REPORT SUMMARY

Power Plant Practices to Ensure Cable Operability

Installation practices as well as environmental conditions affect the operability of electrical cables in power plants. This report evaluates operability criteria for nuclear power plant cables, good practices for cable installation, and cable maintenance and surveillance. As a reference source for utility practices, this report suggests potential improvements that could benefit the industry.

INTEREST CATEGORIES

Nuclear plant operations and maintenance
Plant electrical systems and equipment

KEYWORDS

Electrical cables
Cable installers
Equipment qualification
Cable insulation
Electrical testing
Maintenance

BACKGROUND The basic functions of electrical cable in a power plant are to transmit instrument signals, control signals, and electrical power. Recently, cable installation and operability concerns focused on low-voltage cabling that could potentially be exposed to harsh accident environments in nuclear safety-related service. In 1987, NRC's technical evaluation report concluded that there was no definite source containing a complete description of standard utility cable installation practices; this prompted development of a reference source describing the state of industry information and experience related to cable installation and operability.

OBJECTIVES

- To assess industry practices, guidelines, and standards as they relate to nuclear safety-related cable operability.
- To provide a reference source for utility practices while identifying potential improvements or research areas that will benefit the industry.

APPROACH The project team examined existing reports, information, and data on nuclear power plant cable operability concerns. They reviewed various textbooks, handbooks, and other comprehensive references relating to maintenance, cabling, electrical insulation, and electrical engineering. In addition, they investigated manufacturers' recommendations and industry standards.

RESULTS This report discusses specific operability aspects of cables, such as construction features, cable applications, and physical installation practices. Moreover, it addresses in some detail the margin-of-safety differences in medium-voltage power, low-voltage power, control, and instrumentation cable stresses during service and testing. The report also evaluates the history of installation practices and in situ testing, with emphasis on state-of-the-art testing methods and recommendations for their improvement.

EPRI PERSPECTIVE Industry experience dictates that more-effective, practical techniques and clearer guidelines should be developed to better determine cable operability. The research discussed in this report will help utilities better understand and resolve concerns related to performance and expected service life of cables in nuclear and fossil power plants. Other related research on this subject includes EPRI reports NP-4997 and TR-100245, which address natural versus artificial aging of nuclear power plant components. Report NP-5920 describes the cable indenter aging monitor, an insulation embrittlement evaluation system. EPRI research projects RP2927 and RP7348 provide additional background on insulation aging methodology and aging monitoring.

PROJECTS

RP2814-08, 2814-37

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Power Plant Practices to Ensure Cable Operability

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ABSTRACT

This report describes the design, installation, qualification, maintenance, and testing of nuclear power plant cables with regard to continued operability. The report was initiated after questions arose concerning inadvertent abuse of cables during installation at two nuclear power plants. The extent of the damage was not clear and there was a concern as to whether cables, if damaged, would be able to function under accident conditions. This report reviews and discusses installation practices in the industry. The report also discusses currently available troubleshooting and in-situ testing techniques and provides cautions for some cases which may lead to further cable damage. Improved troubleshooting techniques currently under development are also discussed. These techniques may reduce the difficulty of testing while being able to identify cable flaws more definitively. The report finds, in general, that nuclear power plant cables have been relatively trouble-free; however, there is a need for further research and development of troubleshooting techniques which will make cable condition testing easier and more reliable. Also, recommendations for "good" installation practices are needed.

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EXECUTIVE SUMMARY

This report evaluates operability criteria for nuclear power plant cables, good practices for cable installation, and cable maintenance and surveillance. For cables in non-nuclear power plants and non-safety-related applications in nuclear power plants, operability means that the cable IS capable of supporting the function of the connected electrical equipment. For safety-related cables in areas of nuclear plants subject to harsh environment conditions, operability includes being able to support the function of the connected equipment even when the cable is exposed to harsh environments related to accidents.

Concerns for operability of safety-related cable related to inadvertent abuse during installation arose at two Tennessee Valley Authority (TVA) plants in the mid-1980s. The concern was that damaged cable might not be capable of supporting the function of the connected safety-related equipment under harsh environment accident conditions. The types of suspected damage included severe abrasion from pulling new cables past existing cables in conduits, crush damage to softer silicone rubber insulations, and damage of insulations at the top of long vertical runs due to a lack of proper support at the top of the run and at intermediate points along the vertical run.

The evaluation of cable installation "good" practices determined that there are no definitive sources of acceptable practices and that existing standards often dictate use of a manufacturer's installation recommendations rather than providing direct guidance. The development of this report also determined that few non-destructive diagnostic techniques are currently available for use in detecting damaged cables. Those that are available have limited applicability, and may be controversial (i.e., some engineers strongly believe they should be used and others believe they foster cable deterioration, e.g., high-potential dc testing).

The report covers construction, installation, qualification, and maintenance for low- and medium-voltage cable. Although some special cable constructions (e.g., coaxial, triaxial, and mineral insulated) are in use in nuclear plants, the predominant type of cable is low-voltage (<600 volts), unshielded, multi-conductor cable. When damage or deterioration of an unshielded cable is suspected, the lack of a shield presents a significant impediment to electrical testing of the insulation in that there is no consistent ground plane.

The lack of a consistent ground plane makes testing for insulation resistance, high-voltage, and partial discharge difficult. With insulation resistance tests, even severely damaged cables may have what appears to be satisfactory insulation resistances because the damaged section can be supported by other cables or facing away from the conduit or tray. Therefore, damage and severe deterioration may not be readily detected by such a test. High potential tests also require an intimate ground plane with the insulation surface for best results. Without such a ground plane, corona discharge and localized conditions, such as surface tracking, may cause inadvertent damage

even to good insulation during the testing Some tests have been performed in which conduits have been filled with water to provide a ground plane at the cable surface. Use of water is problematic in that conduit systems are rarely well sealed and leakage of water is hazardous to surrounding equipment. In addition, draining of the conduit system and complete drying of the cable at the end of the test may be difficult.

Research into other alternatives for establishing a ground plane and reducing test voltages is under way, but test methodology is not ready for use in power plants. In this research, use of ionizable gas to provide a ground plane within a conduit is being evaluated. A relatively low voltage will ionize the gas, after which it is conductive and will simulate a ground plane. Use of partial discharge testing is also being considered as a means of detecting defects and reducing test voltages. Partial discharges occur at the site of flaws at a given test voltage. These discharges begin to occur at voltages significantly below breakdown voltage and may be evaluated with no further damage to the cable. Development of these two methods may provide troubleshooting techniques for future use.

Review of trouble reports and discussions of cable in-service performance with industry experts shows that under normal service conditions, <u>very few cable problems</u> have occurred. The evaluation determined that the causes of those problems that did occur were predominantly related to physical damage after installation, poorly made terminations, and abuse during installation. Electrical deterioration of low-voltage cable was not expected because of the low electrical stresses in the insulations, and no such deterioration has been observed in low-voltage cables.

Low-voltage cables by nature require little maintenance. Manufacturers do not require maintenance programs. A formal cable surveillance and monitoring program is not recommended herein; however, condition awareness concepts are described. Aging especially at hot spots, can lead to embrittlement and cracking. When maintenance is performed on the equipment connected to the cables to evaluate existing installations, an opportunity exists to observe the cable terminations and a short section of the cables for signs of aging or distress. Since termination problems at power loads could lead to cable failures, and thermal hot spots are often in the vicinity of the connected loads, incorporation of a cable visual inspection routine in the vicinity of the connected equipment at the time of equipment maintenance would tend to enhance the knowledge of the condition of the cables and provide further assurance that the cable system remains sound. With respect to evaluating deterioration of cable jacket and insulation materials from hot spots, and long term thermal and radiation aging, a non-destructive hardness test that measures the (<u>insulation material's elasticity)</u> modulus is under development. The test device is called the Indenter and is being developed under EPRI auspices.

The basic conclusions of the report are:

- Significant operational problems do not exist in the general population of power plant cable.
- Electrical breakdown of low-voltage cable is not expected during normal plant operation. However, some medium-voltage cables may experience electrical deterioration especially if exposed to continuous wet and low load conditions.
- Useful condition monitoring and troubleshooting techniques are not currently available. However, research and development of an insulation hardness (embrittlement) evaluation system (the Indenter), partial discharge testing, and use of ionizable gas test media are under way.

The main recommendations from this report are:

- Further industry effort is necessary to promote sufficient understanding of cable populations, cable installation methods, and cable assessment efficacy for those needing this information in the industry.
- Further work is needed to document "good" cable installation practices in industry standards.
- Identification and control of hot spots in the vicinity of cables is desirable to preclude cable damage.
- Incorporation of local inspection of cables connected to electrical equipment that is being maintained can give early warning of embrittlement from hot spots or long-term aging.

Section 1.0

Introduction and Scope

Section 1.0
INTRODUCTION AND SCOPE

BACKGROUND

The basic function of electrical cable in a power plant is to transmit instrument signals, control signals, and electrical power. In most non-nuclear power applications, cables are not required to function under adverse environmental conditions. For these cables, operability means that the cable will continue to conduct the signal or power, while maintaining satisfactory insulation characteristics such that unacceptable levels of signal attenuation or shorting do not occur. However, certain cables in safety-related applications in nuclear power plants may be required to function while exposed to harsh environmental conditions if an accident occurs. For these cables, operability includes the ability to remain functional during normal conditions while maintaining the capability to operate satisfactorily for a specific period in an accident environment (e.g., loss-of-coolant accident).

Recently, cable installation and operability concerns were raised about low-voltage cabling in nuclear safety-related service that could potentially be exposed to accident environments. The concerns were first raised as a result of installation practices [1] that were alleged to have deviated from industry "standard, accepted, or good practices." The deviations consisted of excessive lengths of unsupported vertical cable drops, reduced bending radii of cable during and after installation, installation of new cable in raceways in a manner that could damage existing cable, impact damage to cable during installation, and other related handling and installation concerns. With regard to the identification of "standard, accepted, or good practices," the Technical Evaluation Report (TER) [1] issued by the U.S. Nuclear Regulatory Commission stated that, "The evaluators arrived at the heightened awareness that no definitive source exists that contains a complete description of standard utility-industry practices for cable installations." Furthermore, the NRC's TER concluded that the lack of published industry guidance could lead to continued concerns regarding cable abuse during installation.

The following quotation from the TER [1] summarizes the evaluation of industry-published guidance for cable installation:

> Today, there is a definite awareness in the cable engineering community that the utility industry's published guidance for cable installation is incomplete, and initial steps are being taken to fill some gaps in specific areas relating to cable installation abuse. The task is difficult because of the complexity of evolving cable materials and designs and the variety of installation conditions. Unfortunately, those persons most aware of the inadequacy of the standards are also those most knowledgeable

> and informed about proper cable installation practices and, thus, personally have not felt the need for producing more detailed, up-to-date standards. Until such standards are produced jointly by users, designers, and manufacturers, there will be continued concern that cable abuse has occurred during installation as judged by various experts each having their own obviously different biases and opinions.

At Tennessee Valley Authority, where concerns about installation practices originated, unshielded low-voltage cables were tested in-situ using high potential dc tests (10,800 volts dc for primarily 120-volt as application cables). This testing resulted in the failure of a number of silicone rubber insulated cables that had sustained crushing type damage [2]. TVA then submitted a 10CFR21 report (i.e., a report to the Nuclear Regulatory Commission indicating that a potential for substantial safety hazard exists) based on a preliminary evaluation that the test failures were an indication of the inability of the cables to provide adequate service. As a result, the NRC issued Information Notice 87-52 [3], advising the industry of its concern about silicone-rubber insulated cables.

During the NRC's evaluation of TVA's cable installation practices, NRC staff members and industry personnel discussed various issues, including differences in cable constructions, utilization versus rated voltages, the relationship between required safety function and intrinsic cable capability, degree of margin in environmental qualification, the relevance of electric stress during service and testing, and the impact of these differences on cable operability. Also discussed were the heretofore accepted degree of surveillance and maintenance for cabling, "standard" in-situ cable testing methods, significance of cable shielding in testability, and the severity and applicability of test parameters. During these discussions, the technical bases, validity, and intent of industry guidelines, standards, and practices that formed the basis for cable operability determination by utilities were challenged.

The research for this report determined that the existing guidance for in-situ determination of operability is primarily for medium-voltage cables (e.g., nominal 2400 volts and above in nuclear power plants). However, the cables predominately used in nuclear power plants are in low-voltage applications (600 volts or below) and are unshielded. The nuclear safety-related low-voltage cables in containment, which must be able to survive a accident environment after a lifetime of satisfactory service, are of primary concern with respect to continued operability.

In addition to cable operability concerns, the research examined suspect installations, acceptability of original environmental qualification with respect to installation damage, and preservation of that qualification [4-5].

OBJECTIVE OF RESEARCH

The objective was to assess industry practices, guidelines, and standards for cable installation, maintenance, and testing in relation to cable operability. The assessment was undertaken to provide a reference source for utility practices and to identify potential improvements or research areas that would benefit the industry.

