Marking	Alloy
F468A	Cu 110	F468S	Ni 335	F468AT	Ti 1
F468B	Cu 270	F468T	Ni 276	F468BT	Ti 2
F468C	Cu 462	F468U	Ni 400	F468CT	Ti 4
F468D	Cu 464	F468HF	Ni 400 HF	F468DT	Ti 5 Class A
F468E	Cu 510	F468V	Ni 405	F468HT	Ti 5 Class B
F468F	Cu 613	F468W	Ni 500	F468ET	Ti 7
F468G	Cu 614	F468BN	Ni 686	F468FT	Ti 19
F468H	Cu 630			F468GT	Ti 23
F468J	Cu 642	F468X	Al 2024-T4	F468HT	Ti-5-1-1-1
F468K	Cu 651	F468Y	Al 6061-T6		
F468L	Cu 655	F468Z	Al 7075-T73		
F468M	Cu 661				
F468N	Cu 675				
F468P	Cu 710				
F468R	Cu 715				

- **Connector torque** - Manufacturers generally specify torque (and, in some cases, lubrication requirements) for bolted electrical connections. Qualification of connectors is normally performed using these manufacturer-specified parameters; accordingly, the manufacturer torque specifications should be used for bolted connections. Nuclear plants surveyed generally have procedural requirements to torque bolts in accordance with the manufacturer's specifications. However, there are many bolted electrical connections in power plants for which no manufacturer torque specification is available. As a result, many plants have developed their own torque requirements to be used when no manufacturer specification is available. These requirements are often based on the UL torque tables, which UL uses for qualification testing when no manufacturer specification is offered. Table 3-8 summarizes torque values used by UL [4]. These torque values are for illustrative purposes only and should not be used where manufacturers have provided torque specifications.

Key Technical Point

Qualification tests of bolted connections are generally performed with the bolted connection torqued per the manufacturer's recommendations. Use the manufacturer's specified torque for bolted connections in the plant, unless otherwise directed by engineering.

Table 3-8
Underwriters Laboratories Inc. Tightening Torque Values Used for Testing

Part I: Bolted Electrical Connections with Large Screws

Tightening Torques for Large Screws – Pound Inches[a]				
	Slotted Head No. 10 and Larger		Hexagonal Head – External Drive Socket Wrench	
Wire Size	Slot Width to 0.047 in. and Slot Length to ¼ in.[b]	Slot Width over 0.047 in. or Slot Length over ¼ in.[b]	Split-Bolt Connectors	Other Connectors
30–10 AWG	20	35	80	75
8	25	40	80	75
6–4	35	45	165	110
3	35	50	275	150
2	40	50	275	150
1	--	50	275	150
1/0	--	50	385	180
2/0	--	50	385	180
3/0	--	50	500	250
4/0	--	50	500	250
250 kcmil	--	50	650	325
300	--	50	650	325
350	--	50	650	325
400	--	50	825	325
500	--	50	825	375

Table 3-8 (cont.)
Underwriters Laboratories Inc. Tightening Torque Values Used for Testing

Wire Size	Slot Width to 0.047 in. and Slot Length to ¼ in.[b]	Slot Width over 0.047 in. or Slot Length over ¼ in.[b]	Split-Bolt Connectors	Other Connectors
600	--	50	1000	375
700	--	50	1000	375
750	--	50	1000	375
800	--	50	1100	500
900	--	50	1100	500
1000	--	50	1100	500
1250–2000	--	--	1100	600

a. Connectors having clamping screws with multiple tightening means (for example, a slotted hexagonal head screw) are tested by UL using both values of torque. For installation, use the torque value associated with the tool used in the installation.

b. For values of slot width or length not corresponding to those specified, select the largest torque value associated with conductor size. Slot width is the nominal design value, and slot length is measured at the bottom of the slot.

Part II: Bolted Electrical Connections with Small Screws

Tightening Torques in Pound-Inches for Slotted Head Screws[a]
Smaller Than No. 10, for Use With No. 8 AWG or Smaller Conductors

Screw-Slot Length – Inches[b]	Screw-Slot Width Less than 0.047 in.	Screw-Slot Width 0.047 in. and Larger
Less than 5/32	7	9
5/32	7	12
3/16	7	12
7/32	7	12
1/4	9	12
9/32	--	15
Above 9/32	--	20

When clamping screws with multiple tightening means (for example, a slotted hexagonal head screw), use the torque value associated with the tool used in the installation. UL uses both values when testing.

For slot lengths of intermediate values, select torques pertaining to next shorter slot length.

Table 3-8 (cont.)
Underwriters Laboratories Inc. Tightening Torque Values Used for Testing

Part III: Bolted Electrical Connections With Recessed Allen Head Screws

Socket Size Across Flats, Inches	Torque, Pound-Inches
1/8	45
5/32	100
3/16	120
7/32	150
1/4	200
5/16	275
3/8	375
1/2	500
9/16	600

Source: This material is reproduced, with permission, from Underwriters Laboratories Inc., *Wire Connectors for Use with Aluminum Conductors*, 4th Edition, UL Standard 486B, February 1997, copyright by Underwriters Laboratories Inc. [4].

3.3.2 Assembly

The specific steps required for assembly vary depending on the materials being connected. However, the assembly process generally includes cleaning, surface preparation, sealing, bolting, and cleaning. Good practices determined from review of industry documents [1] are as follows:

1. Clean contact surfaces immediately prior to making connections. Use a rag or emery cloth to remove dirt, black deposits, and any old joint compound. If surfaces are plated, clean by a few light rubs with fine steel wool, taking care not to disrupt the plating layer.
2. Remove the oxide layer from the connector and conductor surfaces, if necessary. This is done to prevent the oxide from impeding current flow. Specifically:
   - Oxide forms very quickly on bare aluminum surfaces upon exposure to air. These layers are tightly adherent and transparent to the eye. Once formed, the surface oxide layer prevents further oxidation of the aluminum metal. Aluminum oxide is highly resistant to current flow and consequently must be removed from the aluminum contact surface prior to assembling the connection. The oxide layer can be removed by abrading the aluminum surface using an emery cloth, steel wool, file, or wire brush. Some manufacturers recommend applying a liberal amount of joint compound to the aluminum surface first, prior to abrading the surface through the compound. Because the oxide layer can form quickly when bare aluminum is exposed to air, it is important not to remove the joint compound after abrading and to bolt the connection together immediately after preparation

Note: Some manufacturers chemically etch aluminum and apply an antioxidant coating just after fabrication. Such connectors need to be cleaned, but abrasion is not necessary. Antioxidant coatings appear as a whitish coating when exposed to black light.

- Oxides also form quickly on bare copper or bronze surfaces upon exposure to air. The oxide layer acts to protect the metal from further oxidation. Again, the oxide is resistant to current flow and must be removed prior to assembling the connection. Copper oxide can be removed from contact surfaces using an emery cloth to obtain a bright metal finish. Wipe off all copper particles. Do not abrade or wire brush copper or bronze surface, as this will roughen the contact surface. (Smooth surfaces have higher incidences of microscopic point-to-point contacts and thus exhibit lower contact resistance.) It is not necessary to apply joint compound to the copper or bronze surfaces prior to oxide removal.
- Plated materials are protected from oxidation by a thin layer of plating material (for example, silver or tin). Plated surfaces should not be abraded since doing so could disrupt the thin layer of plating material and potentially lead to corrosion of the base metal. Care should be taken when cleaning and handling plated surfaces to avoid disrupting this protective layer.

3. Following surface preparation, completely coat the contact surfaces with a liberal amount of joint compound. Joint compound prevents the formation of oxides on the contact surfaces and prevents moisture from entering the connection. Typically, gritty compounds are used for aluminum surfaces. These compounds contain a suspension of zinc particles that tend to imbed in the aluminum contact surface and penetrate the oxide layer, thus providing additional current paths between contact surfaces. Common joint compounds used in industry are discussed in Section 2 of this guide.
4. Bolt the connection together. As discussed earlier, bolt torque is generally specified by the connector manufacturer or by plant procedure. Table 3–8 provides torque values used by UL during testing of connectors when no torque is specified by the connector manufacturer. Good practices for making bolted connections include the following:
   - Use a calibrated torque wrench to ensure the proper torque is achieved.
   - To ensure full thread engagement in the nut of a bolted connection, the bolt should extend past the nut for at least two threads. However, the connection is generally considered acceptable provided all the usable threads of the nut are fully engaged on the bolt.
   - In multiple bolt connections, tighten bolts in a cross pattern.
   - Take care to torque the joints within the design range. Improper torquing has led to system and plant outages (see the case histories presented in Section 3.3.5).
5. After torquing, remove excess joint compound squeezed out of the joint, but leave a bead around the edges to prevent the entrance of moisture and dirt. Ensure that all joint compound is removed from the conductors themselves.

3.3.3 Inspection of Bolted Electrical Connectors

Upon assembly, utility personnel typically check electrical connections by hand or with a wrench to ensure that bolts are not loose. The applied torque is not checked after assembly. Retorquing the joint after assembly is not an appropriate method to confirm installation torque since repeated tightening could actually damage the connector and eventually lead to failure.

Key O&M Cost Point

Do not attempt to retorque a bolted joint after assembly. Retorquing can damage a bolted connection and lead to a failure.

The assembly of the joint should also be checked to verify that it meets the design. Incorrectly installed hardware has led to equipment inoperability (see the case histories at the end of this section).

Some plants also verify that the connection has low electrical resistance using a low range ohm meter. Critical connections are periodically inspected visually for evidence of overheating, burning, or discoloration, and indication of loose bolts.

3.3.4 Maintenance of Bolted Electrical Connectors

Bolted connections do not require periodic retightening. As described above, once a connector is installed with the proper torque, repeated tightening could actually damage the connector and eventually lead to failure.

Hardware from disassembled connections can be reused if determined to be in good condition. However, some nuclear power plants have procedural restrictions on reuse of Belleville washers due to concerns with possible fatigue damage.

3.3.5 Case Histories of Problems with Bolted Connectors

Although the overall performance of bolted electrical connectors has been satisfactory in the nuclear power industry, there are selected instances when problems with connectors have impacted reliable plant operation. Some case histories of events are briefly summarized in this section.

- **Incorrectly installed hardware** - During a plant shutdown, a connection to a battery terminal plate was found to have an electrical resistance that exceeded the maximum permitted per plant surveillance requirements. Investigation showed that a single washer was installed between the battery terminal plate and the battery cable lug. The design of the connection required instead that the washer be installed on the opposite side of the cable lug, between the lug and the hex nut. The presence of the washer in the current flow path increased the connector electrical resistance to a level above the resistance permitted by the surveillance procedure. Plant personnel postulate that the washer had been initially installed when test cables had been placed on the terminal during a service discharge test and that the washer adhered to the backside of the terminal plate (where it was obscured from view) in a layer of anticorrosive grease. The washer was inadvertently left in place after the test, until it was discovered during surveillance testing about one year later.

- **Bolt material misidentification and over-torquing** - With the reactor at 100% power, a bolted connection failed on a generator neutral overcurrent transformer, leading to a main generator trip and a reactor trip. The root cause was traced back to workers misidentifying the bolt material and improperly torquing the bolt. The bolt was made from coated silicon bronze material similar in appearance to steel. Plant procedures called for silicon bronze bolts of this size to be torqued to 20 foot-pounds (20 ft.lb) (27.1 N-m). With each refueling outage, the generator neutral transformer leads are disconnected and then reconnected. During two outages, workers reconnecting the leads incorrectly torqued the bolt to 33–40 ft.lb. This torque value was incorrect for two reasons: 1) the bolt was actually coated silicon bronze rather than steel, and 2) the torque value for steel was misread from the procedure as 33–40 ft.lb when the correct procedure value for steel was 33–40 Newton-meters (equivalent to 24–30 ft.lb). Upon realizing that the wrong units were used, workers remade the connection using 24–30 ft.lb. In a later outage, the bolt was again torqued to 24–30 ft.lb. Several months later, the connecting bolt failed due to repeated over-torquing. Later testing showed that silicon bronze bolts failed between 35–42 ft.lb.
- **Bolt over-torquing** - During an inspection of motor control centers and switchboards, a utility found numerous failures of 5/16 in. (7.94 mm) silicon bronze carriage bolts used for electrical connections. The percentage of failed bolts approached 35% in some inspected equipment. Research revealed that during original construction the bolts should have been torqued to 9 ft.lb (12.2 N-m), but were instead torqued to 18 ft.lb (24.4 N-m) due to an error on an assembly drawing. This led to many failures of the bolts for splices and battery cable connections. Although all of the broken bolts were replaced during original construction, it is not known if bolts that did not fail were replaced or merely retorqued.