SCOPE OF RESEARCH

The scope of the research covered the following specific areas and their relevance to cable operability:

- General cable construction features
- Cable applications
- Physical installation practices
- Environmental qualification practices
- Record of past cable performance
- Differences in medium-voltage power, low-voltage power, control, and instrumentation cable stresses during service and testing
- Efficacy of "standard" in-situ testing for
  a. Suspect installations
  b. General cable condition monitoring
- Significance of available ground plane at the surface of cable insulation in relationship to cable condition monitoring via electrical tests
- Cable performance in support of connected devices during accident conditions
- Operating voltage versus rated voltage
- Relationship between required safety function and intrinsic cable capability
- Efficacy of existing industry standards, codes, and guidelines

Section 2.0

Defining Cable Operability

Section 2.0

DEFINING CABLE OPERABILITY

The concepts of cable operability, cable functionality, and cable serviceability are interpreted differently by many individuals and organizations within the power industry. To facilitate the research reported herein, a firm definition of cable operability was necessary. If there is no common definition, a utility, manufacturer, consultant, regulator, or test facility may assess a cable as "operable" on the basis of differing criteria. Various general and scientific dictionaries were consulted for a definition [6-8] of these terms relevant to device or equipment condition. Finally, various textbooks [9, 10], handbooks [11, 12], and other comprehensive references [13-15] were reviewed as they related to maintenance, cabling, electrical insulation, and electrical engineering.

Some of the references had definitions that supported the concept that serviceability, operability, and functionality corresponded to the inherent capability of the cables. Other references espoused the concept that the terminology should relate to the requirements of a specific application rather than the inherent cable capability.

For nuclear power plants, operability concepts are complicated by adding accident considerations. Nuclear safety-related equipment must be able to perform its safety function during normal operating conditions, anticipated operational occurrences, and design basis events (i.e., accidents including loss of coolant (LOCA), main steam Iine break (MSLB), and high energy line break (HELB) for the entire time they remain in service. In general, cables themselves do not perform an active safety function; rather, they transmit signals for indication, provide control commands, annunciation, or deliver power to loads that act to complete a safety function.

Consequently, the application requirement for a nuclear safety-related cable is the enabling of connected equipment to complete a safety function. A cable may be suitable for and rated to withstand 600 volts or more continuously, and yet be used in an instrument service circuit with a nominal voltage of less than 50 volts. In this application, even with significant degradation in voltage withstand capability from intrinsic capability, the cable's condition may have little impact on the plant safety function. This research considered the needs of the complete cable equipment system when determining the following definition.

DEFINITION OF CABLE OPERABILITY FOR NUCLEAR POWER PLANTS

> *Cable operability is defined as the continued ability of the cable to support the performance of its connected equipment's nuclear safety-related function.*

For the nuclear safety-related cable to retain operability, it must continue to be able to support the nuclear safety-related function of the connected equipment during and after exposure to an applicable design basis event environment (including a LOCA) for as long as the cable remains in service (i.e., to the end of its qualified life).

The conditions for which cable operability can be maintained are a function of many factors. These factors include the design of the cable, its physical installation, the severity of electrical and mechanical loading, the normal and accident application environment, and the critical characteristics (e.g., allowable leakage current) necessary for successful operation of the connected equipment.

Section 3.0

Cable Descriptions and Criteria

Section 3.0
CABLE DESCRIPTIONS AND SELECTION CRITERIA

3.1 CABLE DESCRIPTIONS

Many types of electric cable are used throughout the electric power industry. In nuclear power plants, electric cables are used for the transmission of power, communication, and control signals and data. Cable is generally designed for a specific application. The design process for cables includes the selection of conductor, insulation, shield, jacket, and armor material and the determination of the size of the conductor required for the anticipated service requirements of the cable. Because cables are designed for a particular application, interchanging different types of cables for different applications is normally not permitted. The reader is referred to the bibliography of the EPRI Power Plant Electrical Reference Series, Volume 4, "Wire and Cable" [15] and other references [16-24] for additional coverage of cable design practice.

Conductor Materials

Copper is the most widely used conductor material due to its relatively high electrical and thermal conductivity, good ductility and malleability, reasonable cost, and strength. Annealed copper is the predominant metal used for power, control, and instrumentation cables. A copper conductor is acceptable for use at continuous temperatures up to 300°F. Copper is often coated with tin, tin-lead alloy, pure lead, nickel, or silver at coating thicknesses of 50 micro-inches or less. These coatings minimize copper oxidation, enhance solderability, and may allow operation at higher conductor temperatures. Tinned copper is favored for ease of making connections. Most cable conductors in nuclear power plants are made of copper and most are tinned.

Aluminum is also used as a conductor although its conductivity is only approximately 60 percent of that of copper. Aluminum is usually used for large conductors because its ductility, oxidation, and cold flow characteristics could result in conductor breakage or high contact resistance when used as a small conductor. For medium- and low-voltage power cables, aluminum conductors generally only used for sizes No. 6 AWG and larger.

Aluminum conductors are lighter in weight than copper conductors. For this reason, they compete in price with copper conductors for the same ampacity ratings. However, installation costs may be higher because larger conduit is required. In addition, extra attention to detail at terminations is required to prevent the formation of oxide film, cold flow, and electrolytic corrosion. A high-resistance oxide film forms rapidly on aluminum surfaces exposed to air, requiring a termination compound for its removal and the formation of a low-resistance connection. Aluminum is relatively soft and subject to cold flow. The necessary high contact pressures used in bolted connections may make the material relax, reducing the stability of the termination; therefore, aluminum terminations generally have spring-loaded terminations. Also, the larger coefficient of expansion of aluminum may lead to joint deterioration. When connecting aluminum cables with fittings of dissimilar metals, the fittings require plating with tin, zinc, or silver to avoid of electrolytic corrosion caused by humidity. Aluminum conductors are rarely used in nuclear safety-related cables; if they are, they are not located in areas that are potentially subject to accident environments.

A copper-steel conductor is composed of a steel core and a copper covering welded together by a molten welding process. As a bare conductor, this is often used for plant grounding. Conductivities typically range from 30 to 40 percent of that of copper. An insulated copper-steel cable is occasionally used for small instrument control cabling where strength of the steel core is important for preventing tensile breakage of the conductor.

Various special purpose conductor materials are used in nuclear power plants. Thermocouple extension wire is used to connect a thermocouple to the temperature instrument receiving the thermocouple signal (e.g., a controller, or indicator). The cable is typically a shielded [25], twisted pair; this construction minimizes the interference or noise experienced by thermocouple signal. The conductor materials of thermocouple extension wires conductors may be:

ANSI MC96.1 Type	Positive Wire	Negative Wire
EX	Chromel	Constantan
JX	Iron	Constantan
KX	Chromel	Alumel
TX	Copper	Constantan

Resistance heating conductors are also used in nuclear plants as trace heaters for systems that must remain at elevated temperatures or must have freeze protection. These conductors are intentionally selected because they have a higher resistivity than copper or aluminum. Current passing through these conductors produces a significant power loss resulting in heating of the conductors. For example, the same current passing through a nichrome V conductor (typically 650 ohms/cmil-ft) would produce about 65 times the heat loss as it would through a copper conductor (typically 10.37 ohms/cmil-ft) of the same size. Various conductor materials are used for resistance wire. The common materials are alloys of nickel-chromium (nichrome), nickel-copper, and nickel-iron.

Photo-optic conductors are non-metallic control and instrumentation conductors that use fibers to transmit optical signals rather than electricity. They are used to transmit "information" between two units that may be at very different voltages or have other characteristics that make an electric conducting path undesirable. Installation and operability of photo-optic conductors are outside of the scope of this document.

Insulation

The function of cable insulation is to electrically separate the conductors in a cable from each other and from ground. Insulation used for nuclear safety-related cables is qualified for the application, environments, and service conditions through tests and analyses that simulate and evaluate these conditions. Cable qualification is discussed further in Section 6. Electric cables are insulated according to their intended service voltage. The standard insulation voltage classes for power plant applications are 300 V, 600 V, 1 kV, 5 kV, 8 kV, and 15 kV. As indicated in earlier sections, there are no medium-voltage (5 kV, 8 kV, 15 kV) nuclear safety-related cables in primary containment in nuclear power plants.

Temperature and radiation conditions are predominant factors in choosing the type of cable insulation necessary for use in nuclear power plants. Ambient temperature coupled with temperature rise associated with resistive heating from currents in the cable affects the choice. There are typically three distinct environmental conditions present in a nuclear plant: (1) standard or normal service conditions, (2) high temperature conditions, and (3) high temperature and high radiation conditions. Each condition is described below.

Standard Service Conditions

Integrated Dose (Gamma) Radiation Withstand	2 x 10^8 rads
Insulation/Conductor Max. Temp. Rating	90°C
Normal Ambient Temperature	60°C or less

Accident Environment bounded by IEEE 323-1974 "Appendix A typical" profile

The standard service conditions for specification and design of nuclear cables generally envelop the great majority of plant conditions. Most actual nuclear service conditions are bounded by 35° to 60°C normal ambients and total integrated gamma doses of 2×10^{7} to 1×10^{8} rads.

High Temperature Service Conditions

Integrated Dose (Gamma) Radiation Withstand	2×10^{8} rads
Insulation/Conductor Max. Temp. Rating	125°C, 150°C or >
Normal Ambient Temperature	75°-100°C

Accident Environment bounded by IEEE 323-1974 "Appendix A typical" profile

These elevated thermal conditions exist in the vicinity of pressurizer electric heaters in a pressurized water reactor (PWR) and in certain high elevations in the drywell of a boiling water reactor (BWR). Elevated temperatures may also occur close to such components as continuously energized solenoids, which require lead cables with higher temperature ratings.

High Temperature and High Radiation Service Conditions

Integrated Dose Radiation Withstand	2×10^{11} rads
Insulation/Conductor Max. Temp. Rating	200°C
Normal Ambient Temperature	75-125°C

Accident Environment bounded by IEEE 323-1974 "Appendix A typical" profile

These conditions are generally limited to those immediately adjacent to the reactor vessel (e.g., for neutron detection instrumentation).

The primary insulation materials used in each environment are described below.

- Ethylene-propylene-rubber-based (EPR) and cross-linked polyethylene (XLPE) insulations, complying with IEEE Std 383-1974 and the specific ICEA/AEIC Standards, are used in standard environmental conditions. These insulations are rated for 90°C continuous conductor temperature, 130°C emergency temperature (as defined in ICEA Standards), and 250°C short-circuit maximum conductor temperature (also as defined in ICEA Standards). These insulations are manufactured by mixing or "compounding" the raw polymer with selected chemicals, fillers, plasticizers, accelerators, and vulcanizing agents to enhance their electrical and physical properties. These two materials are thermosetting, i.e., the material will have little tendency to soften if reheated.

- Silicone rubber compounds are the predominant insulators of cables in high ambient temperature environments. Silicone rubber retains good physical and electrical properties at high temperatures; it is rated for continuous operation at a temperature of 125° to 150°C. Although silicone can withstand high ambient temperatures, it has poor tear or low abrasion resistance properties. Therefore, these cables often have an abrasion- and fire- resistant asbestos glass braid or silicone glass braid covering. Asbestos is no longer used as a jacketing material and is found in few new installations. Silicone rubber is substantially more costly than ethylene propylene rubber and cross-linked polyethylene. As a result, it has not found wide acceptance as a substitute for these materials.

Almost all cable runs terminating in "hot" (radiation or thermal) areas are exposed to normal ambient temperature over the majority of the run. Generally, cables with 125° to 150°C rated insulation are installed only in the thermally hot areas. Cables acceptable for the majority of the run are terminated in a terminal or splice box relatively close to the hot device with splices made to the high temperature cables. The high temperature cables then connect to a level switch, pressure switch, heater, or other device in the thermally hot region.

Where both temperature and radiation are high, special cables are used. Typical applications include the cabling for out-of-core neutron detectors and the reactor head cabling of a pressurized water reactor. Inorganic mineral insulation or polyimide film (trade name Kapton) insulation is typically used in these severe environments.

Mineral insulation (MI), having magnesium oxide, aluminum oxide or quartz insulation, requires a metallic watertight sheath since these insulations are hygroscopic and would absorb moisture in humid environments. If unprotected from moisture, the insulation resistance would degrade severely, resulting in cable failure. The use of a metallic sheath for protection (copper-bronze, stainless steel, etc.) results in a rather stiff cable that does not lend itself to installation in a raceway. However, MI cable itself is equivalent to a raceway and does find application in areas where its non-combustible, extremely radiation-resistant and temperature-resistant properties are needed. Similar inorganic MI insulations are used in the cables of temperature and radiation detectors within the reactor vessel itself. Kapton insulation was developed by E. I. du Pont de Nemours and Company, Inc. Although the temperature and radiation withstand capabilities of Kapton may exceed 262°C (504°F) and 10^{13} rads, respectively, it is expensive and not as flexible as EPR or XLPE. In recent years, there has been concern [26, 27] over Kapton's stability in warm moist environments.

Other insulations, which are an outgrowth of the aerospace industry, are used occasionally for hook-up wires. These materials include Halar (by Allied Chemical), Kynar (by Pennwalt), and Tefzel (by du Pont). Another hook-up wire material, PEEK, is used in electrical penetration assemblies in France. In the United States, its use is being reviewed for pigtail use on thermally hot coils.

Shields

Instrumentation and medium-voltage cable are typically shielded. Shielding of instrumentation cables is an effective method of reducing electrostatically induced noise in the instrumentation circuit. Shielding also reduces the crosstalk of information between adjacent circuits [25].

Shielding is provided for cable 5 kV and above to provide a symmetrical radial distribution of voltage stress within the insulation. This type of shielding helps to prevent corona discharge. However, non-shielded power cables may be used up to 8 kV under the following conditions:

- The insulation material is resistant to ozone, electric discharge, and surface tracking.

- There is an overall non-metallic jacket or a continuous metallic sheath that is impervious to moisture when used in wet locations.

- When used at 5000 to 8000 volts, there is a metallic jacket over the insulation.

For medium-voltage cables, shields are usually made of thin copper tape. This tape is spirally wound around the insulation. The shields must be kept at ground potential by connection at a splice or termination. In some applications, a semi-conducting tape is applied between the shield and the insulation, and the conductor and the insulation. The presence of semi-conducting tape in these areas reduces the possibility of air ionization in any remaining air spaces by draining surfaces charges from the insulation surface. Ionization of the air could lead to insulation damage due to corona discharge.

Instrument cables use various types of shields, including braided copper wire and aluminized mylar with a drain wire. The criticality of the shield to the application will determine the type of shield used.

Jackets

Cable jackets are primarily designed to protect the cable from mechanical damage during installation. The jacket can also provide chemical and fire protection to the cable insulation. Certain jacket materials can be color coded for identification.

The jacket materials predominantly used for standard or normal conditions are Neoprene (polychloroprene), Hypalon (chlorosulfonated polyethylene), and PVC (polyvinyl chloride). PVC jackets are not currently used in the design of nuclear safety-related areas per the U.S. NRC Regulatory Guide 1.120 [28] requirement to minimize release of halogens (chlorine in this case) in the event of a fire.

Hypalon has slightly better overall characteristics than Neoprene and shows good stability and excellent moisture resistance. Hypalon is also better for color coding than Neoprene; therefore, safety-related circuits that require cable color coding for identification purposes, as stipulated by Regulatory Guide 1.75 [29], often have Hypalon jackets. Consequently, in recent years, Hypalon has been replacing Neoprene as the standard cable jacket.

Special braids or compositions of asbestos, glass, or cross-linked polyolefins are used as coverings for high temperature or high radiation conditions.

Jackets of Hypalon, Neoprene, and PVC are extruded over the cable core. When the cable core consists of twisted conductors, the jacket permits relative motion between the conductors inside. Cables with extruded jackets may have a non-round appearance. Cables often have separators, fillers, and other construction features that keep the cable shields from cutting into the jacket or cable insulation. Fillers are used to fill the gaps in extruded jackets to round out the construction.

Armor/Sheaths

For certain applications, metallic sheaths/armor (jackets) are used. The insulated conductors are enclosed in a metallic covering of lead or aluminum, plain or galvanized steel tape, interlocked steel tape, or galvanized steel wire armor. Armored cable can resist moderate blows or abrasions. Additional mechanical protection, however, may be necessary when cables are installed in places where physical damage is expected to be a possibility. Armored cable also offers positive physical separation. During a short circuit, armored cable will keep the damage internal to the cable such that it will not affect the adjacent circuits. Jackets are often installed over the metallic sheath to protect the metal from corrosive environments, especially when directly buried in the earth. The U.S. NRC staff position in Regulatory Guide 1.75 [29], position C.2, is that interlocked armor enclosed cable should not be construed as a raceway and therefore is not acceptable as a physical barrier for independence. A utility may be required to demonstrate the suitability of armored cable as a separation barrier.

CABLE SELECTION CRITERIA

Applications and Cable Design

There are four major electric cable service applications: power, control, instrumentation, and grounding. These applications are discussed in the following subsections.

Power Cable

Typical power cables are shown in Figures 3-1 and 3-2. These cables are used to transmit power from the distribution equipment to the electrical loads. They also interconnect large power supplies or switchgear to smaller distribution equipment such as motor control centers and distribution panels. Power cables in nuclear power plants are typically grouped by voltage or service rating.

Medium-voltage power cables interconnect medium-voltage switchgear to motors, transformers, and other equipment. They also connect the on-site, standby nuclear safety-related power system (generally diesel generator units) to the nuclear safety-related medium-voltage system. The nominal system voltages are typically 4.16 kV, 6.9 kV, and 13.8 kV and use cables rated 5 kV, 8 kV, and 15 kV, respectively. The nuclear safety-related medium-voltage systems in the newer nuclear power plants are a nominal 4.16 kV or 6.9 kV, 3-phase, 3-wire, 60-Hertz systems. Typical loads for these cables include motors above 250 horsepower and feeds to transformers for low-voltage switchgear (e.g., power centers or load centers). Nuclear safety-related medium-voltage power cables do not exist in primary containment of any nuclear power plant in the United States. (Note: Medium-voltage cables do penetrate containment and are used

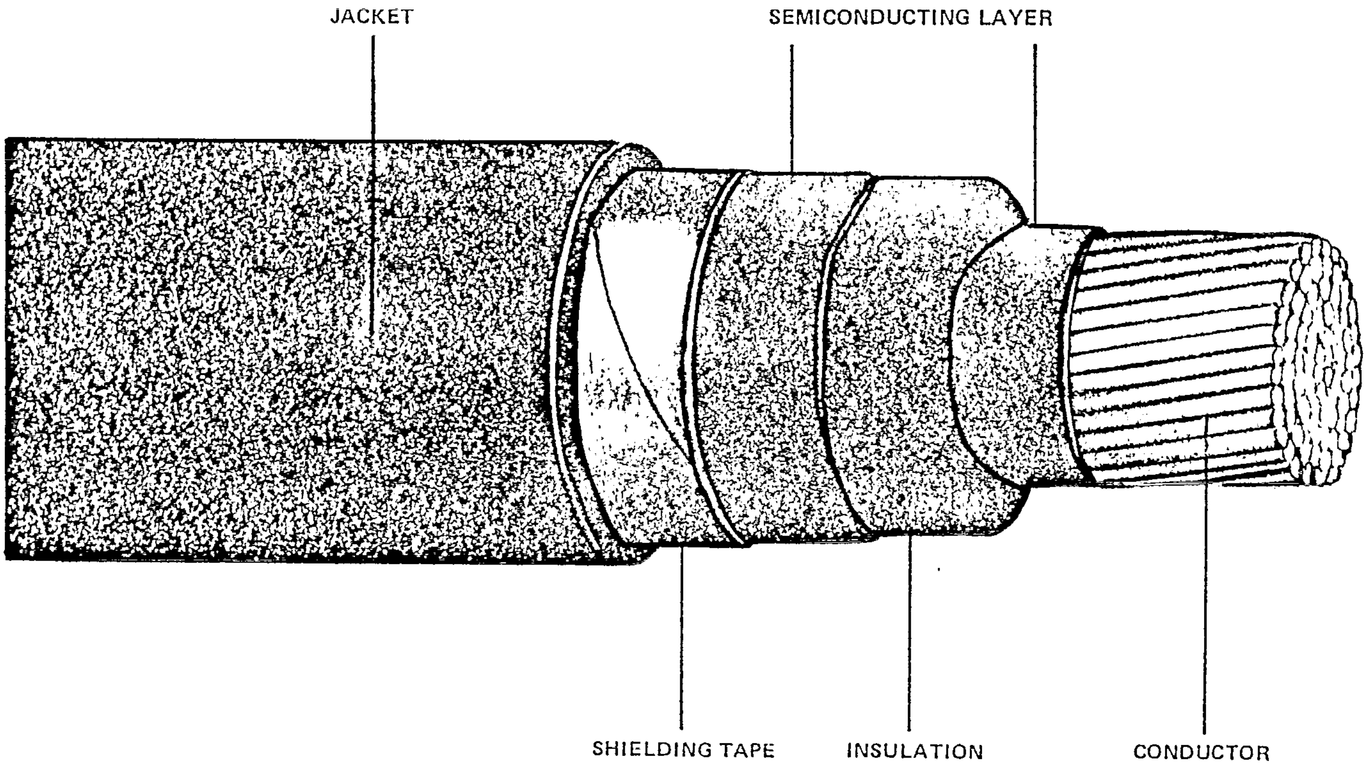


Figure 3-1
Medium-Voltage (MV) Power Cable

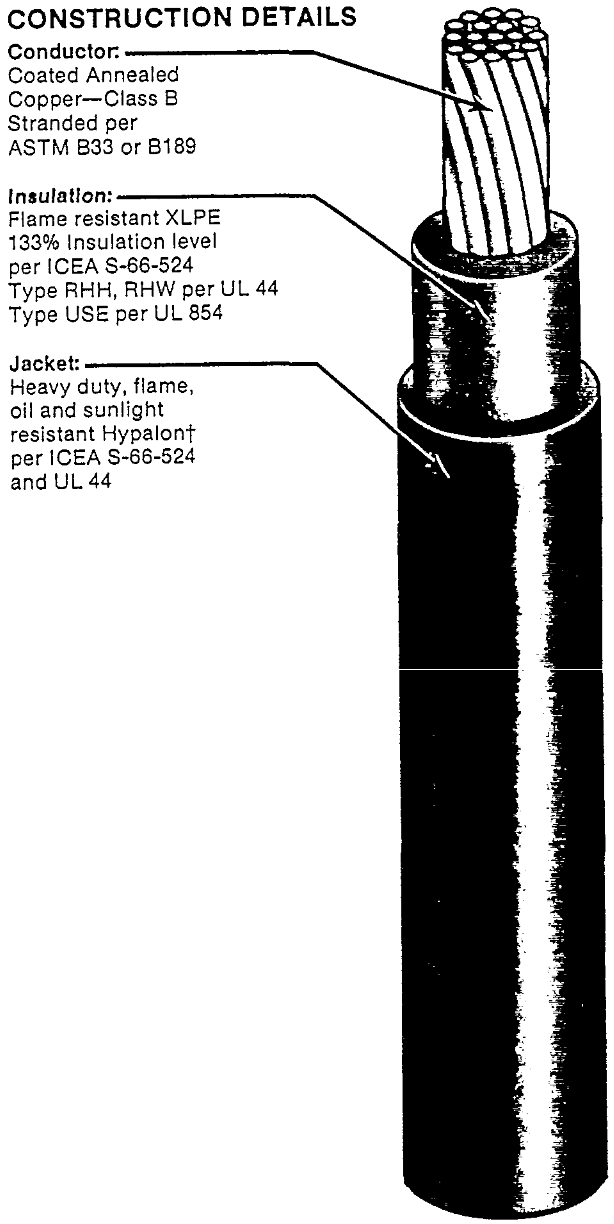


Figure 3-2

Low-Voltage (LV) Power Cable

to power reactor circulating water pumps. However, these pumps are not required during an accident. Therefore, these cables are not safety-related.)

The older, smaller nuclear plants operating since the 1960s (e.g., Yankee Rowe, Indian Point 2, Surry) did not use nuclear safety-related medium-voltage power systems to support safety functions as larger and newer plants do. Consequently, there are no nuclear safety-related medium-voltage cables in the older, smaller nuclear power plants.

Low-voltage power cable interconnects low-voltage electrical equipment such as switchgear, motors, motor control centers, and batteries. The low-voltage power systems operate at nominal voltages of 600 V, 480 V, and 208 V, 3 phase; 277 V,240 V, and 120 V single phase; and 250 V and 125 Vdc. Power cable rated 600 V is typically used for these applications, although some utilities have used cables rated at 1000 V or greater. Only special nuclear safety-related applications, such as monitoring systems using radiation resistant coaxial and triaxial cables, operate at high voltages. The highest nominal system voltage for nuclear safety-related cable in primary containment is 600 V or less.

For three-phase power circuits, a three-conductor cable is required. 3/C cables or 1/C cables that have been "triplexed or "paralleled can be used. In triplex construction, three equal lengths of 1/C cables are twisted (cabled) together and then wound on a cable reel by the manufacturer. In parallel construction, the cables are not twisted; three equal lengths of conductor are wound at the factory side by side on a cable reel. Both constructions permit three conductors to be pulled off the reel simultaneously and installed in much the same way as three-conductor cable.

Triplex construction has several advantages over parallel construction. Lower pulling tension is required to pull triplexed cables into conduits or ducts. This is a result of the uniform triangular configuration of the three conductors instead of the "cradled" spacing inherent in paralleled conductors. For certain applications, the reduced impedance of triplexed cables becomes important. When heavy short circuits flow, triplex construction minimizes the movement of the 1/C cables in the tray.

Conductor size limits the practicality of triplexing and paralleling. When the conductor size reaches 350 to 500 kcmil, the weight of the cable makes it difficult to handle efficiently and the reel needed is very large. When long cable runs are required in conduits or ducts, the normal practice of avoiding splices whenever possible would again require excessively large reels of cable for the entire length of the run if triplexed or paralleled cable were used. For such long runs, 1/C cable can be used with three separate reels, each containing the length of 1/C cable required.

Control Cable

Typical control cable, shown in Figure 3-3, is used to interconnect control components of a system. Control cables transmit signals between control devices such as solenoid operated valves, relays, limit switches, and control switches. For example, a control cable would be used to connect a control room switch to a motor starter located in a remote motor center; this would enable the operator to control the motor from a completely separate location. These cables typically provide the feedback signal path for status indication, i.e., motor running, valve closed, and plant annunciation.