3.4 Good Practices for Grounding and Bonding Electrical Connectors

There are several main objectives for providing a well-designed ground system. Safety of personnel tops the list, followed by equipment protection, signal reference quality, return path for faults and/or surges, and static dissipation. In order to meet these objectives, ground system interconnections must maintain a low contact resistance, often under adverse conditions, for the expected life of the ground system. Connections in a ground network are subject to severe corrosion, high mechanical stress due to electromagnetic forces, and rapid thermal heating due to high current magnitudes during fault conditions.

Copper conductor is the premier choice for constructing ground systems. Copper has excellent electrical conductivity, dissipates thermal energy quickly, and has good resistance to corrosion. Ground connectors should have similar properties to ensure similar performance. Copper and high-copper content alloys are used to minimize galvanic corrosion with copper ground conductors. These alloys increase longevity in below-grade applications and withstand the rigors of repeated fault currents.

A minimal requirement for ground connectors should be the ability to pass requirements listed in UL Standard 467, *Grounding and Bonding Equipment* [11]. By meeting the requirements in this standard, the user can be confident that the connector is greater than 80% copper (if marked *direct burial*) and has withstood a fault current test. Alternate connector testing may be substituted, but none should require less than UL 467 criteria.

IEEE Standard 837*, Standard for Qualifying Permanent Connections Used in Substation Grounding* [12] exceeds the requirements of all other ground connection performance standards. IEEE Standard 837 testing closely simulates the application performance requirements of substation ground connections. Mechanical and electrical strength is tested with pull-out and electromagnetic force tests, and longevity is proved through sequential testing on the same set of connectors for static heat cycling, freeze-thaw cycling, corrosion exposure (acidic or alkaline), and finally fault current. Connectors passing IEEE Standard 837 criteria are suitable for all grounding applications and require no special considerations, such as temperature derating.

3.5 General Guidance and Good Practices for Electrical Connectors

- Before starting work on existing connectors, ensure that the circuit or component is deenergized, properly isolated, and tagged in accordance with the work order and applicable station procedures.
- The workmanship and materials used should be of high quality to ensure that the connection has sufficient electrical and mechanical contact.
- Be sure to verify that the correct bolting materials are used. The use of incorrect or counterfeit materials has led to connector failures. Improper identification of materials has led to over- and under-torquing problems.
- When selecting connectors, choose materials that are compatible with the conductors being joined. Note that aluminum is anodic to copper and is, therefore, subject to galvanic corrosion when the two materials are placed in contact. There are special precautions that must be taken to prevent degradation of aluminum when present in the joint.
- For insulated electrical connections (for example, cable splices), the insulation materials used should provide insulation properties equivalent to the insulation on the conductors joined by the connector.
- Use the appropriate tools for installing electrical connectors. In general, use tooling approved by the connector manufacturer or qualified equivalent tools. Use crimping tools with die stops to prevent over-crimping, and ratchet-type features to prevent under-crimping.
- Cable and wire ends should remain sealed, trained, and protected to prevent moisture intrusion prior to final termination. Cable and wire ends can be effectively sealed with commercially available heat shrink materials to prevent moisture intrusion.
- Prior to terminating a cable, cut and remove the end of the cable that was held within the pulling device.
- Use care when stripping cable jackets and wire insulation to prevent cutting or nicking cable shields, conductor insulation, or conductor material. Care should be exercised to ensure that all insulation layers and fillers are removed from the conductors and that no conductor strands are clipped or nicked.

- The use of connectors or splices outside the range of the manufacturer's specifications, recommendations, and ratings should generally be avoided. Where necessary, some form of special verification tests should be completed prior to installing these items in the plant.
- Do not exceed a manufacturer's requirements or recommendations concerning minimum bending and training radius for cables, wires, and insulated splices.
- Avoid contamination of cable and wire ends, splices, connectors, and lugs. Common contaminants to watch for include moisture, cable pulling compounds, oil, grease, dirt, steel shavings and burrs, and shavings of jacket material, cable filler material, and insulation. When working with fiber-optic terminations, insulating tapes, and heat shrink materials, personnel must be sure to clean their hands prior to touching any materials.
- Remove temporary identification tags and labels, and install permanent tags and labels prior to completing the work. Cables should carry unique identification codes in conformance with the plant's cable schedule. Conductor labeling, where required, should match circuit and wire diagrams. IEEE Standards 803 and 803A [13, 14] provide recommended practices for uniquely identifying power plant systems and components.
- For power cable terminations, conductors should be clearly identified for polarity and phasing. Proper phasing and direction of rotation for rotating equipment should be verified prior to making final terminations.
- Plant evolutions that involve the temporary lifting of leads (such as normal surveillance tests and troubleshooting activities) should be controlled by a written work order or procedure that includes explicit steps to restore lifted leads. Failure to properly control such activities and vague or general instructions to restore the system have led to inoperable equipment and reportable events at nuclear power plants.
- Thermography (or *thermal imaging* as it is sometimes called) is a condition-monitoring technique that measures the radiant heat from bodies or objects. Thermography is an effective, proven technique for monitoring the condition of electrical equipment and connectors. Appendix B of this guide provides an overview of the technology and some good practices to consider when using thermography.
- Where possible, install all wiring using stress-relief supports—the electrical connector should not carry the weight of the conductor. Furthermore, in high vibration environments (such as near rotating equipment), sufficient slack should be given to the conductor so as not to stress the connection in the event of relative movement.
- Only socket connectors and plug-in connectors with positive locking devices, hold-down straps, or retention clips that provide adequate retention and clamping force should be used.
- Connector installations should be housed, protected, or shielded from dirt or moisture intrusion, excessive dust, chemical sprays, and salt sprays.

3.6 References

1. U.S. Department of Commerce. National Information Service. *Electrical Connections for Power Circuits: Facilities Instructions, Standards and Techniques,* Vol. 3-3, November 1991.

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4
CONNECTOR FAILURE AND DEGRADATION MECHANISMS

Although electrical connectors in nuclear power plants generally perform as designed and with high reliability, when connector failures do occur, they can lead to plant trips, inoperable safety-related equipment, and reportable events. Some examples include:

- In June 2001, a pressurized water reactor (PWR) experienced an automatic reactor trip from 100% power due to over-torquing of a bolted connection on the main generator neutral transformer.
- In March 2000, a broken solder connection (cold-solder joint) on an excore linear calibration switch resulted in the inoperability of a reactor protection system channel and a reportable event.
- In January 2001, temperature-induced aging degradation of a cable connector caused a partial drop of a control rod with the reactor operating at full power.

This section focuses on connector failures—specifically, failure experience and the mechanisms that cause connectors to degrade and fail in service.

4.1 Connector Failure Modes

Experience shows that connectors fail in a variety of ways. Table 4-1 summarizes some common failure modes that should be considered when inspecting electrical connections and when troubleshooting equipment failures or malfunctions.

Table 4-1
Common Connector Failure Modes

Termination Failures	**Fatigue-Induced Failures**
Poor solder joint	Excessive flexing of conductors
Under-crimped/over-crimped lug	Excessive vibration
Improperly crimped lug	
Mismatch between lug and wire size	**Human Factor Issues**
Inadequate insertion of wire in lug	Misidentification of materials
Insertion of insulation into lug barrel	Failure to restore lifted leads
	Mishandling of cabling and wire bundles
Connector Coupling Failures	Limited or obstructed access
Connector loosened	Use of undersized hardware
Connector completely uncoupled	Installation of wrong hardware
Under-torqued fastener	
Over-torqued fastener	**Corrosion-Related Failures**
Insufficient thread engagement	Use of incompatible materials
Retention clip improperly installed	Contamination
	Poor housekeeping
Short Circuits and High-Leakage Currents	
Moisture intrusion	**Procurement-Related Failures**
Insufficient insulation	Manufacturing defects
Insulation stripped back too far	Inadequate receipt inspection
Missing or damaged seal	

4.2 Failure Rate Data

The United States military has performed detailed studies of electrical connector failure rates. Table 4-2 provides some failure rate data published in *Reliability Prediction of Electronic Equipment* (MIL-HDBK-217F) for various types of connectors [1]. The data in the table are presented in terms of failures per component per million hours of service. A predicted failure rate can be determined by multiplying this rate by the number of similar components in a population.

As shown in the table, failure rates vary with environmental conditions and connector type. The failure rates for all types of connectors are quite low (less than one failure per million hours). The MIL-HDBK-217F data also show that failure rates for components procured in accordance with military specifications were substantially lower than the failure rates for materials purchased as commercial grade. Note that these are operating life failure rates and do not represent infant mortality or end-of-life failure modes.

Table 4-2
Connector Reliability Data Extracted from MIL-HDBK-217F [1]

Component Type	Generic Failure Rate per 10^6 Hours of Service per Component	
Multi-Conductor Connectors	**Benign, Ground-Based Environment, 30°C (86°F)**	**Sheltered, Naval (Below Decks) Environment, 40°C (104°F)**
Circular	0.0011	0.0065
PCB card edge	0.044	0.26
Hexagonal	0.16	0.97
RF coaxial	0.00045	0.0027
Telephone	0.0082	0.049
IC sockets (DIP, SIP, PGA)	0.0035	0.021
Single Connections		
Hand solder, without wrapping	0.0013	0.0052
Hand-solder, with wrapping	7.0×10^{-5}	0.00028
Crimp	0.00026	0.0010
Weld	1.5×10^{-5}	6×10^{-5}
Solderless Wrap	6.8×10^{-6}	2.7×10^{-5}
Clip termination	0.00012	0.00048
Reflow solder	6.9×10^{-5}	0.00028
Terminal block	0.062	0.25

The following information should be noted about the data in Table 4-2:

- These data were adapted from Appendix A of MIL-HDBK-217F, *Reliability Prediction of Electronic Equipment*, December 1991 [1]. The data are for generic components. More specific failure rate approximations may be calculated using the guidance in Sections 15 and 17 of MIL-HDBK-217F.
- The environments selected are b*enign, ground-based* and s*heltered, naval*, which are analogous to a climate-controlled area and a non-climate controlled industrial environment, respectively. Benign, ground-based environments are defined in the reference as "non-mobile, temperature and humidity-controlled environments readily accessible to maintenance." A sheltered, naval environment is defined as including "sheltered or below deck conditions on surface ships and equipment installed in submarines." [1]
- Failure rates for multi-conductor parts require adjustment to account for quality assurance of manufacture. The failure rate of commercial-grade connectors is a factor of 2.0 times what is

shown. The failure rate of inductance capacitance (IC) sockets that are military specification (MIL-SPEC) is a factor of 0.3 times what is shown.

4.3 Nuclear Power Industry Connector Failure Data

The nuclear power industry has programs in place that record reported failure data for plant equipment. Review of these data provides an understanding of the frequency of equipment failures, the causes, and consequences. Data collected in these programs pertaining to electrical connectors were reviewed for this guide, and the results are presented herein.

The specific data collections reviewed are as follows:

- For the period from November 1975 through 1997, failure data were recorded in the INPO-NPRDS database. A detailed evaluation of data collected through mid-1994 is presented by R. F. Gazdzinsky, et al. [2]. Key results of that evaluation are summarized in this application guide.
- Starting in 1997, failure data were recorded by INPO in the EPIX System. EPIX replaced the NPRDS as the primary device used in exchanging operating experience among U.S. nuclear power plants. Data from EPIX from 1997 to June 2002 were reviewed for this guide.
- Records on file at the U.S. NRC were also reviewed for information pertinent to electrical connector failures at nuclear power plants. The key resources reviewed were Licensee Event Reports (LERs) and Information and Enforcement (I&E) Notices. Results of these reviews are also presented in this section.

4.3.1 Evaluation of NPRDS Failure Data

A search for reports of failures of electrical connectors was conducted [2] of the NPRDS database from November 1975 through mid-1994. Failure reports were individually evaluated to determine their applicability to aging and aging mechanisms.

Based on analysis of the NPRDS data, a total of 959 failures was attributed to termination component failures. Of this total, 840 were attributed to age-related causes, and 119 were attributed to maintenance-induced causes (for example, failures resulting from prior installation, maintenance, modification, or surveillance testing). Results are presented in Table 4-3.

Table 4-3
Failures of Electrical Connectors Reported in NPRDS Database (1977–1994)

Voltage Range	Component	Number of Aging-Related Failures	Number of Maintenance-Induced Failures
Low (max. 1000 Vac)	Connector	314	21
	Compression/fusion fitting	132	33
	Terminal block	36	2
	Splice/insulation	26	6
Medium (max. 15 kVac)	Connector	4	0
	Splice/insulation	6	0
	Compression/fusion fitting	1	4
Medium (neutron monitor; 1–5 kV)	Connector	321	53
	Overall total	959	

The following conclusions were made, based on NPRDS data [2]:

- The most common failure modes for low-voltage electrical connectors were high resistance and open circuiting. Oxidation, corrosion, and dirt buildup on contact surfaces were the most common causes of failure (44%).
- The most common failure mode for low-voltage compression/fusion fittings was loosening or breakage (71%) and was most often caused by mechanical stress or oxidation/corrosion.
- Roughly two-thirds of all low-voltage termination failures noted were detected during operation and affected functionality of the circuit/connected load. Surveillance testing and maintenance were the next most common methods of detection, respectively, accounting for roughly 30% of all low-voltage termination failure reports collectively. Hence, surveillance testing and maintenance activities may identify only a fraction of incipient low-voltage system component failures or instances of degradation.
- The single most common failure mode for connectors was high resistance/open circuit (47%). Significant failure causes included oxidation, corrosion, and contamination (34%). The majority of failures noted (63%) were detected during operation, and all of these failures affected circuit or equipment functionality.

Key Technical Point

More failures of low-voltage terminations are detected during operation than during testing. Hence, surveillance testing and maintenance may identify only a fraction of incipient failures/degradation for low-voltage terminations.

4.3.2 Evaluation of EPIX Failure Data

The EPIX system was searched for reports pertaining to failures in electrical connections. Because there is no separate classification for electrical connections in the EPIX system, the full-text search function was chosen in order to identify as many applicable reports as possible. The terms *electrical AND connection*, *splice*, and *electrical AND termination* were used in the full-text search yielding a total of 678 hits for the period from 1997 to June 2002 pertaining to electrical connections. These reports were then categorized and evaluated according to the impact of the failure on the plant and the type of electrical connection that failed. A summary of the results is provided below.

4.3.2.1 Summary of Failure Impacts

The EPIX reports were categorized according to the impact that the failed electrical connection had on the plant. Results are shown graphically in Figure 4-1. The majority of the failures either had no impact (24%), led to faulty or erratic operation (37%), or caused equipment to be inoperable (27%). These failures were discovered and repaired without having any serious effect on the plant generation. However, a smaller percentage of the failures led to a plant trip (3%), reduced generation (7%), or an outage extension (2%). These failures led to a total of approximately 3.75 million lost megawatt-hours (MWh).

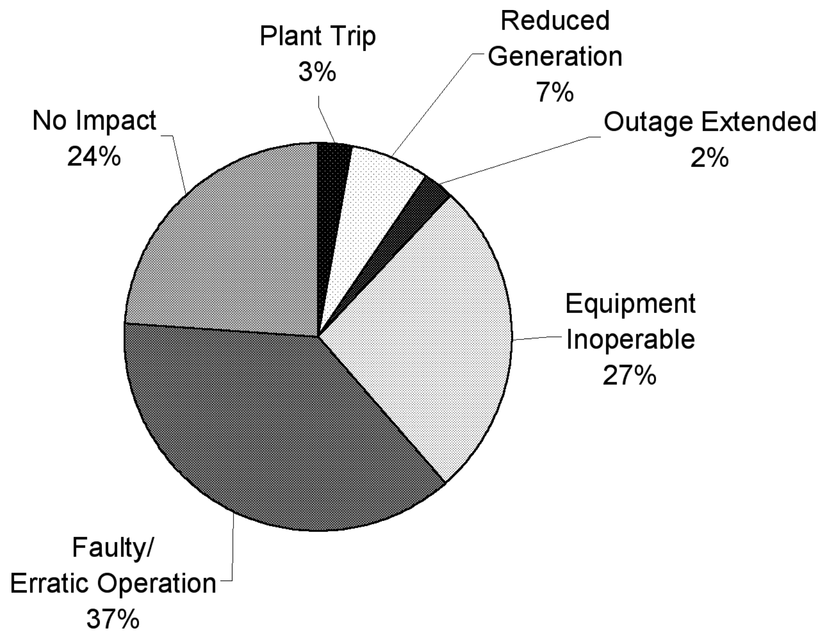

Figure 4-1
Impact of Electrical Connector Failures on Nuclear Plants (From EPIX Data, 1997–June 2002)

4.3.2.2 Summary of Electrical Connection Failures by Type

The EPIX reports were also categorized according to the type of electrical connection that failed. (**Note:** Many of the reports did not provide explicit descriptions of the type of electrical connection that failed. Therefore, some interpretation was necessary to categorize such data.)

Figure 4-2 is a graphical representation of data breakdown by type of failure. Key results are as follows:

- Cable (coax, triax) connections (for example, BNC connectors) represented the largest percentage of failures in the reports reviewed (26%).
- Threaded connections and crimped connections accounted for 11% and 7% of the failures, respectively.
- Some of the connections in the *Other* category included clamp connections, plug connections, and card connections.

Of the 678 reports identified, 185 did not contain sufficient description of the type of electrical connection that failed and, therefore, were not included in the figure.

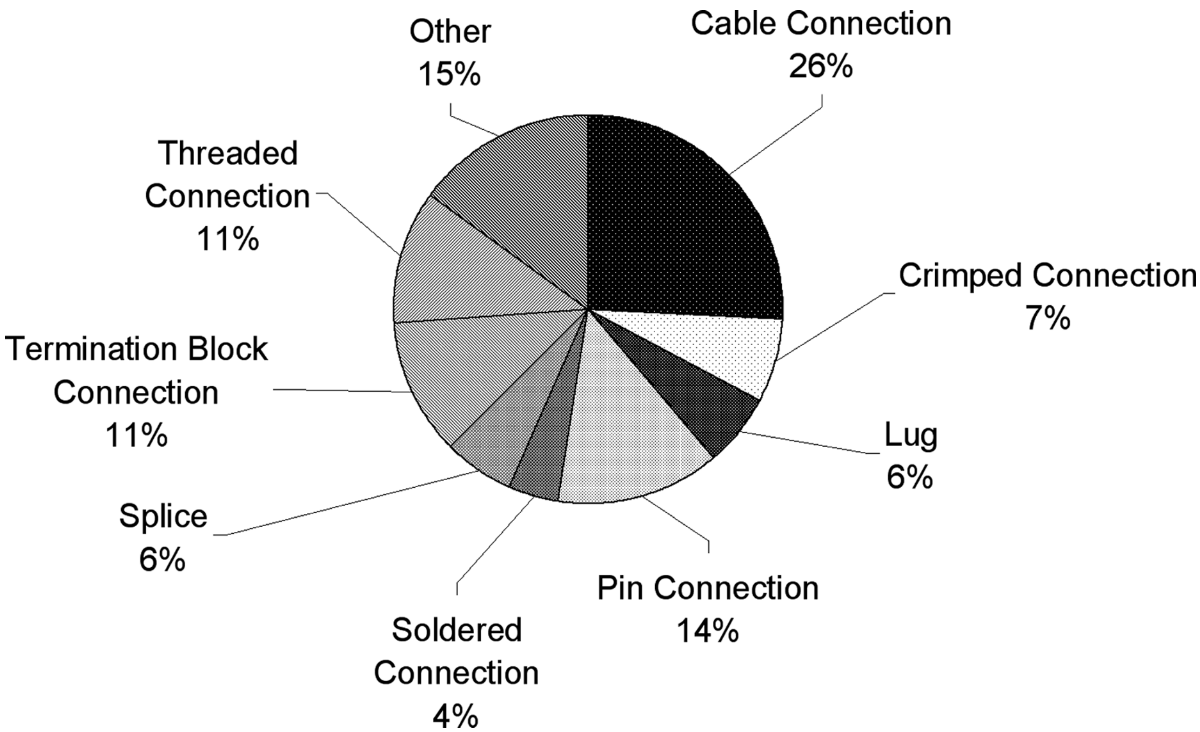

Figure 4-2
Types of Electrical Connector Failures in Nuclear Plants (From EPIX Data, 1997–June 2002)

4.3.3 Evaluation of LER Failure Data

U.S. NRC reports (LERs) are another source of termination failure and degradation data. LERs covering the period from early 1980 through April 1994 were reviewed [2]. The abstracts of LERs pertinent to failures of connectors or other termination components were identified through a keyword search of the LER database. Of the 411 reports reviewed, 13 of the reports were considered maintenance-induced and were not analyzed in detail. The remaining 398 reports were categorized by voltage range (low, medium, or neutron monitoring, to be consistent with NPRDS data), component, subcomponent, failure mode, failure cause, and method of detection. Results are shown in Table 4-4.

Table 4-4
Failures of Electrical Connectors Reported in LERs (1980—April 1994)

Voltage Range	Component	Number of Aging-Related Failures	Number of Maintenance-Induced Failures
Low (max. 1000 Vac)	Connector	316	7
	Compression/fusion fitting	22	0
	Terminal block	21	4
	Splice/insulation	10	1
Medium (max. 15 kVac)	Connector	20	0
	Splice/insulation	3	0
	Compression/fusion fitting	1	1
Medium (neutron monitor; 1–5 kV)	Connector	5	No data
	Overall total	411	

Of the total 398 applicable reports (excluding maintenance-induced reports), 341 (86%) were related to connector failures, and the remaining 14% were distributed among terminal blocks, splices, and compression/fusion fittings. For all components and voltage ranges, the great majority of failures noted were detected during operation of the component (as opposed to surveillance testing) and affected its functionality. Also, the following observations were made:

- Of the total, 319 aging-related failure reports covered low-voltage connectors. The single most common failure mode for connectors was loose or broken subcomponents (59%).
- Twenty-two failure reports covered low-voltage compression fittings. The most prevalent failed subcomponent was the lug itself (89%). The single most common failure mode for compression fittings was loosening or breakage (68%).
- The LER database contained 25 reports related to medium-voltage terminations, of which one was maintenance-induced. Out of the other 24 reports, 20 were attributed to connectors, and the remaining four were attributed to compression/fusion fittings and splices.
- Twenty failure reports covered medium-voltage connectors. Failed subcomponents included hardware (70%) and contacts/pins (30%). Broken or loose subcomponents accounted for 55% of the failures. The majority of medium-voltage connector reports did not identify a cause.

The following conclusions were drawn from the analysis of NPRDS and LER data [2]:

- The number of termination failures during normal operating conditions (all voltage classes) that have occurred throughout the industry is extremely low in proportion to the total number of terminations.
- Localized radiolytic degradation affects low-voltage terminations to a lesser degree, as compared to other aging mechanisms. This is consistent with the comparatively low percentage of the total circuit population that is installed in high-dose spaces and high-radiation damage thresholds of most component materials. Degradation resulting from exposure to external chemical substances appears to occur very infrequently.
- Connector failures constitute a large percentage of all termination failures noted for low-voltage (62% for NPRDS, 86% for LERs). A large percentage of these failures can be attributed to oxidized, corroded, or dirty contact surfaces.
- Loosening and breakage of lugs are the most significant compression fitting failures by a wide margin, based on both NPRDS and LER data.

4.3.4 Evaluation of Failure Data Reported in Other U.S. NRC Documents

The literature review included U.S. NRC circulars, generic letters, information notices, and bulletins. Circulars were used from 1976 to 1981, and two were found that are related to connector integrity issues. A review of all generic letters from 1977 to 1999 found that none were specifically related to connectors. Information notices issued from 1979 to the present were searched. This review identified 31 information notices relating to cabling and connectors. U.S. NRC bulletins have been used since 1971, and eight were found to contain information related to cabling and connectors.

Additionally, a search was conducted of the U.S. NRC public database to assess the frequency, severity, and mechanisms of connector failures resulting in LERs. Only LERs submitted since November 1999 have been converted to files that can be readily searched in the U.S. NRC database. A search located 28 LERs submitted from November 1999 to June 2002 that were directly caused by connector failures. Another three LERs submitted during that time were due to problems indirectly caused by connector failures.

4.4 Service-Induced Electrical Connector Degradation Mechanisms

The main functions of an electrical connector are to provide:

- A mechanical connection to a termination point of component (termination) or a mechanical connection between two or more wires or cables (splice)
- A low-resistance electrical conduction path across the mechanical connection
- High electrical isolation to other conductors and to ground

The complete mechanical failure of a connector or splice is rare, but gradual mechanical and electrical degradation of both the conducting and insulating portions of connectors are commonly observed in power plant environments. The most prevalent degradation mechanisms are:

- Corrosion of contacting surfaces
- Corrosion product transport to contacting surfaces
- Loss of contact normal force due to:
  - Long-term creep
  - Vibration
  - Flexure in service
  - Mechanical shock
  - Differential thermal expansion stresses
- Fretting wear of contact surfaces due to:
  - Vibration
  - Thermal expansion effects
- Sliding wear of contacting surfaces
- Thermal degradation of insulating materials
- Radiation damage to insulation materials

These degradation mechanisms are discussed in more detail below.