Typical control cables have stranded copper conductors and thermosetting insulations and jackets. They are suitable for operation at a conductor temperature not to exceed 90°C in wet or dry service conditions. Flame resistant ethylene-propylene-rubber (EPR) or cross-linked polyethylene (XLPE) insulation and Neoprene or chlorosulfonated polyethylene (Hypalon) jacket material is generally used. These cables do not carry large currents; the conductors are usually smaller in size than power cables with typical sizes of No. 16 to 12 AWG. The conductors are generally larger than necessary for carrying the typical low currents of 1 amp or less to prevent excessive voltage drops over the length of the circuit. The service voltage of control circuits and associated cables is generally 120 Vac, 125/250 Vdc, or occasionally 24148 Vdc. While control circuits operate at 120 Vac or 125 Vdc, the control cable is rated either 300 or 600 Vac. The 600-V rated control cable is most common as it permits routing 600-V rated control and 600-V rated power cables for the same system to be placed in the same raceway. This eliminates the need to separate cables with different voltage ratings, as is common practice for control of low-voltage switchgear and motor control centers.

Some special applications may require 1000-volt shielded control cables. A control cable run from a high voltage switchyard area to a main plant area where a fault may produce a relatively high voltage gradient over the cable run is such a high voltage application.

Shielded control cables may be used where protection against electrostatic fields is required, as in extra-high voltage switchyards, and where mechanical protection against termites, gophers, borers, etc., is required due to direct burial installation. In this case, a 10-mil bronze tape or other similar "barrier" is used in place of copper tape.

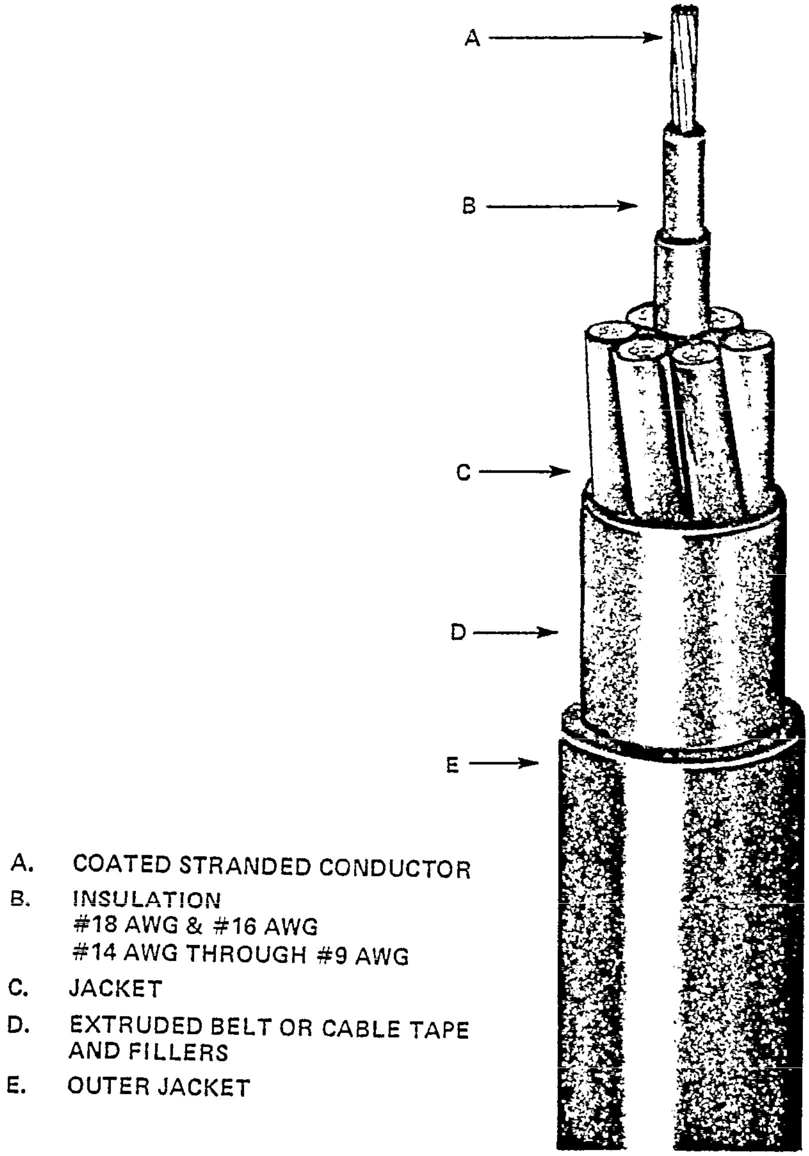


Figure 3-3

Control Cable

Special Control Board Instrumentation Cables

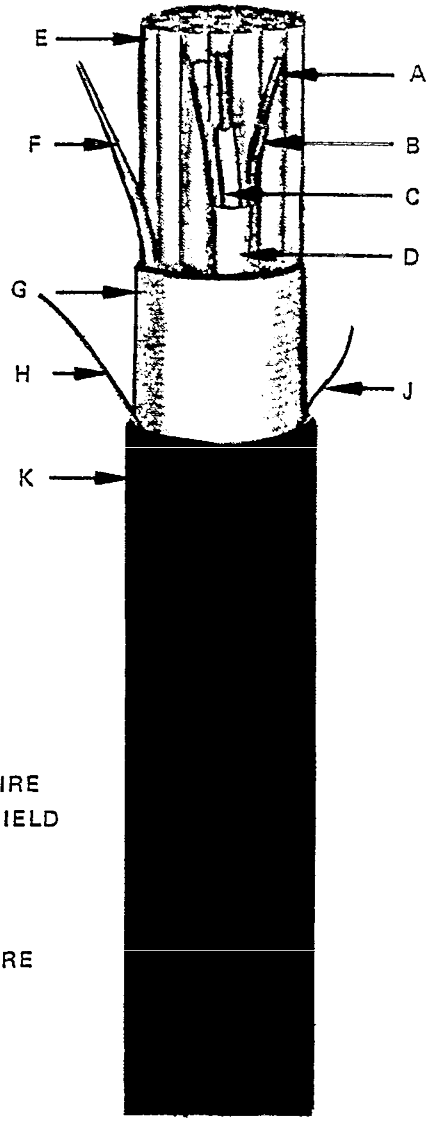
Miniature control boards, such as those used in reactor turbine generator boards, require very flexible and small diameter cables due to the limited amount of space and high wiring density. Conventional wiring and screw type terminations are also impractical. Therefore, these applications have plug-in type wiring receptacles for the external cables.

Cable construction for these control board applications is usually limited to five, seven, or ten conductor cable to maintain flexibility. These cables are typically rated 600 volts and are suitable for 120 volts ac and 125 and 250 volts do applications. The insulation is often heat and moisture resistant. Typically, these cables would operate at ambient temperatures not exceeding 50°C during normal operating conditions. An insulation rated for continuous operation at a conductor temperature of 200°C is often chosen because the cables may be subjected to short circuit currents which are so low that overcurrent devices do not respond rapidly, but are high enough to cause severe heating in the small conductors used.

When choosing cable for this application, minimizing the voltage drop is usually a main concern. The ampacity of these cables is not usually a concern since the continuous current requirement is typically 4 to 50 milliamperes, or a maximum of 10 amperes momentarily for the control room instrumentation. A No. 16 AWG wire can carry a maximum short circuit current of about 1800 amps for 0.0167 seconds without exceeding a maximum final conductor temperature of 300°C (assuming Teflon, Tefzel, or other high temperature insulation system is used) with an initial conductor temperature of 50°C. The wire size is typically No. 16 AWG.

Instrumentation Cable

A typical instrumentation cable is shown in Figure 3-4. The function of instrumentation cable is to transmit low-level (milliampere or microampere) low-voltage (50 volts or less) analog or digital signals that are generated by sensors such as temperature detectors, pressure transmitters, vibration detectors, and fluid analyzers. The analog signals, which represent a particular physical condition, are susceptible to error caused by spurious signals induced into the conductor, leakage current through the insulation, or random noise. In general, these cables are shielded to eliminate induced "noise" or spurious signals and to minimize radio frequency or electromagnetic interference.



A. BARE STRANDED COPPER CONDUCTOR
B. INSULATION
C. TINNED STRANDED COPPER GROUP DRAIN WIRE
D. ALUMINUM-POLYESTER ISOLATED GROUP SHIELD
E. TWISTED, SHIELDED PAIRS/TRIADS
F. COMMUNICATION WIRE
G. ALUMINUM-POLYESTER CABLE SHIELD
H. TINNED STRANDED COPPER CABLE DRAIN WIRE
J. RIP CORD
K. JACKET

Figure 3-4

Instrumentation Cable

This cable grouping includes single- and multi-pair cables, usually having copper conductors and 300-volt rated insulation (some designers use 600-volt rated cables). The cables are used for instrumentation, communication and computer input cables, and single or multiple pair thermocouple extension wire. Pairs of each type are generally twisted and shielded to reduce magnetically induced and electrostatically produced noise. The shorter the lay of twist, the larger the reduction in magnetically induced voltages. The typically found minimum lay of twist is 2 inches, because the small gain in noise reduction for smaller lays does not generally justify the higher cable cost.

The cable shield is generally grounded at one point, with only shield isolation and continuity maintained at all other points. The ground point is generally located as close as practicable to associated circuit ground (there usually is only one), especially for grounded thermocouples. Normal variations in ground potential with multiple shield grounds produce shield circulating current "noise." With a single shield ground remote from associated circuit ground, the voltage variations produce "charging" currents from the cable conductors to the shield. With different conductor resistances, as for thermocouple extension cable, these charging currents may produce different voltage drops in the two cable conductors, resulting in "noise." If the instrumentation circuit has no ground, the cable shield ground is often near the transducer or thermocouple. It is more likely that in operation a ground will develop there than at the other end of the circuit. However, for ungrounded instrumentation circuits connected to digital computers, the manufacturer may require the shield ground at the computer.

Hook-up Wire

Hook-up wire is generally 600-volt, single, concentric-lay-stranded copper conductor, nonshielded or shielded with a 90°C or 150°C insulation rating. The range of conductor sizes is from No. 16 through 10 AWG.

The wire is generally used for short runs between terminals in switchgear, panels, cabinets, limit switches, and boxes where single-conductor wire would be more adaptable and suitable for making connections than would multiconductor cable. The wire is typically suitable for applications for indoors and outdoors, above ground in wet or dry locations, and in short lengths of conduits. The wire also typically has passed the vertical tray flame tests in accordance with UL-44 [30], Section 85, VW-1 (Vertical-Wire) Flame Test and is tested to ASTM D3032.

The 90°C rated hook-up wire would be used m areas where 90°C rated cables are used (i.e., the "standard or normal" service conditions). The 150°C rated hook-up wire would be used in high "temperature service condition" areas. For such applications, the hook-up wire runs should extend beyond the hot areas into the normal ambient areas where the connection to the 90°C rated wire would be made.

Ground Cable

Typical ground cable is shown in Figure 3-5. Ground cable is unique among the four functional categories of cables and, in some instances, may not be considered part of the cable system since it is usually bare and does not normally convey power or electrical signals. Ground cable is specifically designed to provide electrical continuity between metallic structures, which could become energized by an electrical fault, and the under ground conducting grid system surrounding the plant. These cables safeguard plant personnel from shock hazard, reduce radio frequency interference and electromagnetic interference to help reduce electrical noise in instrumentation equipment, and dissipate lightning strikes. Ground cable usually is uninsulated although in certain situations the design requires insulation to protect the ground cable, its connections, or other metallic structures from corrosion. The ground conductor may be No. 16 AWG or as large as any power cable conductor found in the plant (e.g., 1000 kcmil). Ordinarily ground cables do not carry current except during an electrical fault (short circuit to plant ground) or some other abnormal condition.

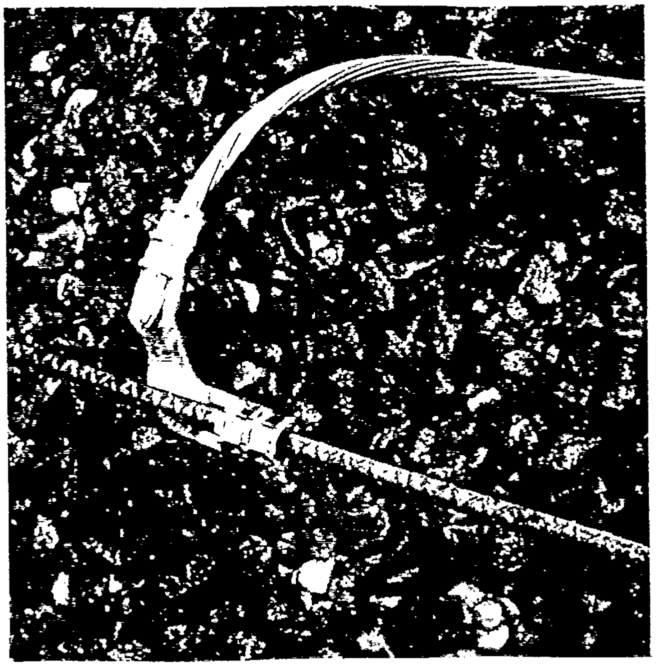


Figure 3-5
Ground Cable

Conductor Sizes

Conductor sizes are typically given in American Wire Gage (AWG). This wire gage (others exist but are generally not used in the US) is retrogressive: large numbers denote small conductors. There are 40 sizes starting from the smallest, No. 36 AWG (0.0050 inch diameter). For practical purposes, the minimum cable size actually used in power plants is No. 22 AWG, which is used in large communications cables that contain large numbers of paired conductors.