4.4.1 Corrosion Phenomena

Electrical connectors can fail to function due to the formation of small amounts of corrosion products, often virtually invisible, on contacting surfaces. A second, more obvious category of corrosion attack is the visible corrosion of metallic components. This category of corrosion is most often observed in highly corrosive environments that include excessive moisture, and may be exacerbated by galvanic corrosion effects between different metals. A detailed study of both subtle and gross corrosion mechanisms on connectors was performed by Battelle Columbus Laboratories and is referenced in *Metals and Ceramics Information Center Report* [3]. Information from that study is discussed below.

Subtle, localized corrosion of contact surfaces in connectors, especially connectors of the pin/socket type with low normal (contact) forces, is caused by airborne contamination by common industrial pollutants such as chlorides, sulfides, sulfur dioxide, and oxides of nitrogen. It appears that combinations of pollutants are most corrosive, and concentrations in the parts per billion level are sufficient to cause intermittent or poor electrical contact.

Key Technical Point

Concentrations of airborne pollutants in the parts per billion range are sufficient to cause intermittent or poor electrical contact in a connector.

Degradation of electrical performance in even relatively clean atmospheres is often observed when there is fretting wear between the contact surfaces. (Fretting wear is discussed later in Section 4.4.3.) In more heavily polluted atmospheres, subtle corrosion of contact surfaces occurs in bare metals (copper, nickel) and can even occur on precious metal plated surfaces (gold, gold-palladium) in microscopic pores in the plating that expose less corrosion resistant substrate material to the atmosphere. The porosity of the precious metal electroplates becomes an issue. It has been found that plating porosity levels are decreased dramatically as the surface roughness of the base metal is decreased.

As pollution levels continue to rise, rapid (but still subtle) corrosion can occur in nearby base-metal structures, producing corrosion products that can migrate onto contact areas, especially precious metal contacts. This is called corrosion product creep and is most often observed in gold contacts contaminated by the nearby corrosion of copper surfaces. Nickel corrosion products do not appear to migrate at a high rate, so nearby nickel plated structures are not as much of a problem.

When corrosion conditions become quite aggressive and moisture levels are also high, corrosion kinetics are dominated by airborne sulfides. Connector failures are caused by loss of electrical contact when visible corrosion products (produced by crevice corrosion, pitting corrosion, and galvanic corrosion) contaminate contact surfaces. Corrosion product creep from nearby surfaces can also contaminate contacting surfaces. Experience suggests that few connectors can long survive such conditions unless the contact areas are specially sealed from the environment. Little can be done from a purely material standpoint to mitigate corrosion in severe environments.

4.4.2 Loss of Normal Force

The electrical conduction across mating surfaces in a connector is provided by the intimate contact produced by the normal force. The normal force must be sufficient to disrupt any oxide films at microscopic surface asperities and allow metal-to-metal contact at a sufficient number of microscopic contact points to carry the current. Reduction in normal force, tightness, or joint torque (no matter what the cause) reduces the total contact area and increases the surface resistance. Connector failure in power circuits (as opposed to low-level signal or digital circuits) is often accompanied by overheating which may be detected by infrared thermography inspections (see Appendix B).

Low normal force connectors of the pin/socket type or card edge connector type rarely suffer from loss of normal force. This is because the normal force is provided by the socket spring action, and there are few aging-related mechanisms affecting the spring. Loss of normal force is most often observed in screw-terminal or bolted connectors, where normal force is provided by a threaded mechanical preload. The normal force is provided by a stiff (low compliance) screw or bolt connection. These connections cannot tolerate elongation of the screw or bolt or relaxation of the lug material without serious loss of preload.

Oxygen-free copper, which is often used in electrical applications due to its excellent electrical conductivity, is subject to long-term material plastic flow (mechanical creep) at or above ambient temperatures under conditions of high stress. Bolted connections involving a copper lug-in, perhaps a busbar application or in a motor, are subject to long-term creep and loss of preload. This is especially true if clamp stresses are well into the plastic range. Copper, brass, and nickel alloys are not subject to mechanical creep at near ambient temperatures but can creep if the connection runs hot for extended periods of time. For circuits carrying significant currents, loss of preload increases contact resistance and results in increased temperatures in service. This in turn causes further creep, further reductions in preload, and increases in contact resistance and operating temperature until the connector fails completely (sometimes by melting).

Long-term operation under vibration conditions can cause loss of preload and connector failure. Connectors subject to vibration should be inspected frequently for looseness or overheating. Such connectors include those mounted on or near rotating or reciprocating equipment.

Key Technical Point

Electrical connectors located near rotating or reciprocating equipment should be routinely inspected for looseness or overheating.

Repeated flexure of wiring can lead to loosening of connectors and eventual failure. Flexure may occur during repair or maintenance activities when personnel working in tight confines within electrical cabinets inadvertently displace wire bundles while attempting to access areas deep within the cabinet.

In addition, mechanical shocks can loosen connectors. Shocks can result from collision of wiring with moving equipment, personnel movement near wiring, or from misoperation of rotating equipment.

Differential thermal expansion properties in bolted or screwed connectors can cause very high stresses under high-temperature conditions, which cause plastic deformation of softer materials and loss of preload. Copper busbar and heavy flexible cable copper lugs used for bolted connections with steel bolts are especially subject to differential thermal expansion problems because the copper busbar material and copper lug materials have a larger thermal expansion coefficient than the steel bolt. Normal operation at elevated (but not excessive) temperatures can cause high stress in the copper, leading to local yielding and loss of preload [4]. This problem can be mitigated by increasing the bolted joint compliance with Belleville washers that can absorb differential expansion displacements without causing excessive stress.

4.4.3 Fretting Wear

Pin/socket, card-edge, and other low normal force connectors are subject to fretting wear of contact surfaces. This wear results from small relative motions between contact surfaces caused by vibration or small differential thermal expansion displacements that occur when switching power on and off. Fretting wear displacements are small (on the order of a few thousandths of an inch), and wear products (metal particles) build up on the contact surface. If these particles are made of reactive metals (that is, everything but precious metal), they can quickly oxidize and cause increased contact resistance [5].

Fretting wear in gold-plated electrical connectors does not manifest itself until the gold layer has been eroded through and nickel or tin sublayer metal particles are formed by the fretting action. Gold does not oxidize and gold particles do not affect contact resistance. Nickel and tin sublayer debris rapidly oxidizes and increases contact resistance. Fretting wear can be mitigated to some extent by use of contact lubricants, but these are not completely effective.

4.4.4 Sliding Wear

Sliding wear occurs in pin/socket and card-edge type connectors each time the connection is broken or remade in normal service. This wear results from relative motions on the order of 0.1 inch (2.5 mm) or more, which is large compared to fretting wear motions. In sliding wear, the wear particles are often pushed out of the contact area, and particle oxidation has less of an immediate impact on contact resistance. Sliding wear is a normal degradation mechanism that manifests itself as one or more sudden increases in contact resistance as the various contact plating layers are worn away, exposing sublayers that can oxidize (that is, gold plating wears away to a nickel sublayer, which in turn wears away to copper or brass base metal). The oxidizing properties of the non-noble sublayers then determine the contact resistance.

The rate of sliding wear and the rate of oxidation can be mitigated, to some extent, by the use of contact lubricants. Lubricants commonly used can be as simple as Vaseline or as sophisticated as polyphenylether-wax mixtures available as commercial products [6, 7].

4.4.5 Thermal Degradation of Insulating Materials

Plastics are used in many types of insulation for connectors. The main function of insulation is to isolate electrical conductors from one another and from grounding. In some applications, the insulation also serves to maintain very high resistivity (high-voltage and high-impedance circuits) or low alternating current dielectric losses. The insulating properties of plastics can be degraded or lost after long-term service at elevated temperatures.

One mode of degradation is the decomposition of a plastic/plasticizer composition, such as flexible polyvinyl chloride (PVC) insulation. There have been undocumented reports of wire and termination corrosion caused by decomposition of the PVC insulation on wiring. Documented reports of PVC plasticizer migration out of the insulation and onto relay contacts suggest that PVC insulation on wiring may not be stable at plant operating temperatures [8, 9]. PVC insulation degradation appears as a liquid discharge from the cut end of the insulation near the termination. Often the fluid is greenish in color, which suggests that the chlorinated plasticizers (commonly dioctyl phthalates) are corrosive to the copper wiring. PVC breakdown products from older PVC cables may be considered health hazards due to potential polychlorinated biphenyl (PCB) contamination. Personnel required to work with degraded PVC insulation should be warned to avoid skin contact.

Key Human Performance Point

PVC insulation breakdown products may contain PCBs. Personnel working with degraded PVC insulation should avoid skin contact with breakdown products.

If PVC breakdown is occurring, this is a strong indication that the cable is operating at elevated temperature, and the cause of the elevated temperature should be investigated. Action should be taken to replace the cable with a type of cable that is rated with the higher temperature or to eliminate the cause of the elevated temperature. Wiring should also be replaced if cracks are found in the insulation. Over time, plasticizer leached out of insulation will result in embrittlement, which in turn leads to wire insulation failure when the wires are bent [10].

Key Technical Point

Breakdown of PVC insulation may result in damage to cables. This breakdown may be evidenced by the presence of greenish fluid at the cut ends of insulation, near terminations.

The plasticizer/copper corrosion products can migrate to various connector surfaces and cause corrosion and electrical connector failure there as well. In addition, leached plasticizer can enter moving parts such as relay contacts or motor starters.

Plastics and some rubber insulation materials are also subject to oxidation in high-temperature service. Oxidation results in embrittlement, cracking, and potential loss of insulation material due to spalling. Further, the surface resistance of insulators can degrade by oxidation or contamination, which can lead to arcing or electrical tracking under high-voltage conditions.

4.4.6 Radiation Damage

Ionizing radiation in power plant environments has little effect on the metallic components in connectors. It can, however, cause degradation in contact lubricants and joint compounds through polymerization and can cause cross-linking or delinking of polymer insulation materials. For example, cable splices and insulated crimp lugs contain two main components—tubing/sealant tape and crimps. The tubing/sealant tape is subject to thermal degradation and radiation damage, which can cause embrittlement and cracking of the insulation. This allows moisture into the crimp and possible corrosion and connector failure.

Special polymers have been developed that are resistant to ionizing radiation, such as ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE). These are used as flexible cable insulation in high-radiation environments and can be found in radiation-resistant connectors. Normal polymers are much less resistant to ionizing radiation, and their suitability in such environments is problematical for long-term (60 years) service [11].

4.5 Other Electrical Connector Degradation Mechanisms

4.5.1 Dirt, Moisture, and Other Contaminants

Intrusion of dirt, moisture, or other contaminants is a common failure mechanism for electrical connectors. Intrusion can lead to short circuits and arcing, or high resistance and false or erratic signals. Instances of problems with such intrusion are as follows:

- In October 1999, a two-unit PWR site experienced a loss of normal power event on two safety-related buses. The event was caused by moisture intrusion into the protective sleeve of a 4160 V bus feeder cable. The moisture provided a conductive path along the cable and caused electrical arcing at the busbar-to-bus cable connections. The arcing also resulted in a small fire.
- In May 2001, a BWR experienced an automatic reactor scram event with the unit operating at 80% full power. The cause of the scram event was a contaminated connector on a linear variable differential transformer (LVDT) for one of the main turbine control valves. The connector was contaminated with electro-hydraulic control fluid. The contamination increased the resistance in the connection, which produced an incorrect position indication during turbine control valve testing.
- I&E Circular 77-06 [12], which was issued by the U.S. NRC in 1977, describes the adverse effects of certain fire-resistant, synthetic hydraulic fluids on cable insulation and jacket materials. The circular recommends that procedures for systems containing synthetic hydraulic fluids and other potentially aggressive fluids be reviewed to ensure that adequate steps are taken to minimize the likelihood of leakage, overflow, or inadvertent spills of fluid. The circular also recommends a review of housekeeping practices to ensure that station practices provide for prompt cleanup of leakage or spills.
- In June 2001, a reportable event occurred involving the failure of a temperature controller on a hydrogen recombiner. The temperature failed to respond to set-point adjustment demands following system restoration from a planned maintenance activity. Investigation of the event determined that similar failures of the hydrogen recombiner had occurred on two prior occasions. A dirty edge connector on a controller card was determined to be the cause of the failures.

Key Technical Point

Intrusion of dirt, moisture, or other contaminants is a common failure mechanism for electrical connectors. Periodic maintenance and equipment inspection procedures should include specific instructions to look for this type of condition.

4.5.2 Wear

Wires that connect electrical equipment mounted on cubicle doors or in sliding drawers have the potential to degrade over time. U.S. NRC Information Notice (IN) 2002-04 [10] documents an instance where wires degraded due to cold working and aging in 4 kV breaker cubicles. Such wire installations can also overstress electrical connectors.

Another similar situation that can adversely affect electrical connectors are contacts that *break* and *make* by opening and closing the door or drawer. Such connectors are found in metal-clad switchgear and voltage-regulator cabinets.

4.5.3 Human Factor Issues

Some connector failures are caused by human factors. Improper component selection, misidentification of materials, failure to restore lifted leads following testing or troubleshooting, and over- or under-torquing bolts are some of the types of human factor issues that can lead to electrical connector failure.

U.S. NRC IN 88-27 [13] documents several deficiencies in safety-related electrical terminations that were traced to human factor issues. These deficiencies included the use of oversized termination lugs, improper stripping of conductors, and inadequately crimped lugs. The information notice also discusses cracked termination lugs on motor leads due to excessive bending of the leads during maintenance work.

U.S. NRC IN 84-37 [14] documents a number of industry events that resulted from plant personnel failing to reconnect leads that had been lifted during planned maintenance, testing, or troubleshooting. The events described in the notice emphasize the safety value of independent review of the use of lifted leads and jumpers.

U.S. NRC IN 84-37 also notes that, although it may not be possible to totally eliminate the use of lifted leads and jumpers, initiating one or more of the following actions would serve to reduce the likelihood of adverse effects on safety systems:

- Installing permanent test hardware for use in lieu of lifting leads and installing jumpers (for example, switches with either spring-return from the test position or with control room indication while in the test position)
- Including additional procedural checks on system configuration during surveillance testing and maintenance (for example, recording initial and final positions of leads on equipment and/or adding precautionary statements to procedures regarding effects of oversight)
- Reviewing procedures to ensure that instructions for surveillance and maintenance specify explicitly and unambiguously the importance of reconnecting any lifted leads and the removal of any jumpers
- Using at least two qualified operators to independently verify proper system configuration before safety-related equipment is returned to service
- Performing functional tests designed to verify the restoration of proper system configuration following surveillance tests or maintenance
- Reviewing with operators and maintenance personnel specific instances of errors involving lifted leads or jumpers and the safety impact of such errors

IN 84-37 also refers to U.S. NRC Regulatory Guide 1.118, *Periodic Testing of Electric Power and Protection Systems* [15], for general guidelines and good practice in the use of lifted leads and jumpers and to Generic Letter 83-28 [16] on the general topic of post-maintenance testing.

Key Human Performance Point

Connector failures have been attributed to human factor causes, including improper component selection, misidentification of materials, failure to restore lifted leads, and over- or under-torquing bolted connections. U.S. NRC IN 84-37 describes methods for reducing the likelihood of problems associated with the practice of lifting leads.

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B
INFRARED THERMOGRAPHY

Because all metals have some resistance to current flow, electrical current generates heat. Heat is also generated at metal-to-metal contacts, such as those in mechanical connectors, due to the imperfect mating of the surfaces. Under normal conditions, a properly designed connector runs cooler than the attached wire or cable since by design it contains more metal cross-sectional area than the attached wire or cable. As connectors age, their contact resistance can increase due to loss of bolt, screw, or crimp preload, or because of wear, oxidation, or corrosion. Further, improperly performed maintenance and testing activities can result in poorly tightened connections or in short circuits. Loose connectors will generate excess heat due to the increased contact resistance. Short circuits can generate excess heat due to the large short-circuit current that often develops. In both cases, the excess heat will cause increased temperatures in the connector and wiring.

Increased temperatures are often a sign of trouble. Methods have been developed to remotely measure connector and wiring temperatures while the equipment is on-line using infrared thermography. This appendix deals with the use of this technology as a condition-based maintenance activity in power plants.

B.1 Thermal Radiation

All bodies emit heat energy as electromagnetic radiation. The spectrum, or spread in wavelengths of the radiation, depends on the temperature of the body. The intensity or strength of radiation at any given wavelength depends on the emissivity of the body as well as the temperature. Figure B-1 shows the emissive power for a black body (efficient radiator with an emissivity near 1.0 and a gray body (emissivity 0.6) as a function of wavelength of emitted radiation (λ). Both bodies are at the same temperature, and both have a radiation peak at the same wavelength, λ_m. The shape of the emissive power curve is determined by Planck's Law, which stipulates that the hotter the object is, the shorter the peak wavelength, λ_m, becomes. For objects near room temperature, $\lambda_m \approx 10$ µm, which is in the infrared portion of the spectrum. No part of the emitted spectrum reaches visible wavelengths. At very high temperatures, for example at 1020°F (548.89°C), the peak is still in the infrared range (3.5 µm), but the eye can detect the leading edge of the curve (shortest wavelengths) at 0.85 µm and the object appears to be dark red. The object is *red hot*; even though at this temperature, most of the radiation is in the infrared range (see Figure B-2). This guide will focus on infrared emissions in the 2 to 20 µm range, which can be used to determine temperatures in the 14°F–1000°F (-10°C–537.78°C) range.

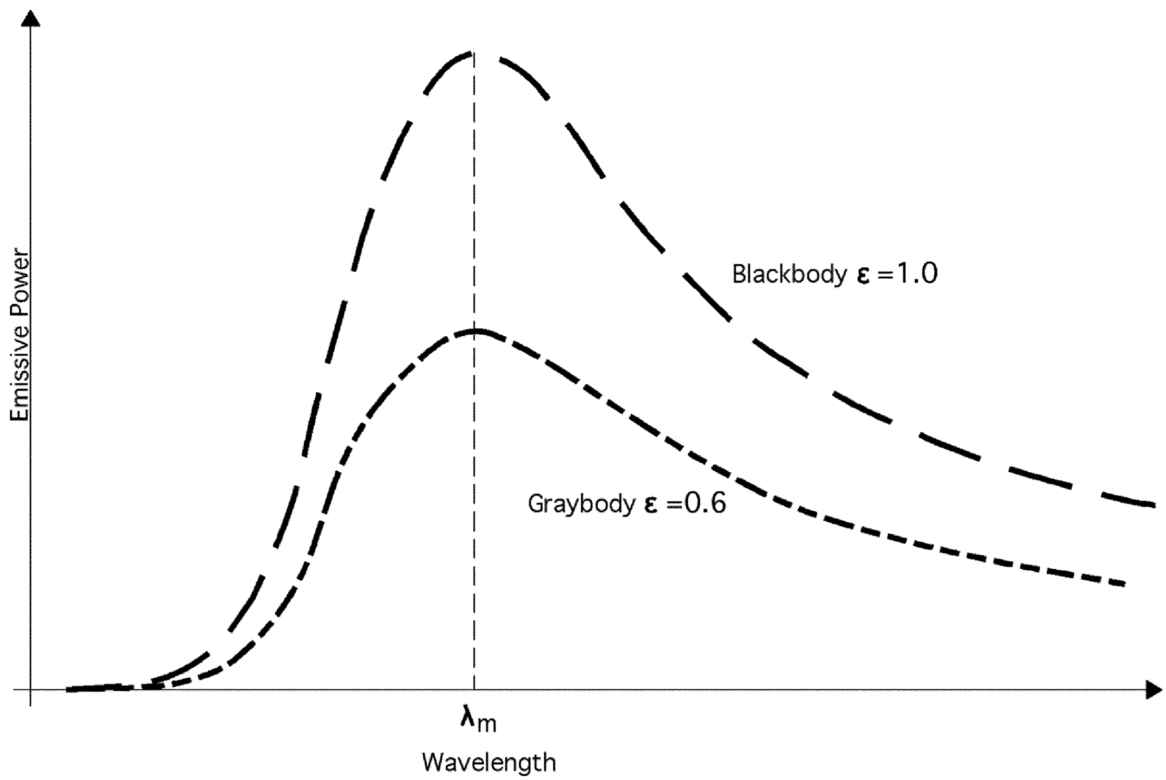

Figure B-1
Infrared Radiation from Two Different Objects at the Same Temperature

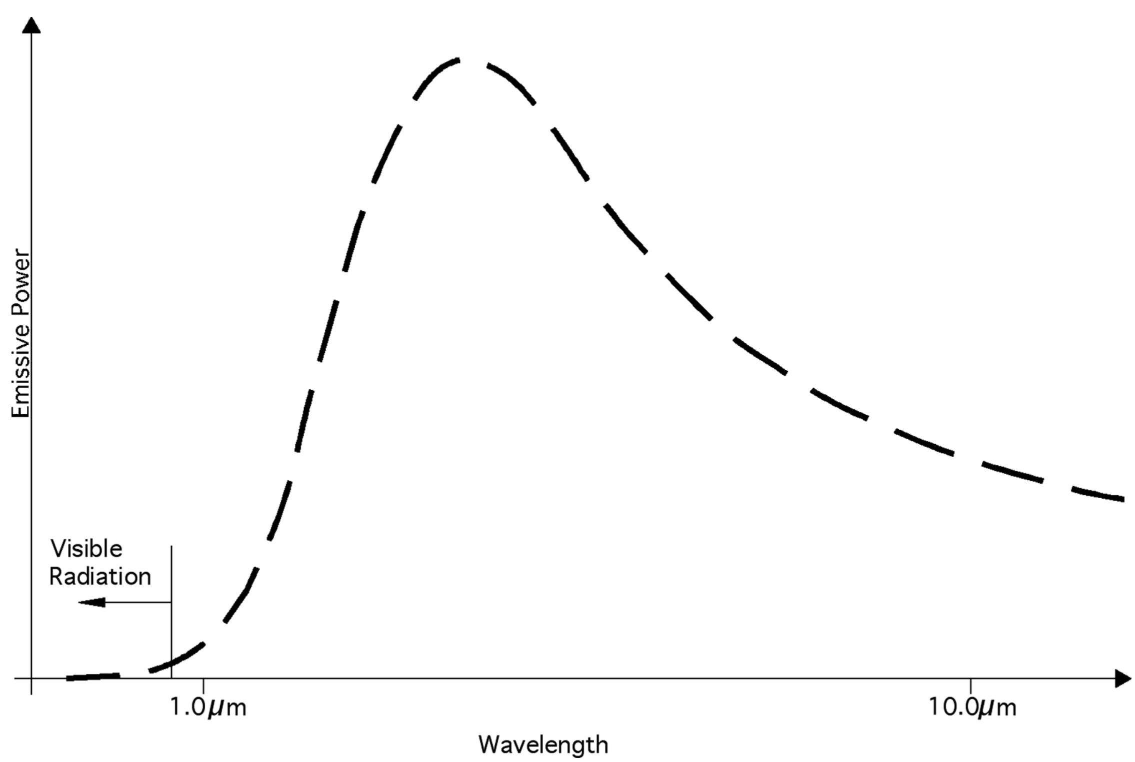

Figure B-2
Radiation from Object at 1020°F (548.89°C)

Figure B-3 illustrates another important characteristic of the emissive power curve. If measurements are made at two wavelengths, λ_1 and λ_2, the ratio of the intensities I_1 and I_2 is the same at any given temperature, independent of the emissivity. From the figure, $Ia_1/Ia_2 = Ib_1/Ib_2$. In principle, one can determine the temperature of any object without knowledge of the emissivity if one makes measurements at two wavelengths and uses Planck's law.