Cables larger than No. 4/0 AWG are usually expressed in "thousands of circular mile" (kcmil). A mil is a unit dimension being 0.001 inch and the circular unit being equal to the diameter squared. Thus, 1000 units (1000 kcmil) is 4/π square inches.

Originally, large conductor sizes were stated in MCM sizes (e.g., 500 MCM). MCM is a commercial term to represent 1000 circular mils. However, in the term MCM, in accordance with engineering terminology, the first "M" would represent "Mega," which would be incorrect. Therefore, "kcmil" has been used more recently. Both terms continue to be used currently in the cable industry. (For further clarification of the correct usage for unit symbols, refer to IEEE Standard 260 [31].)

Conductor Sizing Criteria

There are three general criteria on which to base cable conductor minimum size: ampacity, fault current capability, and voltage drop. These criteria must be considered when sizing a cable for the applications discussed above.

Cable ampacity is important when sizing cables for power and, to a lesser extent, for control applications. Ampacity refers to the amount of current a cable can carry while remaining within its specified temperature rating. Resistance to current flow during normal operation causes cable heating. If the cable ampacity is exceeded, overheating of the insulation may occur. Therefore, cable ampacities are determined such that the conductor operating temperature does not exceed the rated insulation temperature under continuous, 100 percent loading for the application when the postulated maximum ambient temperature is considered. The practice of certain designers is to limit conductor continuous temperature to less than rated temperature to provide design margin. Ampacities used for power design are given in the latest editions of ICEA publications [32, 33]. Several recommendations for ampacity determination are discussed below.

Ambient air temperature is conservatively assumed to be the "worst case." Particular attention must be given to continuously loaded cables that may operate during the long-term post-LOCA environment, because the thermal aging of these cables will be the most severe. Excessive thermal aging could reduce LOCA withstand capability.

The ampacities of cables installed in underground ducts and in isolated conduits in earth, and of direct buried cables are based on an earth temperature appropriate to the area and a typical earth thermal resistivity (RHO) of 90 (suggested value of RHO per ICEA P-46-426 [32]). This value of thermal resistivity is also used for conduits embedded in walls and floors along with the ambient temperature of the building area to determine cable ampacity. Ampacity ratings for groups of conduits in air, where the spacing between conduit surfaces is not greater than the conduit diameter or less than 1/4 of the conduit diameters, are typically reduced in accordance with the requirements of ICEA P-46-426 [32].

Motor feeders typically have an ampacity not less than 115 to 125 percent of the motor full load current rating. The full load current for feeder cables to power transformers is typically determined from the rating corresponding to the highest allowable continuous temperature rise and cooling mode of the transformers.

Ampacity is also affected by the cable tray fill. For an open ladder type tray, the actual cable fill depth limit is determined using the ICEA P-54-440 [33] ampacity methods. The depth, and not the percentage fill, is the basis for ampacity per ICEA P-54-440 [33].

Fault (short circuit) current withstand capability is another design criterion that must be met. Power and control cable must be able to withstand fault current per IEEE Std 690-1984 [17]. This standard, which was issued after the licensing basis for all nuclear plants within the United States was established, requires sizing to withstand short circuit current for all Class BE (i.e., nuclear safety-related) circuits. All medium-voltage cable is required to withstand a fault on interconnected equipment to avoid the cost of replacement of a damaged medium-voltage cable. Many utilities also size low-voltage power cable to withstand faults. The main concern for short-circuit conditions is prevention of overheating the insulation.

Under short-circuit conditions, the ultimate conductor temperature depends on the magnitude of fault current, its duration, the cross-sectional area of the conductor, and the conductor temperature prior to the short circuit. Since the period of fault current flow is very short, short circuit temperature rise calculations assume that all the energy produced during the fault current flow is fully effective in raising the conductor temperature. No credit is taken for heat transfer through the insulation. To preserve the insulation, the allowable conductor temperature for the insulation should not be exceeded.

For cables with EPR and XLPE insulation, the fault current capability of a given conductor size and for a specific fault duration is defined as the short circuit current that will raise the conductor temperature from 90°C to a final value of 250°C. Curves of fault current versus fault duration for these insulations and for the normal range of sizes of copper are shown in various references [15, 19, 20, 34, 35]. This data is essentially a reproduction of ICEA P-32-382, "Short

Circuit Characteristics of Insulated Cable" [36]. Calculation of the fault current rms value for a given interval is available in various references [37].

The short circuit current for a specific conductor size is the fault current rms value for a given interval. For example, a No. 8 AWG copper cable may be suitable for 10,000 amperes of current when the fault is cleared by a current limiting fuse opening the circuit in 1/2 cycle; the same current requires a No. 4 AWG cable for a low-voltage power circuit breaker that clears the fault in 2 to 3 cycles. Should the fault remain for 10 seconds, the minimum required cable size would be 500 kcmil.

The determination of fault current capability in this manner typically results in substantial oversizing of medium-voltage cables feeding motor loads. Use of such higher ampacity cables reduces normal operating temperatures for the insulation. This contributes substantially to enhanced cable life.

For power and control cables, cable voltage drop,should also be considered during design since the auxiliary power system must deliver acceptable voltage to the connected loads. Control cable size is typically selected to deliver voltage at the controlled device within its specified operating range. Typical low- and medium-voltage switchgear [38, 39] must have a tripping coil voltage of 70 to 140 Vdc with the dc batteries at their lowest voltage (typically 1.75 volt per cell [40] or 105 volts for a 60-cell battery).

The voltage drop for ac motor loads under running or starting conditions is typically limited to a value such that the voltage at the motor terminals will not be less than 90 percent of its rating when the voltage at the bus is at the lowest calculated steady state value. The 90 percent value is consistent with industry motor standards [41].

Medium-Voltage Cable Insulation Levels

ICEA standards for cables rated 600 to 15,000 volts recognize the influence of different types of system grounding and ground fault clearing times on the transient overvoltages produced during fault conditions. These standards, which are typically used, establish three insulation levels for a given cable voltage rating:

- 100 percent level for rapid clearing of ground faults, i.e., within one minute (formerly designated as the "grounded neutral level")

- 133 percent level for clearing or de-energizing a ground fault within one hour (formerly designed as the "ungrounded neutral level")

- <u>173 percent level</u> for conditions where time for clearing or de-energizing a ground fault is indefinite (appropriate to high impedance grounding)

<u>Conductor Stranding</u>

The requirements for stranding relate to the requirements for flexibility or "limpness." Flexibility is needed to allow cables to be pulled around bends in conduits and to be arranged in trays and junction boxes. Stranded conductors are typically used for all power, control, and instrumentation service, except for small gauge conductors (No. 10 AWG and smaller) that terminate using an "eye or a solder type connector. The eye termination is often used for thermocouple extension wire. Thermocouple extension wire is generally 20 AWG to 16 AWG, whereas lighting wire is typically 12 AWG.

Most stranding is to ICEA Class B concentric stranding requirements. This stranding has been called "standard strand." For cables in general, practical experience has indicated that this degree of stranding is adequate. Other strand classes such as C (semiflexible), D (flexible), G (extra flexible), and H (very flexible) exist but are less frequently used for general use cable construction in nuclear power plants. The flexibility of the cable is generally a function of the conductor stranding (i.e. the finer the stranding, the more flexible the cable) as well as of the insulation material and thickness.

Special purpose cables (e.g., trolley festooned cables that serve movable devices, motor leads, portable cables, and cables that cross panel doors inside cabinets) often use stranding that is finer than Class B. commensurate with the requirement for flexibility. The ICEA standards [42-45] as well as various handbooks [15, 46] provide additional coverage of stranding practice.

Section 4.0

Raceways and Terminations

Section 4.0

RACEWAYS AND TERMINATIONS

This section describes the raceways and terminations for cables used in power plants.

RACEWAYS

Raceways provide a pathway, support, and protection for a cable between its termination points. For convenience, this report includes conduits, ducts, and trays within the definition of raceways (Note: The National Electric Code excludes trays from the definition of raceways). Requirements for physical protection of the cables, the economics of installation, and interference with normal plant operation are considered when selecting a raceway system. The ability of the raceway to withstand standard seismic events and to meet independence requirements of redundant systems, pursuant to IEEE Std 384 [47] and IEEE Std 690 [17], must also be considered in the design of raceway systems.

The main considerations in the selection of raceway material are combustibility and generation of combustible gases. These considerations suggest that metallic raceways should be preferred. Steel and aluminum can be used for raceway materials. However, aluminum raceways are not generally used, especially inside the containment building. This leaves plated steel as the predominant raceway material.

Non-metallic materials (conduits) are best suited for underground installations as they are less costly to install.

The degree of seismic activity in a given area is the overriding design criterion for development of supports for safety-related raceway in nuclear plants. Raceway supports use either rigid or flexible design. The rigid design does not permit relative movement between the raceway and the structure, whereas a flexible design permits some freedom of movement.

IEEE has recently issued a new and rather comprehensive standard, IEEE Std 628 [48], which "sets forth the minimum requirements and guidelines in the design and installation of raceway systems for Class 1E Circuits..." It further describes the means used to demonstrate that raceway systems are adequate for a particular application.

Cable Trays

A cable tray is generally used when routing a group of cables from one point to another. It is available in widths that range from 6 inches to 36 inches. There are several types of trays: ladder, trough, solid bottom, and channel. Each has specific features that suit typical applications.

A ladder-type cable tray is a prefabricated metal structure consisting of two longitudinal side rails connected by individual transverse members. Ladder trays differ from all other trays because they facilitate ventilation. Rung spacing is available at 6, 9, 12, or 18 inches on center. The rung spacing required is determined by cable stiffness. A tray with rungs 18 inches apart is the most economical, but many cables would sag between the rungs in such a tray. The more flexible the cable, the closer the rung spacing must be to eliminate sagging. When rungs are only 6 inches apart, even extremely flexible cables may be supported without cable sagging.

A trough-type cable tray is a prefabricated metal structure that is at least 4 inches wide and consists of a ventilated bottom within integral or separate longitudinal side rails. Rung spacing is 4 inches or less. Trough-type trays permit less ventilation than ladder-type trays. Trough trays provide good protection from physical damage.

A solid-bottom type cable tray is a prefabricated metal structure consisting of a solid bottom (no openings) within integral or separate longitudinal rails. This type of tray is used for low-level signal cables. When installed with a solid metal plate cover, this type of tray acts as an additional shield, above that provided by any shields contained in the cable itself, from possible signal interference caused by electrical noise sources external to the cable.

The primary application of a solid-bottom tray is for instrumentation (low-level signal) or communication cables. This raceway can also be used when complete cable enclosure is desired. With a solid cover in place, it qualifies as a fire barrier capable of containing fire internally without affecting other circuits in adjacent raceways. Note, however, that it may not be an effective barrier against external fire, which could heat the enclosure and cause damage to the enclosed cables.

A channel-type cable tray is a prefabricated metal structure with a one-piece ventilated bottom and/or solid-bottom channel section not exceeding 4 inches in width. These channels are generally used to carry one to three cables from the main cable tray system to the vicinity of the cable termination. They are used in this manner when it is not economical to use a larger tray and when it is not desirable to use conduit.

Conduits and Duct Banks

Conduits are defined as a round raceways. They are used to route branch circuits such as those from distribution panels to individual loads. They are either metallic or non-metallic and may be flexible or non-flexible. In the United States, they are available in 1/2, 3/4, 1, 1-1/2, 2-1/2, 3, 3-1/2, 4, 5, and 6 inch diameters. 90° and 45° conduit sections with sweeping bends are generally available for standard diameter conduit.

Ducts are conduits that are installed underground or are imbedded in the plant's concrete structure. Frequently, ducts are installed in parallel groups called banks. Duct banks are often used when large numbers of cables must be connected between separate buildings.

Components of a conduit system include fittings, conduit bodies, and junction boxes. Fittings allow interconnection of the individual sections of conduit. In metallic conduit systems, they also provide electrical continuity of the system. A conduit body is a separate portion of a conduit system. It provides access to the interior of the system through a removable cover at a junction of two or more sections of the system or at a terminal point of the system. Conduit bodies are generally cast metal fittings and provide limited space for access to the cables. A junction box is a box with a cover. It joins different runs of raceways and/or cables and provides space for the connection and branching of the enclosed conductors. Junction boxes may be custom fabricated to provide the necessary room for cable pulling activities and splicing.

Conduits are usually used in place of a channel-type tray when routing one to three cables from a main cable tray system. Other applications include those that require enclosed raceways for mechanical or environmental protection, and those that facilitate replacement of the cables (i.e., cables are often easier to remove from conduits than they are from densely filled cable trays).

Rigid steel conduit has the heaviest wall. Intermediate steel metallic conduit has thinner walls than rigid conduit, but is less expensive than rigid metal conduit. It is an economical option where its use is warranted. Thinwall electric steel metallic tubing provides the least mechanical strength.

Non-metallic rigid conduits are constructed from such materials as PVC and materials filled with asbestos or other fibers. Non-metallic conduit is used in place of metallic conduit when corrosion is a consideration or when the metallic type is too expensive to install. Conduits to be embedded in a duct bank and buried underground are typically non-metallic rigid conduits. Exposed non-metallic conduits are not known to be used for nuclear safety-related circuits designed for seismic conditions.