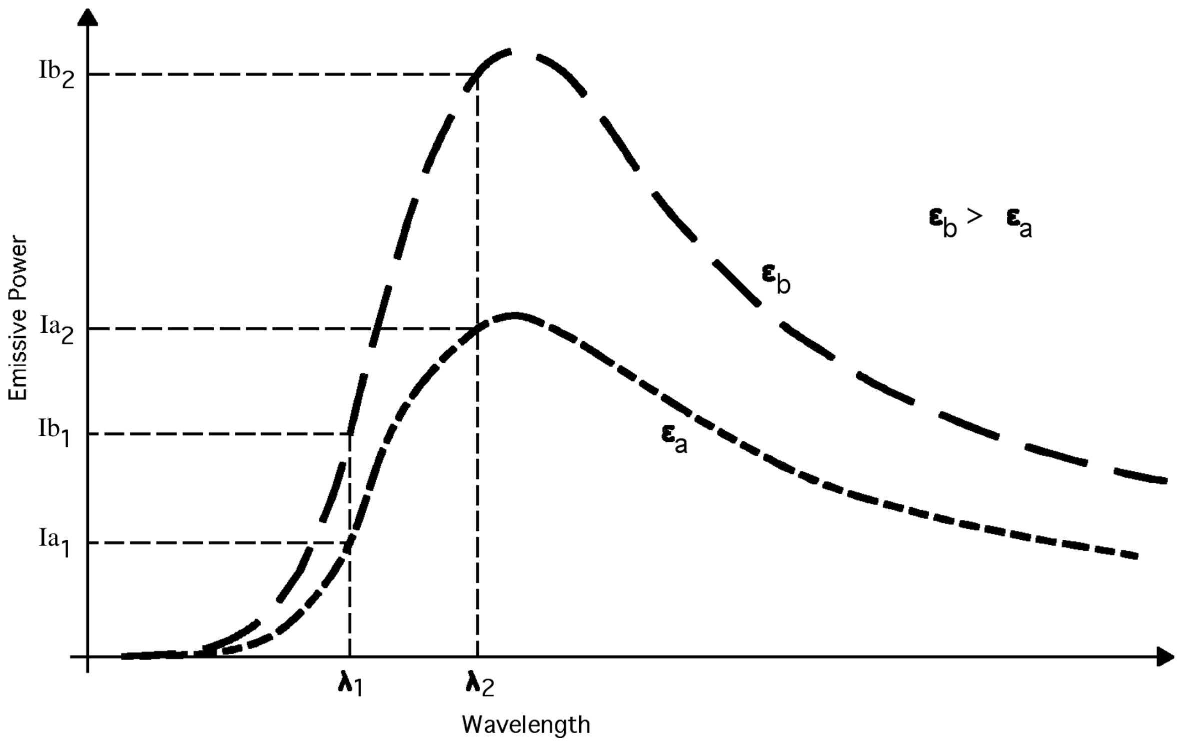

Figure B-3
Ratios of Emissive Power at Two Wavelengths Are Independent of Emissivity

Note: For a given temperature, $Ia_1 / Ia_2 = Ib_1 / Ib_2$

If, as is usual, only one wavelength or the total radiation in one band of wavelengths is being recorded, temperature cannot be determined without knowledge of the object's emissivity. Most infrared imaging devices can be adjusted for various emissivities. In general, if the emissivity of an object is unknown, its temperature cannot be determined precisely without further action. In some cases, such as for shiny, metallic objects with emissivities less than 0.1, more radiation is reflected from surrounding structures than is emitted, and no true temperature measurement can be obtained using passive infrared methods.

B.2 Infrared Monitoring Devices

Since precise infrared thermography (temperature measurement) is difficult without knowing component emissivity, an inspector conducting a survey of switchgear and connectors, for example, must generally settle for less than precise temperature measurements. What can best be done is to image a group of connectors in the infrared and compare apparent temperatures (or infrared intensities) among similar connectors. Such an image can be produced from an infrared camera, which uses a focal plane array of sensors as film. Assuming similar electrical load on the components surveyed, the image can be used to look for thermal outliers among similar connectors or fuses. Such an image is shown in Figure B-4, where three similar fuses can be seen in the infrared. One fuse is clearly hotter than the other two in the fuse clamp, indicating a poor (high-resistance) connection. A circuit breaker shown in the infrared in Figure B-5 reveals a poor connection. A poor connection in a bus duct is shown in Figure B-6.

Infrared cameras suitable for imaging and spot temperature measurements are widely available in a simple and useable format. Most cameras contain a built-in liquid crystal display that allows real-time monitoring of the image and floppy disk or flash memory. These cameras come in short wavelength band (~ 3.6–5 μm) and long wavelength band (~ 7.5–13 μm) capabilities. For power plant work with connectors, either band is acceptable.

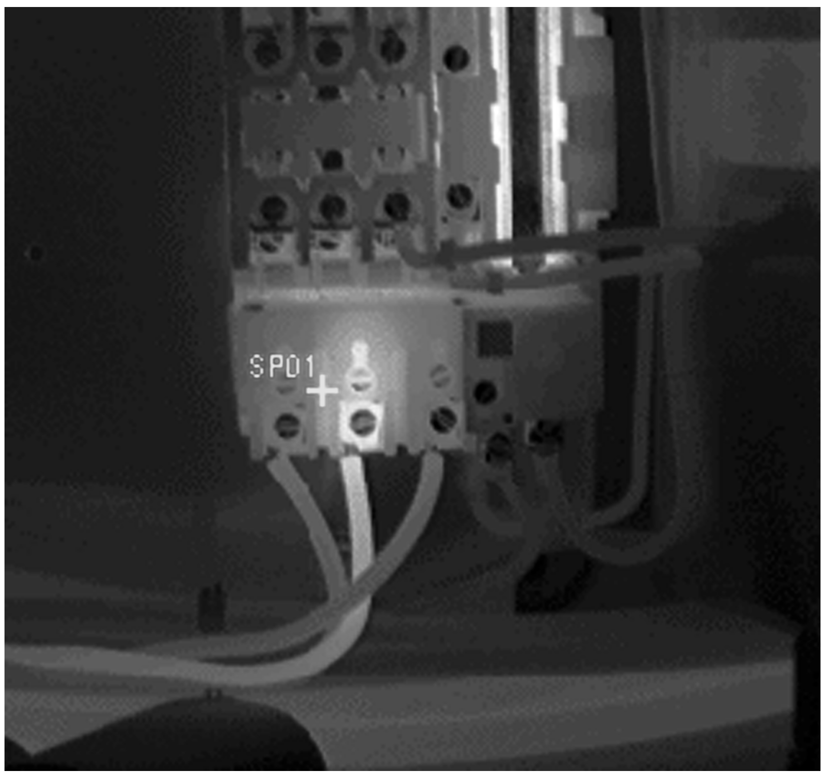

Figure B-4
Hot Fuse Clamp Connection

Courtesy of Sierra Pacific Infrared (SPi), www.x20.org.

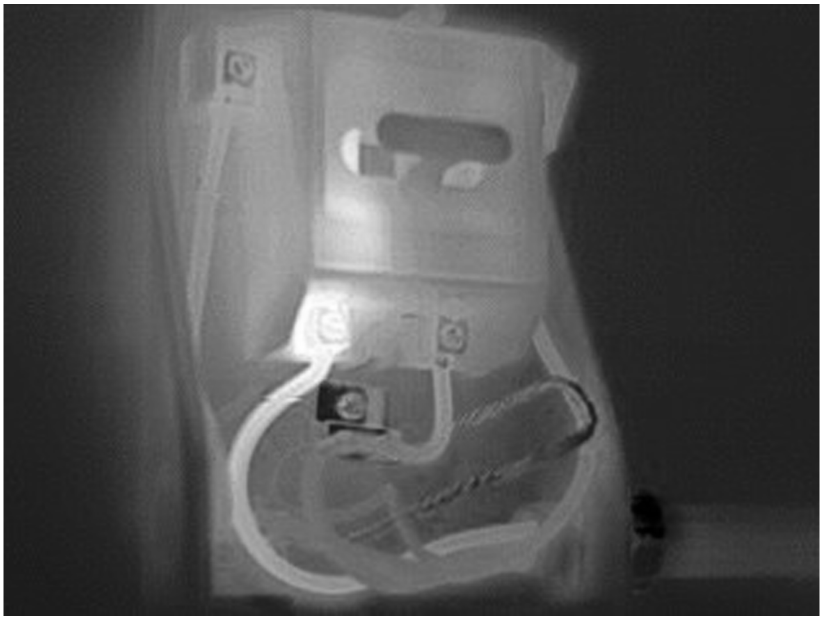

Figure B-5
Hot Circuit Breaker Connection

Courtesy of FLIR Systems, Inc., N. Billerica, MA, www.flirthermography.com.

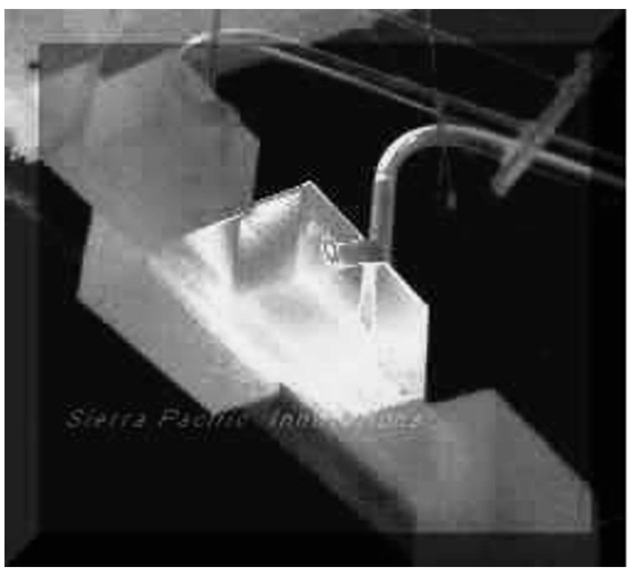

Figure B-6
Hot Bus Duct Connection

Courtesy of Sierra Pacific Infrared (SPi), www.x20.org.

Because metal housings and traditional glass and Perspex windows do not transmit infrared radiation, inspectors must open cabinets to obtain images with infrared cameras. This practice can be time consuming, disruptive to operation, and hazardous. To avoid opening cabinets, images can be taken through specially designed infrared windows that transmit at least 95% of short and/or long wavelength infrared radiation and are transparent in the visible spectrum. Infrared windows specifically designed for thermographic inspection of electrical components are commercially available for permanent mounting in electrical cabinets and enclosures.

B.3 Thermal Imaging Strategy

A thermal imaging strategy for connectors is best integrated into a condition-based maintenance program. The program can be implemented by the utility or by professional thermography services. The American Society for Nondestructive Testing (ASNT) and the American National Standards Institute (ANSI) provide standards for thermographic inspections and inspector qualification to Level 1, 2, or 3 degrees of proficiency [1].

The thermal imaging program for connectors should contain several basic elements, as follows:

- A list of connectors, cabinets, and equipment to be monitored. This can cover high voltage, high current distribution equipment, bus ducts, critical motors, batteries, and power supplies. The low currents involved with logic and signal circuitry make the methodology unsuitable for such low power components (little heat is generated).
- Baseline inspections of the (apparent) temperature of the equipment must be performed and results recorded in baseline inspection reports. Critical connectors should be recorded as false color images in the infrared, and normal operating temperature (at power) should be noted, as well as the ambient temperature. Potential problem connectors discovered in the baseline work should be investigated and repaired, if necessary. Repeat baseline work on repaired components as required.
- Formal documentation of procedures for inspections should be developed so inspection reports are consistent among components and over the years. Reports are often prepared with the help of software supplied by the camera vendor or an inspection services company. Such software is also useful for making image-to-image comparisons of identical equipment over the years to monitor gradual degradation.
- Periodic (typically once per year or once per each refueling outage) reinspections should be performed to monitor potential connector degradation. Inspection intervals should be based on the impact of component failure, expected failure rates, and vendor recommendations. In addition, inspections of infrequently used power systems (such as emergency diesel generator wiring) should be scheduled to coincide with periodic surveillance tests of the equipment. Reports should be incorporated in a database of inspections that records changes in apparent connector temperatures from inspection to inspection. Large changes should flag repair activities, and small changes can be used to trend long-term performance, if necessary.

B.4 Good Inspection Practices

Good inspection practices, both methods and equipment, are covered in both ASNT and the International Electrical Testing Association (NETA) specifications [2]. Some good practices noted in the literature include:

- Select a camera that uses a liquid crystal display type viewer in the back of the camera, has a flip-out panel, or has a monitor that is separate from the camera. It is more difficult to use a camera with an internal viewer and eyepiece since the inspector cannot see his surroundings well (in the visible) when using the eyepiece. Therefore, collisions with equipment are possible. Always provide an electrician with the inspector to monitor the activity and provide access to cabinets and restricted areas.