Flexible conduits are a special type of conduit. They are used where the conduit system and connecting junction box or piece of equipment must be free to move with respect to one another. The use of an interconnecting flexible conduit allows isolation of vibration from equipment operation or seismic disturbances. Flexible conduits are generally used at motor terminals and dry-type transformer connections to prevent transmission of vibration, transformer hum, and motor noise.

A pull box is a box with a cover that is installed between one or more sections of a conduit run to facilitate pulling the cables through the conduit. Cables are not usually spliced in this type of box unless it has the required space and features necessary to qualify as a splice box.

A manhole is a portion of a duct bank system that has removable cover and has sufficient space and access for men and equipment to allow cable pulling and splicing.

A handhole is that portion of a duct bank system that has a removable cover and has sufficient space and access to permit training (i.e., placing cables in the permanently installed positions) of cables from the outside. It is similar to a pull box in function.

CABLE TERMINATIONS

A termination is the electrical and physical connection of a cable end to a piece of equipment or another cable. A splice is the electrical connection of a cable end to another cable with the same cable number. Cable terminations (splices) are designed and installed to interconnect two cable ends both electrically and physically. The physical requirements relate to mechanical security and environmental protection of the connection; the electrical requirements relate to current carrying capacity, connection voltage drop and compatibility of materials (e.g., thermocouple extension wire connections must join like conductor materials). Soldered connections, wire-wrapping connections, crimp connections, compression terminations, and loop or "eye" connections are the most common types of terminations used.

In a soldered connection, the like conductors of the cables are soldered together or into connectors to form a physically secure, low-resistance termination. Various solder lugs are available, ranging from a post with a round hole through which wire is passed to a"cupped" solder terminal. Solder terminations are infrequently used except when circular "military type" connectors are used.

Wire-wrapping connections are connections in which the uninsulated solid conductor is wrapped with significant force about a rectangular metal post for several turns. The wrap is sufficiently tight to deform the post to result in a physically and electrically secure connection. This termination is seldom found for general application, but is often found internal to instrumentation and control equipment such as computers and multiplex panels. This termination method is also popular for telephone circuit distribution boxes in which many small conductor (typically to 19 AWG or smaller) wires are terminated.

Crimp connections are connections using terminals having tubular openings into which the cable conductors are placed. The tube is then mechanically pressed or deformed to tighten it onto the conductor and form a connection. The crimping is performed typically by a crimping tool specially designed for the termination. For nuclear safety-related circuits, the crimping tools are calibrated and are generally used under quality control supervision to ensure proper connections. Crimp connections are commonly available in butt splice, ring lug, and spade lug formats. Crimp connections are available in a wide variety of sizes and may be found in instrument, control, and power circuits.

Compression terminations are terminations in which the uninsulated conductor is inserted into a "box" and the connection is then made with a screw, a flat strap, or other such mechanism that compresses the conductor and forms the connection. Low-voltage circuit breakers use this type of connection.

Loop or "eye" connection at screw terminals is the wrapping of an uninsulated conductor under the head of a screw and around its shank. This connection is inexpensive and is used where the connection would be infrequently disconnected. The conductor loop is made in the direction of screw tightening.

Section 5.0

Cable Installation

Section 5.0

CABLE INSTALLATION

When cable is properly installed, cable installation will not adversely affect cable operability. However, poor installation practices can cause cable damage or conditions that would lead to early degradation of the cable. This section provides an overview of the recommendations for cable installation. The information supplements the EPRI Electrical Reference Series for Wire and Cable [15], IEEE Std 690 [17], IEEE Std 422 [16], IEEE Std 525 [18], ANSI/IEEE 336 [49], and IEEE Std 628 [48]. Much of the information in this section is derived from an Electrical Safety System Training Program [50]. The information contained herein does not constitute a standard nor does it have any national consensus agreement.

This section may repeat some information from the few industry standards dealing with cable installations [16, 17]. It is presented to ensure complete coverage. Currently, industry standards indicate that installation practices should follow manufacturer's recommendations. IEEE Standards [17] state that "pulling instructions for all cables shall follow the cable manufacturer's recommendations." Consequently, the adequacy of an installation is dependent on the adequacy and availability of manufacturer recommendations. The lack of consensus guidance for installation can result in conflicting installation requirements between manufacturers of similar cables or in overly restrictive practices mandated to protect the manufacturers.

The following discussion of cable installation practice is often used for installing ethylene propylene or cross-linked polyethylene insulated, Neoprene or chlorosulfonated (Hypalon) jacketed cables. Other cable types may require different consideration.

DESIGN AND CONSTRUCTION OF A CABLE RUN

Conduit and Tray Routing

The purpose of the cable run is to provide a pathway for the cable between connection points. When designing a routing system, the configuration of the conduits and trays should be kept as simple as possible. Bends should be kept to a minimum. The run should avoid harsh environments where practicable. Wherever possible, the natural force of gravity should be used to aid cable installation (i.e., uphill pulls should be avoided). In areas subject to debris collection or overhead construction, temporary or permanent covers should be used to protect the cables. Entrance holes for cable should have approved sealing bushings, or conduit bushings where sealing is not necessary and bushings alone are permissible. Such bushings will prevent cable jackets and insulation from being cut by metal edges of conduits and boxes. Where conduits do not drain or at points of likely entrance of water into conduit, packing or sealing at conduit bushings should be applied after cable installation. The inside surfaces of cable tray systems should be flat and free of projections, sharp edges, and burrs that can cause damage to the cable insulations. The raceway installation should be complete before cable pulling commences so that no further mechanical work to the support structures is necessary after the cables are in place. Conduit routings should be designed rather than field run whenever possible.

Limitations

During design of the raceway system, vertical runs, bends, separation criteria, and the need for fire lagging should be considered since they affect the design of the run.

Vertical runs should be designed such that the cables are properly supported and excessive sidewall bearing pressure does not occur at the upper support point. At the transition point, the supporting raceway should provide a smooth bend to protect the cable insulation from damage. The use of cable grips may be required at the top of the vertical run and at intermediate points in conduits. Vertical trays should not be used as ladders or to support any other items except the cables. Cables installed in vertical trays should be secured to the trays with qualified cable ties at periodic intervals, typically not exceeding 10 to 20 feet. Sharp projections of ties should be located external to trays.

At a point where the cable run changes direction or bends, the minimum allowed bending radius of the cables must be taken into consideration. The minimum bending radius of a cable is that minimum radius of curvature at which the cable can be bent without damage to the insulation or, in the case of medium-voltage cables, to shields and semi-conducting insulation. Bending cables tighter than the minimum allowable bending radius may cause the insulation to crack after time. In medium-voltage cables, disruption of the shields and semi-conducting may allow electrical deterioration of the insulation system. The degree of raceway bend should be designed to provide the proper radius of curvature for the cables being installed. The radius of an elbow bend should be sufficiently sized to permit the allowable bend of the largest cable to be routed in that section of the tray or conduit system.

Minimum bending radii provided below are found in appendices to ICEA documents [43, 44] and are those to which cables may be bent for permanent training during installation. These limits do not apply to conduit or duct bends, sheaves, or other curved surfaces around which the cables may be pulled under tension while being installed. Larger radius bends are required for such conditions; these larger radii typically are established by taking into account the cable manufacturer's permissible maximum pulling tension for the specific cable involved. Significant industry research on cable installation [51] and standards efforts [52] has indicated that cable bending radii may be less than the ICEA generic values based on specific testing performance.

Such use of values below ICEA values must be based on traceability between testing, unique cable design, service environment, and application. The following table contains information for unshielded power cables.

MINIMUM BENDING RADIUS
AS A MULTIPLE OF OVERALL DIAMETER

Insulation Thickness (Inches)	Diameter 1.00 Inch and Less	Diameter 1.01 to 2.00 Inches	Diameter 2.01 and Over
0.156 and less	4	5	6
0.172 - 0.132	5	6	7
0.328 and over	...	7	8

For power cables with metallic shielding and tape shielded cables, the bending radius is 12 times the cable diameter for cables with voltage ratings up to 15 kV.

When cable runs are long or contain numerous bends, cable pulling tensions can increase to the point where insulation or conductor damage can occur. If such pulls are not controlled, the installation tension may exceed the cable's side wall bearing pressure limit. If installation tensions are high enough, friction between the conduit and the cable may induce insulation damage during the pull. Cable runs with lengths and degrees of bend in excess of the following are typically monitored for pulling tension to assure that damage does not occur to the insulation or conductor:

- 50 feet including equivalent of three 90° bends*
- 100 feet including equivalent of two 90° bends and one 90° sweep*
- 150 feet including equivalent of two 90° bend*
- 200 feet including equivalent of one 90° bend and one 90° sweep*
- 225 feet including equivalent of one 90° bend or two 90° sweeps*
- 250 feet including equivalent of one 90° sweep*
- 300 feet without bends or sweeps*

* A 90° bend is 90° at minimum cable radius. A 90° sweep is 90° at 1.5 times the minimum cable bend conduit radius or greater.

Separation of the cable trays or conduits must also be given consideration in the design of a cable run. Cables should be separated by voltage class in cable trays to prevent the occurrence of induced voltages between cables with different voltages. The cable trays must then be separated to prevent a conducting path from occurring between the trays. Separation also minimizes fire propagation between trays. Trays with the highest voltage cable are typically located closest to the ceiling with the remaining trays located below it in order of descending voltage. This ordering prevents a fire in the high voltage cable tray from propagating into the lower voltage systems because the fire will tend to propagate upwards.

The fire retardancy of the cable run is also important when designing a cable run. In newer plants, cables were installed having fire retardant jackets and insulations. Some older plants that did not use such cables have either coated cables with flame retardants or have wrapped conduits and trays in fire lagging. Such precautions are needed where cables from different safety trains are not separated by sufficient distance of a recognized fire barrier. Where cables pass through one fire zone to another (i.e., pass through walls and floors), fire stops must be placed in the openings.

To minimize the damage to jackets and insulations during cable pulling, cable trays should be cleared of burrs and sharp edges before cable pulling takes place. Conduit and ducts must be swabbed to remove dirt, stones, or concrete that may have been trapped in the lines during the layout. Conduit should then be blown clean, except for short runs that can be visually inspected. A clean, dry conduit is desirable so that during the cable pull, the cable wall will not be subjected to abrasive materials and the end will not be exposed to moisture.

CABLE PULL PREPARATION

A reel (or reels) of qualified cable must be requisitioned from storage, checked against the cable list, and set up. The cable end designated for pulling must contain an identification number; this number will be used by the cable pulling crew. During transportation from storage to the final installation point, cables must not be dragged over rough surfaces or stepped upon. Reel jacks or equivalent should be used to support the reel axle and minimize friction. Cable temperature should be checked; it should not fall below the vendor required minimum temperature prior to or during installation. If the cable temperature is lower, it must be warmed for an appropriate period to assure adequate flexibility. The actual length of each run with additional allowances for training and terminations should be determined if cable is not installed directly from cable reels. Pulling from reels is preferred to minimize waste.

Cable guide pulleys, tray rollers, and sheaves must be installed at tray corners, in manholes, and at raceway ends to prevent violation of cable bending radius and to minimize pulling tension. For monitored cable pulls, a dynamometer, tensiometer, or breakable links are set up to monitor cable pulling tension to make sure that the maximum allowable pulling tension is not exceeded. Alternatively, for hand pulls, an engineering cable pulling chart can be used to assure that the actual pulling tension will not exceed cable allowable pulling tension, or assure that the maximum force during pull is limited (e.g., a limit is established with regard to the number of persons manually pulling the cable). Cables should be pulled at a relatively constant velocity such that slip-stick friction conditions do not occur. Minimizing stick-slip friction will allow cables to be installed utilizing lower overall installation tension.

In general, pulling attachments are connected to cable conductor or to the cable jacket via basket grips. Swivels should be used when possible between the pull rope and the pulling attachment to allow cable rotation during pulling.

At the time of pulling, the cables should be coated with cable pulling lubricants as recommended by the cable manufacturer. The lubricant should be inert; it should not support combustion once dry.

LIMITATIONS ON CABLE PULLS

All mechanical pulls should be tension monitored or tension limited to ensure maximum installation tensions are not exceeded. Uncontrolled pulls using equipment such as cranes, "cherry pickers," and trucks are not recommended. Such equipment can cause excess force to be exerted on the cable jacket and insulation system leading to damage.

During a cable pull, care must be taken to avoid sharply bending or kinking the conductor, damaging insulation or jacket, or stressing cable beyond the manufacturer's recommendations. The cable must be protected at all times from mechanical injury and from absorption of moisture at unprotected ends. Cable on cable racks, in cable trays, and at conduit entries must be trained to avoid bearing against edges of trays, racks, conduit bushings, or supports. "Training" of cable is done at the conclusion of pulling and is the act of assuring that the bends at terminations are appropriate and that the cables are not resting against sharp edges. By training the cable, the cable is placed into the desired position that assures that the jacket and insulation system does not degrade due to overbending or cutting by sharp edges of surrounding components. At the completion of the pull, excess cable length should be trimmed and not stored in the trays.

Cable pull rope selection is important when pulling into a duct bank. The potential for raceway damage should be considered; PVC conduits that are often embedded in concrete slabs and walls may be cut or grooved by steel or nylon pull rope. Cable pull ropes made of Kevlar, hemp, and polyester have relatively low elasticity. During installation, this will prevent the cable from stretching when friction increases at certain pull points.

Cables must be installed into trays in an orderly manner. Crossings should be avoided whenever possible. Care should be exercised at tray junctions to prevent cables from piling up.

Cables leaving the cable tray between rungs may require a dropout at the bottom of the tray to provide a smooth bend for the cables.

When necessary, cables in trays should be tied to provide a neat and orderly installation. Cables requiring a specific spacing should always be tied into the tray. This includes changes in direction of the cable run (i.e., vertical and horizontal turns and exits from trays, conduits, or wire ways

When a horizontal tray cannot be used, cables should be hung on supports and grips at intervals not exceeding design lengths, which take the cable's weight and strength into account.

Cables having shop-installed plugs or connectors for plug-in terminations should not be pulled through conduit. These runs should be located so that the cable can be laid into cable trays or troughs after insertion through floor slots or sleeves. When cable with installed plugs or connectors must be pulled through conduit, the design and pulling method should minimize the probability of damage to the connector, cable, and conduit.

Insulated cable extending to terminals and terminal boards or connections within junction boxes or terminating equipment should be neatly cabled or clamped at approximately 6- to 12-inch intervals between cable entry point and terminals. Where the outlet box, cabinet, cubicle, switchgear, or other terminal devices for cable is equipped with trays, troughs, or gutters, a sufficient length of each cable should be pulled to permit a neat arrangement of entering cables. The leads should be formed and cabled or clamped as each conductor is brought to its terminal connection. "Tangle" box work is generally considered to be "poor workmanship."

Splices of cables in cable runs can only be made when approved by the engineering organization. Splices should not be made in raceways per USNRC Regulatory Guide 1.75 [29].

PULL-BYS, JAMMING, AND SIDEWALL BEARING PRESSURE

Pull-bys

A "pull-by" is the installation of new cable, by pulling, into conduits or ducts already containing cable. The IEEE and manufacturers recommend against the use of pull-bys. Alternate approaches, such as installation of new conduit or bulk pulling of all cable, should be considered. However, removal of existing cables should be discouraged due the possibility of damage of otherwise acceptable cables. NRC Information Notice 92-01[53] describes cable damage where the pull rope used in a pull-by completely cut through the cable insulation to its conductors. Pull-by damage occurred in a number of conduits. The pull ropes used were a highly abrasive nylon cord (parachute cord).

If pull-bys are to be attempted, they must be performed under tight controls. Conduit runs in which pull-bys are to be attempted should be short and have few bends. If pull-bys are not properly controlled, damage to the existing cables most frequently occurs at bends where the new cable is supported by the existing cable. At such a point, the friction at the interface between the pull rope or the new cable and the existing cable can cut through the existing cable's jacket and insulation. The primary concern when considering a pull-by is to establish a clear path that will avoid interference with existing cables during the pull. One technique to establish a clear path involves the use of a fish, which is a flexible, flat pulling tape. The fish is carefully pushed through the conduit. The fish is then used to install a pull rope through the conduit. The cable is then attached to the pull rope and drawn through the conduit. This method helps the pulling crew feel their way through the conduit; they will be able to sense any jams or obstructions present during pulling. An experienced cable puller can usually avoid interference between existing cables. The cable is then pulled through the conduit in the opposite direction. Normally, swivels should not be used. However, small, bullet-nose, break-away swivels are available and may be helpful when pulling machines are used. These are not recommended for high-tension pulls. Under no circumstances should an existing rope or fish tape left in the duct from a previous pull be used as it would not provide the necessary clear cable path. Metal fish tapes should not be used because they may scar or otherwise damage existing cable.

The pulling rope diameter should range from 3/8 and 3/4 inch. The use of fairly large diameter ropes helps distribute frictional forces over the surface of existing cable. The rope should be flexible, double-braided polyester. Abrasive pull ropes such as nylon must be avoided. Manual or automatic lubricating of the pulling rope, interior of the conduit, and existing cable will significantly reduce the abrasive friction and sidewall bearing pressure experienced by both the new and existing cable. Under no circumstances should steel ropes be used. Existing cables and conduit should be lubricated by pulling lubricant-soaked swabs through the conduit. A special lubricating rope can be also be used that sprays lubricant throughout the conduit. The new cable should also be lubricated, either manually or automatically, as it enters the conduit.

In all pull-bys, great care should be taken to cover sharp edges of all pulling equipment hardware that enters the conduit by applying tape or preferably heat-shrinkable sleeves. These methods will not affect the flexibility of the hardware. Leading edges should not be blunt or sharp-edged, but rather cone- or bullet-shaped to provide a streamlined profile that will ease passage through the pull.

Jamming

Jamming can occur when three single cables of similar size are pulled into a conduit when the summation of the cable diameters approximately equal the diameter of the conduit. Jamming results when the center cable is forced between the two outside cables while being pulled around a bend and the jackets of the outer cables are forced against the conduit causing a braking action. There is a specific range of cable diameters (d) to conduit diameters (D) for which a jamming concern exists. This range of D/d is 2.8 to 3.1. Above this range, the cables will lay in parallel around a bend without jamming against the sides of the conduit. Below this value, the center cable will stay in a triangular or cradled configuration with respect to the outer cables and not be able to be forced between them.

Jamming is undesirable since cable insulation may be damaged and extra effort will be required to eliminate the jam. The jam ratio should be checked for the particular cable configuration before proceeding with the cable pull.

Sidewall Bearing Pressure

Sidewall bearing pressure is the radial force exerted on the insulation and jacket of a cable at a bend point when the cable AS under tension. If sidewall bearing pressure is excessive, the conductor will tend to crush the insulation and jacket at the support point. Per Appendix A of IEEE Std 690 [54], the maximum allowable sidewall bearing pressure is 500 lb/ft of radius for power and control cables. The manufacturer's recommendations are to be used for instrumentation cables. Higher values may be used for control and power cables if these values are based on test results or manufacturer's data.

All of the protective pulling measures discussed above are important because they will help reduce the amount of sidewall bearing pressure experienced by the cables. Prevention of side wall bearing pressure damage assumes the use of appropriate lubricants. If lubrication is not used, the cables will tend to stick at the bends. The combination of friction and sidewall bearing pressure at the interface between the cable and the conduit will tend to damage the cable insulation. Controlling sidewall bearing pressure during a pull is essential in protecting the cable insulation and thus ensuring the operability of the cable system. Calculation of pulling tension limits in accordance with Section A9.2.4.3 of IEEE Std 690 [54] will provide for control of sidewall bearing pressure.

TERMINATION REQUIREMENTS

General Requirements

Terminal and connector systems typically use color-keyed lugs, dies, or connectors of a specific manufacturer with go-no-go tooling. All materials used for terminations should be compatible with the cable conductor, insulation, and environment. Wire stripping tools must be used for insulation removal. All low-voltage stranded cable is typically terminated with pre-insulated compression (crimp) type connectors that firmly and completely grip the conductor and the wire insulation. Special care should be taken so that insulating coatings are completely removed from the conductor and that the conductor is not nicked or otherwise damaged. Control cable and low current power cable are frequently terminated on terminal blocks by using compression type ring lugs. Most of these cables use multi-strand conductors. If they were directly terminated under the screw head of standard terminal blocks, capture of all of the strands of the conductor would not be assured. The compression fitting assures that all of the strands are captured in the connection, and the ring lug prevents the connection from being inadvertently pulled off of the terminal.

Terminations at motors, control, and instrumentation pigtails are typically lug-to-lug connections. Termination hardware for copper conductors generally includes silicon bronze or brass bolts, flat washers and lock washers. Torque values for tightening bolts must be in accordance with industry standards or manufacturer's recommendations. Termination hardware for aluminum conductors is usually made of aluminum; if steel hardware is used, Belleville washers must be included. These washers provide a spring loading to the aluminum connection that maintains the contact should the aluminum cold flow. Mating surfaces of lug-to-lug connections and aluminum conductor to terminal interfaces are typically coated with a termination oxide-reducing coating. The coating is usually in accordance with manufacturer's recommendations. If corrosion of the aluminum conductor is identified at the time of termination, the conductor ends must be cut back to the point were no corrosion is present.

Certain control devices, such as limit switches, may have inadequate internal space to allow appropriate cable terminations to be made. In such cases, a separate termination box is typically provided in close proximity to the devices. The individual conductors of cable are connected to single conductor hook-up wires in the termination box and these single conductor wires are then connected to the devices completing the connection.

Quality control of the termination process is important. Wire size, stripping length, stud size, terminal catalog number, and crimp tool type must be controlled when terminations are prepared. The use of the appropriate crimp tool is important. If the lug is under crimped, a high resistance termination will result. If it is over crimped, the lug may fracture or the conductor may be cut leading to a poor connection. Most crimp tools now in use will not release until a complete crimp has been made. Some crimp lug manufacturers recommend the use of go-no-go gages to check the adequacy of the final connection.

Instrumentation Cable Requirements

The termination methods described for low-voltage cables apply to many instrumentation circuits. For environments not subjected to condensing moisture or accident environments with steam conditions, compression type ring lugs are used to connect cable leads to terminal strips. In areas subject to steam or condensing moisture, butt splices with environmentally qualified heatshrink tubing or taped coverings are used to prevent low insulation resistance at the connection from affecting the accuracy of the instrument loop.

Instrument cable shields should be terminated at a terminal point adjacent to the signal conductors of the same instrument cable. Cable shields are grounded at one end of the circuit only to prevent loop currents from being induce in the shield and to provide the best shielding. Care must be taken to insulate shields to prevent unintentional grounds.

Medium Voltage Cable Requirements

The termination and splicing methods for medium voltage cables are specific to the conductor insulation type and environment of the termination. When cable construction uses metallic shielding, this shielding is typically stripped back and insulated at the termination to minimize electrical leakage between the terminal and the shield. An electrical stress relief cone is placed over the cable end. Stress relief cones are generally made of insulating tape and shielding braid. The flare out of the shield in conical shape relieves or minimizes the electrical stress. Pennant kits that use flag-shaped material to wrap the cable to form the cone, heat shrink tubing or preformed stress cones are available.

Section 6.0

Operability Aspects Related to Cable Qualification

Section 6.0

OPERABILITY ASPECTS RELATED TO CABLE QUALIFICATION

Equipment critical to nuclear plant safety must remain operable, not only at installation, but throughout its qualified life. The qualified life is the period during which a component can withstand the rigors of aging and remain functional in an accident environment. For nuclear power plants within the United States, is [55] requires demonstration that safety-related equipment meet its operability requirements throughout its qualified life. Specifically, 10CFR50.49(j) requires that "each item of electrical equipment important to safety ... (1) Is qualified for its applications and (2) meets its specified performance requirements when it is subjected to the conditions predicted to be present when it must perform its safety function up to the end of its qualified life."

This section provides information relating to cable operability given the special needs of a nuclear plant.

ROLE OF ENVIRONMENTAL QUALIFICATION IN CABLE OPERABILITY

Some nuclear safety-related electrical equipment must have the capability to withstand harsh accident conditions that include chemical sprays, and higher levels of temperature, pressure, humidity, and radiation. Cable is included in this category of equipment. In addition, electrical components must be able to withstand the accident environment in an aged state. That is, the effects of normal temperature and radiation must be either simulated or taken into consideration during the qualification process. Aging must be included in a qualification program or analysis must show it is not significant. There are several standards for qualification of cables [56-59].

An aging mechanism is significant for qualification of harsh environment equipment if it satisfies all of the following criteria [60]:

1. In the normal service environments, an aging mechanism promotes the same failure mode as that resulting from exposure to abnormal or design-basis event service conditions.

2. The aging mechanism adversely affects the ability of the equipment to perform its safety function in accordance with its specification requirements.

3. The deterioration caused by aging mechanism is not amenable to assessment by in-service inspection or surveillance activities that provide confidence in the

equipment's ability to function in accordance with its specification requirements during the intervals between surveillance.

4. In the normal service environment, the aging mechanism causes degradation during the design life of the equipment that is appreciable compared to degradation caused by the design-basis events.

In a qualification testing program, the equipment is artificially aged using relatively simple aging models to simulate end-of-life conditions prior to performance testing under severe conditions. Research has demonstrated that unlike many non-organic materials, organic materials may be susceptible to significant changes in properties due to normal aging. Therefore, the operability of an electrical cable is generally considered to be limited by the life of the insulation. During the qualification process, aging is generally simulated prior to performance testing under harsh conditions on the assumption that aging is significant to the equipment's ability to function under accident conditions.

The qualification of cables for harsh environment service has been based upon use of cables within their ratings and limits of qualification and use of appropriate installation practices. The qualification programs indicate that properly installed cable will successfully withstand accident conditions. Few cable problems may be expected under normal service conditions for properly installed cables. However, in a limited number of cases some cable damage has occurred or been suspected. While infrequent, failures have occurred due to physical damage, misapplication, local hot spots with temperatures well beyond the cable design basis, and abusive installation practice. For most of these problems, the scope has been localized. That is, inadvertent physical damage occurred to a limited set of cables in a particular location, localized hot spots affected a small portion of a few cables, or design errors affected a limited set of cables. In each of these cases, limited corrective actions were required when the deficiencies were identified. Cables were replaced or repaired when damaged; cables were replaced and isolated from the hot spot, or higher temperature rated cables were installed; and cables were replaced with those having appropriate ratings when design errors were recognized.