- When infrared viewing windows are purchased for installation in cabinets, make sure that the windows are compatible with the wavelength range of the inspection camera. Install the windows so that a good image of every connector can be taken.
- Take a normal (visible light) photograph of the connectors to accompany the infrared images. This will assist maintenance in accurately locating and repairing equipment. Take the normal image from the same distance and angle as the infrared images.
- Black vinyl electrical tape has an emissivity near 1.0, and can be taped onto surfaces to monitor background or ambient temperatures using spot measurement techniques without emissivity correction. The threshold or critical point for evaluating an overheating situation varies among the electrical systems inspected and the loads carried. The critical point must be established for the system type and load. See EPRI's *Infrared Thermography Guide* [3] for additional guidance.
- Beware of connectors with low emissivities (shiny, metallic surfaces). These usually show up as cool components, even when quite hot. Sometimes they reflect surrounding temperatures as well and can appear hot when not hot. The attached wire or cable is likely to be a better indicator of temperature since wire insulation will normally have a higher emissivity.
- The temperature in a wire typically decreases with distance from a poor (hot) connection. This is shown in Figure B-4. A short-circuit load or unbalanced load in a three-phase circuit will show up as a constant high temperature along the wire. A shorted phase near a bank of motor start capacitors is shown in Figure B-7.
- Perform outdoor measurements in the early morning dawn when all background temperatures are uniform and the sun cannot provide strong reflections. Wind and rain should also be avoided.
- Perform measurements while the equipment is energized and under load. Distribution loads can vary significantly during the day. The distribution load should be recorded. Load should be at a maximum level during inspection or at least 40% of design if maximum load is not possible. Safety information regarding inspection of energized equipment should be included in written inspection procedures.
- If the equipment is connected to more that one circuit (that is, a motor connected to normal and emergency circuits), test both circuits.
- When thermographic images seem to indicate problems, take an image from more than one angle to rule out reflections from nearby hot objects.
- Once an anomaly is detected, conduct more frequent thermographic inspections until corrective action has been taken.

Figure B-7
A Shorted Phase (Temperature Stays Constant with Distance from Connector)

Courtesy of GlencoMetrics, www.glencometrics.com, copyright 2001-2002.

B.5 Reference

1. American National Standards Institute and American Society for Nondestructive Testing. ANSI/ASNI CP-189-2001.

2. International Electrical Testing Association. *Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems.* Morrison, CO, 2001. NETA MTS-2001.

3. *Infrared Thermography Guide*. EPRI, Palo Alto, CA: 2002. 1006534.

C
CONNECTOR QUALIFICATION AND LIFE EXTENSION

C.1 Electrical Connector Qualification

Federal regulations require that nuclear power plant structures, systems, and components important to safety be qualified to withstand or accommodate the effects of natural phenomena and environmental or dynamic effects. These requirements are presented in "General Design Criteria" in Appendix A of the Code of Federal Regulations (Title 10, Part 50). Specifically, the two general design criteria that apply to qualification, Criterion 2 and Criterion 4, are quoted below [1]:

> Criterion 2 -- Design bases for protection against natural phenomena. Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the safety functions to be performed.
>
> Criterion 4 -- Environmental and dynamic effects design bases. Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit.

Qualification is required to ensure that the performance of electrical equipment that is important to safety will be adequate to safeguard the health and safety of the public. The equipment that requires qualification is described in 10 CFR Part 50.49 as follows [1]:

> Electric equipment important to safety covered by this section is:
>
> > (1) Safety-related electric equipment.
> >
> > > (i) This equipment is that relied upon to remain functional during and following design basis events to ensure --

(A) The integrity of the reactor coolant pressure boundary;

(B) The capability to shut down the reactor and maintain it in a safe shutdown condition; or

(C) The capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures…

(ii) Design basis events are defined as conditions of normal operation, including anticipated operational occurrences, design basis accidents, external events, and natural phenomena for which the plant must be designed …

(2) Nonsafety-related electric equipment whose failure under postulated environmental conditions could prevent satisfactory accomplishment of safety functions … by the safety-related equipment.

(3) Certain post-accident monitoring equipment.

Electrical equipment qualification is generally performed in accordance with guidance provided in two key documents developed by the IEEE [2, 3]. Electrical equipment requiring qualification includes electrical connectors. This section will provide an overview of qualification requirements for seismic qualification and environmental qualification of electrical connectors.

C.1.1 Seismic Qualification

ANSI/IEEE Standard 344-1987 was prepared by an IEEE working group to identify the procedures and methods for seismic qualification [2]. The standard provides recommended practices for verifying that the equipment can meet its performance requirements during and following one safe-shutdown earthquake that is preceded by a number of operating-basis earthquakes. This recommended practice may be used to establish tests or analyses that will yield data to substantiate performance claims or to evaluate and verify performance of representative devices and assemblies as part of an overall qualification effort.

In Regulatory Guide 1.100 [4], the U.S. NRC states that it accepts the methods in IEEE Standard 344-1987 for complying with the U.S. NRC regulations for seismic qualification of electrical equipment.

The most commonly used methods for seismic qualification include prediction by analysis, testing under simulated seismic conditions, qualification by a combination of testing and analysis, and qualification through the use of experience data. ANSI/IEEE Standard 344-1987 provides a procedure for each qualification method that can be used for the seismic qualification of electrical connectors [2].

C.1.2 Environmental Qualification

10 CFR Part 50.49, Section (e), provides the following requirements for an environmental qualification program for electrical equipment [1]:

> (e) The electric equipment qualification program must include and be based on the following:
>
>> (1) Temperature and pressure. The time-dependent temperature and pressure at the location of the electric equipment important to safety must be established for the most severe design basis accident during or following which this equipment is required to remain functional.
>>
>> (2) Humidity. Humidity during design basis accidents must be considered.
>>
>> (3) Chemical effects. The composition of chemicals used must be at least as severe as that resulting from the most limiting mode of plant operation (e.g., containment spray, emergency core cooling, or recirculation from containment sump). If the composition of the chemical spray can be affected by equipment malfunctions, the most severe chemical spray environment that results from a single failure in the spray system must be assumed.
>>
>> (4) Radiation. The radiation environment must be based on the type of radiation, the total dose expected during normal operation over the installed life of the equipment, and the radiation environment associated with the most severe design basis accident during or following which the equipment is required to remain functional, including the radiation resulting from recirculating fluids for equipment located near the recirculating lines and including dose-rate effects.
>>
>> (5) Aging. Equipment qualified by test must be preconditioned by natural or artificial (accelerated) aging to its end-of-installed life condition. Consideration must be given to all significant types of degradation which can have an effect on the functional capability of the equipment. If preconditioning to an end-of-installed life condition is not practicable, the equipment may be preconditioned to a shorter designated life. The equipment must be replaced or refurbished at the end of this designated life unless ongoing qualification demonstrates that the item has additional life.
>>
>> (6) Submergence (if subject to being submerged).
>>
>> (7) Synergistic effects. Synergistic effects must be considered when these effects are believed to have a significant effect on equipment performance.
>>
>> (8) Margins. Margins must be applied to account for unquantified uncertainty, such as the effects of production variations and inaccuracies in test instruments. These margins are in addition to any conservatisms applied during the derivation of local environmental conditions of the equipment unless these conservatisms can be quantified and shown to contain appropriate margins.

The actual methods for qualification under these environmental conditions are listed in general terms in 10 CFR 50.49, Section (f), which is quoted below [1].

> (f) Each item of electric equipment important to safety must be qualified by one of the following methods:
>
> > (1) Testing an identical item of equipment under identical conditions or under similar conditions with a supporting analysis to show that the equipment to be qualified is acceptable.
> >
> > (2) Testing a similar item of equipment with a supporting analysis to show that the equipment to be qualified is acceptable.
> >
> > (3) Experience with identical or similar equipment under similar conditions with a supporting analysis to show that the equipment to be qualified is acceptable.
> >
> > (4) Analysis in combination with partial type test data that supports the analytical assumptions and conclusions.

IEEE Standard 323-1983 provides guidance for environmental qualification of electrical equipment [3]. The principles, procedures, and methods of qualification are covered. These qualification requirements, when met, confirm the adequacy of the equipment to perform its safety functions under normal and abnormal service conditions, design-basis and post-design basis events, and in-service test conditions. The methods are to be used for qualifying equipment, extending qualification, and updating qualification if the equipment is modified.

The U.S. NRC has also prepared Regulatory Guide 1.89, *Environmental Qualification of Certain Electrical Equipment Important to Safety For Nuclear Power Plants* [5], to describe a method acceptable to the U.S. NRC staff for complying with 10 CFR Part 50.49 environmental qualification requirements. Regulatory Guide 1.89 states that IEEE Standard 323 is acceptable to the U.S. NRC, and provides guidance on calculating temperature, pressure, and radiation conditions during accident events.

C.1.3 Qualification Standards for Electrical Connectors

IEEE Standard 323 and 344 provide general qualification requirements [2, 4]. Industry standards that address qualification of safety-related electrical connectors, splices, and associated hardware specifically are listed in Table C-1, along with associated Regulatory Guides where applicable.

Table C-1
IEEE Standards Applicable to Qualification of Electrical Connectors

Applicable IEEE Standard	Associated Regulatory Guide
IEEE Standard 323-1983, Qualifying Class 1E Equipment for Nuclear Power Generating Stations [3]	RG 1.89, Environmental Qualification of Certain Electrical Equipment Important to Safety for Nuclear Power Plants [5]. RG 1.89 endorses the 1974 version of IEEE Standard 323 with several clarifications.
ANSI/IEEE Standard 344-1987 (Reaffirmed in 1993), IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations [2]	RG 1.100, Seismic Qualification of Electrical and Mechanical Equipment for Nuclear Power Plants [4]. RG 1.100 endorses the 1987 version of IEEE Standard 344 with several clarifications.
IEEE 317-1983, IEEE Standard for Electrical Penetration Assemblies in Containment Structures for Nuclear Power Generating Stations [6]	RG 1.63, Electric Penetration Assemblies in Containment Structures for Nuclear Power Plants [10]. RG 1.63 endorses the use of IEEE Standard 317-1983 provided the external circuit protection of electrical penetration assemblies meets the provisions of Section 5.4 of IEEE Standard 741-1986, Criteria for the Protection of Class 1E Power Systems and Equipment in Nuclear Power Generating Stations.
IEEE 383-1974 (Reaffirmed in 1980), IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices and Connections for Nuclear Power Generating Stations [7]	RG 1.131, Qualification Tests of Electrical Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants [11]. RG 1.131 endorses the 1974 version of IEEE Standard 383 with several clarifications.
IEEE 572-1985 (Reaffirmed in 1992), IEEE Standard for Qualification of Class 1E Connection Assemblies for Nuclear Power Generating Stations [8]	RG 1.156, Environmental Qualification of Connection Assemblies for Nuclear Power Plants [12]. RG 1.156 endorses the use of IEEE Standard 572-1985 for the environmental qualification of quick disconnect assemblies and cable and wire seals, when the Standard is used in conjunction with RG 1.89.
IEEE 837-1989, IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding [9]	None

C.2 Plant and Component Life Extension

C.2.1 Background

Most connectors have been qualified for a lifetime that ends coincident with that of their parent assemblies. That lifetime may or may not extend through the entire period of extended operation (operation past the expiration date of the original operating license). This section discusses life extension of environmentally qualified electrical connectors in the context of the overall plant life extension/license renewal process.

As part of license renewal, a case must be made for plant life extension based in part on studies related to aging, including an integrated plant assessment and time-limited aging analyses. An integrated plant assessment identifies systems, structures, and components requiring aging management and provides a description of the aging-management programs to be carried out during extended operation. Time-limited aging analyses compare the qualified lifetime of components with the period of extended operation and, if necessary, either provide any reanalysis of the component qualified life or demonstrate that the effects of aging will be managed to ensure that the component will function through the period of extended operation.

Life extension is based on either a reanalysis using refined assumptions for the equipment to account for improved data from experiments and operational experience, or the establishment of a program of periodic surveillance, testing, and refurbishment to serve as an ongoing qualification process.

C.2.2 Plant License Renewal Process

As part of the application process for license renewal, nuclear utilities must perform an evaluation to confirm that they have adequately considered all aging effects that could cause degradation to plant components during extended operation. EPRI Product Number 1003057, *License Renewal Electrical Handbook* [13], presents a methodology for determining which aging effects are applicable to electrical components and how they can be managed.

Key Technical Point

Refer to EPRI's *License Renewal Electrical Handbook* (EPRI Product Number 1003057) to determine which aging effects are applicable to electrical connectors and how the effects can be managed.

U.S. NRC regulations regarding license renewal are documented in 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants" [1]. Regulatory Guide 1.188, *Standard Format and Content for Applications to Renew Nuclear Power Plant Operating Licenses* [14], contains guidance on the information to be provided in a license renewal application. License renewal applications must contain six main items:

1. General information

2. An integrated plant assessment (IPA) that describes the scope and methods of aging management

3. Amendments that describe changes to the current licensing basis that occur during the renewal process, which would materially affect the renewal

4. An evaluation of time-limited aging analyses (TLAA) that in effect complement the IPA scoping of aging management

5. A supplement to the final safety analysis report (FSAR) that summarizes the programs and activities for aging management and evaluation of the TLAA (that is, a summary of item 2 and item 4 listed above that will be added to the FSAR)

6. An environmental support supplement

Of these, item 2 and item 4 (IPA and TLAA) are related to aging management and the process of equipment life extension and are specifically identified as key to issuance of the renewed license by the U.S. NRC in 10 CFR Part 54.29 [1].

Regulatory Guide 1.188 [14] directs that

> The technical information submitted (in the license renewal application) should focus on reviews of aging management, TLAAs, and the activities necessary to ensure that the current licensing basis (CLB) for the plant will be maintained for the period of extended operation.

In a license renewal application, connectors (which are required to provide a pathway for electric power or signals at all times) are discussed separately from environmentally qualified switches or relay contacts (which are designed to serve as intermittent pathways). Relays and switches are excluded from the IPA of a license renewal application because they require moving parts or a state change to accomplish their function. They require a TLAA if they are included in the scope of a license renewal application per the requirements of 10 CFR Part 54.4. Summary descriptions of an IPA and TLAA follow.

The Integrated Plant Assessment (IPA) is defined in 10 CFR Part 54.21, which requires that it identify structures and components that are subject to aging-management review. These components are those “that perform an intended function without moving parts or a change in configuration or properties” and “are not subject to replacement on a qualified life or specified time period.” [1] The license renewal application must show how aging management will ensure that the component’s intended function will be maintained. Even though components subject to the IPA are not subject to periodic replacement, the IPA may determine that to ensure function during the extended operating period, a component must be replaced or refurbished. Extension of the qualified life of these components may be a preferable alternative.

TLAAs are more focused on aging of individual components and systems. Per 10 CFR Part 54, they are those licensee calculations and analyses that [1]:

- Involve systems, structures, and components within the scope of license renewal
- Consider the effects of aging
- Involve time-limited assumptions defined by the current operating term (for example, 40 years)
- Were determined to be relevant by the licensee in making a safety determination
- Involve conclusions, or provide the basis for conclusions, related to the capability of the system, structure, and component to perform its intended functions, as delineated in Part 54.4(b)
- Are contained or incorporated by reference in the current licensing basis

The license renewal application must list all TLAAs and disposition them according to their period of validity. If the TLAA finds that the component's qualified life covers the period of extended operation, no further analysis is required. If the TLAA can be projected to the end of the period of extended operation and shows that the component will continue to function per the current licensing basis, then the analysis supporting that projection (the extension of qualified life) must be included in the application, but the component does not require aging management. If the TLAA cannot be projected through the end of the period of extended operation, then the applicant must demonstrate that the effects of aging on the intended function(s) will be adequately managed.

A general sequence for the process of determining the need for life extension of components (as part of a license renewal application) would begin with the IPA or a TLAA finding that replacement/refurbishment or life extension is necessary. The licensee would compare replacement/refurbishment to life extension of the subject component and determine that life extension is feasible and is the preferred (most economical) option. 10 CFR Part 54 and Regulatory Guide 1.188 do not specify the methods of aging management or life extension [1, 14]. Aging management is discussed in various aging-management and IEEE guidelines [15–18]. Additionally, Regulatory Guide 1.89, paragraph C.5.d, endorses a program of surveillance/testing as a means of ongoing qualification that extends qualified life [5].

The requirements of plant programs to meet the criteria that allow extending a component's qualified life are described in NUREG-1801, *Generic Aging Issues Lessons Learned (GALL) Report* [19], Section X.E1 for equipment qualification (EQ) electrical components. The *GALL* also provides examples of aging-management programs for electrical cables not subject to 10 CFR Part 50.49 (that is, not required to be EQ). These are found in Section XI.E1 for general-use cables and in Section XI.E2 for those in instrumentation circuits [19]. Although these programs in the *GALL* refer to cable degradation, they would also locate and allow for correction of problems due to aging of associated connectors. An overview of life extension for qualified connectors is summarized below.

C.2.3 Life Extension Techniques

In general, the process of life extension involves an analysis of the EQ performed on the equipment in conjunction with condition monitoring. The documentation to support this reanalysis and the use of existing EQ programs to meet the requirements for license renewal is described in the *GALL [19].*

Specific areas of analysis and testing to extend the qualified life of a component are discussed in Section 6.9 of IEEE Standard 323-1983. Qualified life extension can be based on seven methods as described in the IEEE standard [6].

- The first method involves type-testing a piece of equipment similar to that under consideration, using age conditioning to a lifetime longer than the installed component's qualified life and as needed to extend the lifetime to that which equals the anticipated installed life.
- The second method uses testing of a component that has been naturally aged in a service environment at least as severe as the installed component to a lifetime greater than the initially qualified life.
- A variation of these two methods is to use a combination of natural aging and age conditioning to result in an equivalent age that is greater than the initially qualified life of the installed component.
- The fourth method described in IEEE Standard 323-1983 requires a program of periodic surveillance, testing, and refurbishment to extend the equipment's qualified life [3].
- A fifth method uses analysis of the initial qualification program to show that conservative assumptions were made about the component's service conditions or performance. Assumptions that more closely reflect actual conditions and performance are then used to reevaluate the component's qualified life.
- Similarly, the sixth method is based on reanalysis of the age-conditioning process used for initial qualification. If that process is shown to be conservative because it excessively aged the component under test, the qualified life of the installed component can be extended.
- Finally, the seventh method uses a comparison of the actual installed component's environmental conditions to those assumed in the EQ to show that the component is in a milder environment. Thus, its age-related degradation is slower than assumed and its qualified life can be extended.

C.2.4 Life Extension and Aging-Management Publications

Aging of electrical cabling and connectors has been addressed in Department of Energy (DOE) - sponsored Nuclear Plant Aging Research (NPAR) studies (collected in NUREG/CR-5643) [20], EPRI Guides, NUREGs, and various other papers.

Documents that provide an overview of aging effects and aging management with regard to license renewal are:

- *Generic Aging Lessons Learned (GALL) Report,* NUREG-1801 [19]
  - The *GALL* describes component failure modes related to aging and aging-management programs in detail.
- *Industry Guideline for Implementing the Requirements of 10 CFR Part 54—The License Renewal Rule,* NEI [21]
  - NE I95-10 discusses the preparation of a license renewal application and includes the means to address the specific technical requirements related to aging management required by 10 CFR Part 54.
- *License Renewal Electrical Handbook,* EPRI [13] and IEEE Standard 1205-2000 [18]
  - The EPRI handbook and IEEE guide include information more tailored to the aging-management programs for qualified electrical equipment. The EPRI handbook focuses on the application for license renewal, while the IEEE guide is a general guide to addressing electrical equipment aging issues through testing and maintenance practices.

C.3 References

1. *Domestic Licensing of Production and Utilization Facilities.* Title 10, Chapter 1, Code of Federal Regulations, Part 50.
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11. U.S. Nuclear Regulatory Commission. *Qualification Tests of Electrical Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants.* Regulatory Guide 1.131.

12. U.S. Nuclear Regulatory Commission. *Environmental Qualification of Connection Assemblies for Nuclear Power Plants.* Regulatory Guide 1.156.

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14. U.S. Nuclear Regulatory Commission. *Standard Format and Content for Applications to Renew Nuclear Power Plant Operating Licenses.* Regulatory Guide 1.188.

15. G. Toman, et al. *Aging Management Guideline for Commercial Nuclear Power Plants – Electrical Cable and Terminations.* Ogden Environmental and Energy Services, Sandia National Laboratories, September 1996. SAND96-0344.

16. M. Sanwarwalla, "Cable Life Extension for Plant License Renewal." *ASME Conference on Plant Systems/Component Aging Management*, 1993.

17. U.S. Nuclear Regulatory Commission. *Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants.* NUREG/CR-5461, SAND 89-2369, July 1990.

18. Institute of Electrical and Electronics Engineers, Inc. *IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations.* Piscataway, NJ, 2000. IEEE Standard 1205-2000.

19. U.S. Nuclear Regulatory Commission. *Generic Aging Issues Lessons Learned (GALL) Report.* NUREG-1801.

20. U.S. Nuclear Regulatory Commission. *Insights Gained from Aging Research.* NUREG/CR-5643, March 1992.

Industry Guideline For Implementing the Requirements of 10 CFR Part 50 – The License Renewal Rule. Nuclear Energy Institute, March 1, 1996. NEI 95-10, Revision 0.

D
LISTING OF KEY INFORMATION

The following list provides the location of "Key Point" information in this report.

Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.

Referenced Section	Page Number	Key Point
3.3.3	3-29	Do not attempt to retorque a bolted joint after assembly. Retorquing can damage a bolted connection and lead to a failure.

Key Technical Point

Targets information that will lead to improved equipment reliability.

Referenced Section	Page Number	Key Point
2.1	2-2	Most functional connector systems are really a combination of both a separable and a permanent connector. Both parts have to be selected and installed properly using compatible materials and the right tools.
3.1.1	3-3	When aluminum components are involved in a connection, select connector materials so as to minimize the potential for galvanic corrosion of the aluminum components.
3.1.2.4	3-5	If lug bending is required, take care to avoid cracking the lug plating layer during bending. Inspect the lug thoroughly after bending for evidence of cracking or excessive plastic deformation.
3.2.1	3-8	If the conductor thickness decreases in the direction of the current, a hot spot may develop. This will cause increased resistance and voltage drop, which may become a problem if the connection carries a high current relative to its rating.

Referenced Section	Page Number	Key Point
3.2.3.3	3-10	The end of a conductor may be damaged during cable-pulling or by exposure to the environment. Prior to making a crimped connection, cut off the end of the conductor. Strip insulation immediately before crimping to minimize the time the bare conductor is exposed to the environment.
3.2.3.5	3-11	Overshooting the barrel end will cause the strands to fan out when crimped, offering a corrosion path to the interior of the conductor. An excessive overshoot can also interfere with the fastener.
3.2.3.6	3-12	The choice of compound to use should be based on environmental conditions such as temperature and humidity. It is essential to use a compound suitable for the materials being joined, because use of the wrong one might degrade the connection instead of protecting it.
3.2.3.7	3-13	Using a handheld crimping tool without protective features to prevent over- or under-pressurizing the crimp is not recommended for installations where the longevity of the connection is critical.
3.2.3.7	3-14	Under-pressurizing a crimp can lead to a loose connection and reduce the current-carrying capacity of the connector. Over-pressurizing can lead to lug deformation and possible conductor damage, which can increase electrical resistance.
3.2.3.9	3-16	Soldering conductors prior to crimping is not recommended. Soldering after crimping of folded-wing type lugs may be advised to enhance current flow through the connector.
3.3.1	3-20	Belleville washers are included in bolted connections when the connector is subject to vibration or when the bolting hardware and materials being connected have widely varying thermal expansion properties.
3.3.1	3-25	Qualification tests of bolted connections are generally performed with the bolted connection torqued per the manufacturer's recommendations. Use the manufacturer's specified torque for bolted connections in the plant, unless otherwise directed by engineering.
4.3.1	4-6	More failures of low-voltage terminations are detected during operation than during testing. Hence, surveillance testing and maintenance may identify only a fraction of incipient failures/degradation for low-voltage terminations.
4.4.1	4-12	Concentrations of airborne pollutants in the parts per billion range are sufficient to cause intermittent or poor electrical contact in a connector.
4.4.2	4-13	Electrical connectors located near rotating or reciprocating equipment should be routinely inspected for looseness or overheating.
4.4.5	4-15	Breakdown of PVC insulation may result in damage to cables. This breakdown may be evidenced by the presence of greenish fluid at the cut ends of insulation, near terminations.

Referenced Section	Page Number	Key Point
4.5.1	4-16	Intrusion of dirt, moisture, or other contaminants is a common failure mechanism for electrical connectors. Periodic maintenance and equipment inspection procedures should include specific instructions to look for this type of condition.
C.2.2	C-6	Refer to EPRI's *License Renewal Electrical Handbook* (EPRI Product Number 1003057) to determine which aging effects are applicable to electrical connectors and how the effects can be managed.

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or ease completion of the task.

Referenced Section	Page Number	Key Human Performance Points
2.2.2.2	2-8	Joint compounds can cause irritation to the eyes or burns upon prolonged skin contact. Follow the manufacturer's safety precautions when using these materials.
3.1.4	3-6	Requirements regarding 1) the use of specific required tools, 2) required crimping operations, 3) the strip length of the conductor, and 4) the preparation of the conductor are typically marked on a manufacturer's packaging material. Receiving and stocking personnel should retain such information and pass it on to technical personnel.
4.4.5	4-15	PVC insulation breakdown products may contain PCBs. Personnel working with degraded PVC insulation should avoid skin contact with breakdown products.
4.5.3	4-18	Connector failures have been attributed to human factor causes, including improper component selection, misidentification of materials, failure to restore lifted leads, and over- or under-torquing bolted connections. U.S. NRC IN 84-37 describes methods for reducing the likelihood of problems associated with the practice of lifting leads.

Target:
Nuclear Power

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EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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