The effects of such localized problems, even if unrecognized, generally do not represent a common-mode concern in that redundancy built into the plant design would assure safety function. However, if cable problems were widespread in a plant, concern for the overall adequacy of the cable system could occur and extraordinary corrective actions would be required.

Currently, EPRI-sponsored research is seeking both a better understanding of the amount of damage that is significant enough to affect operability under harsh environment conditions, as well as methods to monitor and detect such changes before cable operability is jeopardized [61, 62]. This research is attempting to develop troubleshooting techniques to detect partial-through-wall damage to cable insulations. Subsequent efforts will include verification that partial-through-wall damaged cables can withstand harsh environment conditions. These tests will attempt to verify the degree of damage with which cables can remain in service and be considered to be qualified. In addition, Sandia National Laboratories is performing extensive research for the NRC on cable aging, monitoring, and qualification. This research shows that it is practical to extend cable life to as much as 60 years for cables rated for 40 years of service because of the conservatism in the qualification of cables.

Aging Concerns and Common Mode Failure

> Garfagno and Gibson [64] expressed the basis for their concern on aging as follows: "The concern with equipment aging stems from the fact that it is a mechanism whereby failure can occur simultaneously (or effectively so) in redundant safety systems. Redundancy (coupled with diversity) is the principal means of guarding against the consequences of random failures of equipment and providing assurance that at least one complete chain of safety systems is functional at all times during plant operation. If equipment aging were to degrade functional capability to the point where the increase in stress levels associated with a design basis event could cause simultaneous failure of redundant systems (or their failure within a critical interval of time), the required protection would not be provided. The risk of this type of common-mode failure can be reduced or eliminated by the demonstration that aged equipment is adequately operational to provide its specified function."

Use of the Arrhenius Model to Simulate Thermal Aging

It is impractical to naturally age all organic components of equipment to the projected or desired plant life. The typical 40-year nuclear plant was licensed [65], before the commercial availability of most modern insulations (e.g., cross-linked polyethylene, ethylene propylene rubber, and silicone rubber) by at least a decade. Therefore, 40-year-old specimens of these cables are not available for evaluation. Fortunately, alternative methods have been developed to artificially age insulations so that their properties can be evaluated and compared. The most commonly used method is the Arrhenius method.

Aging in a material is caused by a gradual change in the molecular structure. In 1889, Svante A. Arrhenius developed a method by which the rate of molecular reaction of different materials at varying temperatures could be modeled. He quantified his discovery into a simple formula that bears his name. The formula, which is shown below, has been recognized as a reasonably accurate model of aging of electrical insulation materials since this approach was advocated for electrical insulation by Dakin in 1948 [66].

The Arrhenius equation is as follows:

$$R = A \exp(-E/kT) \qquad \text{Eq. 6-1}$$

where:

R = reaction rate (arbitrary units)
A = molecular collision frequency factor (material constant, same units as for R)
E = activation energy of material (eV)
k = Boltzmann's constant (8.617E-5 eV/K)
T = material temperature (K)

In this form, the equation is of little use in evaluating changes in insulation properties. However, the more common form is derived as follows:

$$t_1R_1 = t_1\, A\, e^{(-E/kT_1)} = t_2R_2 = t_2\, A\, e^{(-E/kT_2)} \qquad \text{Eq. 6-2}$$

where:

t_1, t_2 = lengths of time for reaction period 1 and 2, respectively
R_1, R_2 = reaction rates for period 1 and 2, respectively
T_1, T_2 = temperatures for period 1 and 2, respectively

This reduces to-

$$t_1 = t_2 \exp^{[(E/k)(1/T_1 - 1/T_2)]} \qquad \text{Eq. 6-3}$$

or:

$$T_1 = 1/(1/T_2 - (k/E)\ln(t_2/t_1)) \qquad \text{Eq. 6-4}$$

Empirically derived activation energies associated with specific material property changes are available in the literature. For example, changes in elongation at break are commonly used to judge the adequacy of cable insulations. Therefore, one might try to obtain an activation energy for an insulation that is associated with a 50% drop in elongation at break. The selection of a conservative activation energy for use in an aging analysis is necessary to assure that aging is adequately considered in the qualification program.

Since T_2 and t_2 (the temperature and time period of the projected life, respectively), E, and k are all known, by choosing either the aging temperature or time period, the other unknown can be determined. For example, if T_1 (the aging temperature) is chosen as 100°C (373.15 K), the aging duration is calculated as to = 2201 hours (approximately 92 days or 3 months). Conversely, if the aging duration is chosen to be two weeks (336 hr) to reduce the cost or improve the schedule, the required temperature will be T_1 = 394.8 K (122°C).

When the thermal profile of the equipment's projected life or of the accelerated aging does not conform to a constant temperature, but can be reduced to discrete steps, the cumulative aging reaction may be approximated by summing the reactions caused during each of the steps. In these cases, the above equations may be applied step wise to calculate equivalent temperatures and times.

PRACTICES LEADING TO CONSERVATIVE THERMAL LIVES

A number of conservative practices used in the development of cable standards and the design of cable applications cause the thermal lives of cables to be more conservative than even a conservatively developed cable aging program would indicate. These include conservatively developed ampacity standards, operation of the cable at low current causing small temperature rises, and use of insulations that have improved heat transfer characteristics. Sizing of power cables to withstand fault currents also leads to conservative thermal lives. These conservatisms are discussed in the following subsections.

Conservative Ampacity Determinations in Industry Standards

The basis for cable ampacity determination is based on heat transfer fundamentals. In 1957, Neher and McGrath [67] provided the detailed heat transfer calculations that relate an insulated conductor's ampacity to its operating temperature. The methodology became known as the Neher-McGrath (NM) method [60] for essentially steady heat flow through a cable and its environment. This methodology is followed by ICEA [32] and the National Electrical Code [68], forming the basis of ampacity determination industry wide. Other appropriate heat transfer methods have been developed for cables in cable trays [69, 70]. When current is carried by the cable's conductor, the I^2R heat flows from the conductor radially out to the surrounding environment (through the intervening insulation, jackets, air, raceway, etc.). For low-voltage power cabling, the dielectric losses and metallic raceway effect are negligible [60]. The heat generated at the conductor (w/m) times the total thermal resistance from conductor to ambient (°C cm/w) yields the conductor temperature rise above ambient expressed in Equation 6-5.

$$(I^2R_c)\ TR_{ca} = T_c - T_a \tag{Eq. 6-5}$$

where:

I = current, amperes
T_c = conductor temperature, °C
T_a = ambient temperature, °C
TR_{ca} = thermal resistance between conductor and ambient
R_c = conductor resistance, ohm/cm

The above equation illustrates the sensitivity of the operating cable temperature (T_c) to factors relating to ambient temperature, thermal resistance, conductor resistance, and current. As described in this section, the actual assumptions used in making thermal life assessments of cable are conservative with respect to nearly every factor in the equation.

Cable Insulation Thermal Resistivity

Major factors affecting the thermal resistance path of a cable include the actual specific thermal resistivities of the insulation and jacket, and the physical cable dimensions (e.g., wall and jacket thickness). The actual ampacity tables used in design are based on a series of insulation materials and wall dimensions resulting in higher thermal resistivities than modern insulations (e.g., ampacity tables include asbestos jackets and thicker walled older style insulations for certain cable types in lieu of typical 30-mil wall cross-linked polyethylene). Consequently, the actual plant cables using the modern insulation systems can reasonably be expected to run cooler than the conductor temperature that the ampacity ratings imply. In addition, the resistance of the actual conductor producing heat in the I^2R_c expression can be expected to be appreciably less than used in the determination of temperature rise.

Table 6-1 shows the typical thermal resistivities (°C cm/w) for typical insulations (the ampacity standards are based on the rating of cables for the worst-case insulation types in a given category).

Table 6-1
Typical Cable Insulating Material Thermal Resistivity

Material	Specific Thermal Resistivity
Asbestos	600
Cambric	600
Vinyl	600
Butyl rubber	600
EPR	400 - 500
Natural rubber	500
Cross-linked polyethylene	350 - 450
Polyethylene	350 - 450

Both the ICEA standards and the National Electrical Code [71] allow specific ampacity calculations based on the Neher-McGrath methods and actual insulation thermal resistivities. The standard ampacity determination for EPR and cross-linked polyethylene based on worst-case thermal resistivities is conservative.

Operation at Reduced Currents

The temperature rise of a cable insulation is a function of the square of the operating current. The thermal aging of a cable must consider the temperature rise in conjunction with the ambient temperature. The actual current that the cable carries is a function of the electrical load, which is seldom at the full nameplate rating of the connected equipment. For example, the maximum brake horsepower for a representative pump may be 74.8 bhp, whereas the nameplate rating of the associated motor drive may be 125 hp. If the cable is sized on the motor capability rather than the maximum load drawn by the pump, the cable load will be oversized with respect to the actual load resulting in a significant reduction in cable operating temperature. This is illustrated by Equation 6-6 below:

$$OTR = RTR \times (I_{applied})^2/(I_{rated})^2 \qquad \text{Eq. 6-6}$$

where:

OTR = Operating Temperature Rise at applied current
RTR = Rated Temperature Rise at rated current

Therefore, if the temperature rise used in the aging analysis for the cable was based upon a rated current that is larger than the applied current, the operating temperature would be significantly less than the analyzed temperature leading to conservative results.

Because the loads on cables are expected to be lower than the rated values, the temperature rise from ohmic heating, which is directly proportional to resistance and current, will also be reduced due to lower currents. The resistance of a copper conductor at a reference temperature (e.g., 20°C) is established in ICEA standards [43] as:

$$R_1 = R_2\ (254.5)/(234.5 + T_2) \qquad \text{Eq. 6-7}$$

where:

R_1= resistance at 20°C for copper
R_2= resistance at specific temperature, T_2 for copper
T_2= application temperature, °C

Converting the above equation to determine the resistance at other than the reference temperature:

$$R_2 = R_1/[(254.5)/(234.5 + T_2)] \qquad \text{Eq. 6-8}$$

For a series of conductor temperatures that deviate from the reference temperature (20°C), comparative resistance (R_2 /R_1) becomes:

R2	Temperature
$1.04R_1$	30°C
$1.08R_1$	40°C
$1.12R_1$	50°C
$1.16R_1$	60°C
$1.20R_1$	70°C
$1.24R_1$	80°C
$1.28R_1$	90°C

Using the Equation 6-6, a load of 5 amperes carried by a 20-ampere, 90°C rated cable in a 40°C ambient results in a temperature rise (neglecting conductor resistance change and dielectric losses, which are essentially negligible for power plant cables) of:

$$\text{Application rise} = (\text{rated rise})(I_{\text{application}}/I_{\text{rated}})^2$$
$$= (90°\text{C} - 40^{\text{o}}\text{C})(5/20)^2$$
$$= 3.13\text{-C}$$

The conductor resistance at the total operating temperature (ambient plus rise) will be substantially less. For example, the resistance at the 90°C conductor temperature is 28% greater than at 20°C [$(1.28R_1 - R_1)/R_1$] and 14% greater than at 50°C [$(1.28R_1 - 1.12R_1)/1.12R_1$]. Therefore, the calculated temperature rise of 3.13°C, that was based on the ohmic heating from a conductor resistance corresponding to 90°C, not the resistance at lower operating temperature of approximately 43°C, is still conservative.

Similar results would occur with aluminum conductors. However, as the resistance of aluminum is different than copper, Equation 6-7 becomes:

$$R_1 = R_2(248.1)/(228.1 + T_2) \qquad \text{Eq. 6-9}$$

where:

R_1 = resistance at 20°C for aluminum
R_2 = resistance at specific temperature, T_2 for aluminum

The change in resistance of the conductor is a known phenomenon and forms the basis to determine, by resistance measurement, the winding temperatures of a motor [41, 72], cable [35], transformer, or other insulated wiring based electrical devices.

Cable Fault Current Design and Normal Operating Temperature

A typical design basis for plant cabling is to design cabling to be able to withstand, without failure, the heat produced during a short circuit fault of the connected load (e.g., motor). Plants adopting the current industry standard for Class 1E cable design, IEEE Std 690 [17], are required to select cable sizes that are based on the ability to carry required short-circuit current.

In the evaluation of short circuit conditions, it is conservatively, but reasonably, assumed that the entire I^2R heating is developed in the conductor with no heat transfer through the insulation, jackets, raceway, and surroundings. Under this assumption of no heat transfer during the fault, the temperature of the insulation is maximized leading to conservative results. Because I^2R heating is directly proportional to the resistance of the cable conductor, increasing the size of the conductor reduces the amount of heating during a fault. The minimum conductor size required for the insulation to withstand a specific short-circuit depends on the effective current, the conductor material, the insulation short circuit withstand temperature rating in °C, the operating temperature of the cable at the time of fault, and the opening time of the fault clearing circuit breaker or fuse.

The methodology of determining the conductor size is found in industry standards [36] and is described by the following equations:

For Aluminum:

$$(I_{eff}/A)^2 t = 0.125 \log_{10}[(T_2 + 228.1)/(T_1 + 228.1)] \qquad \text{Eq. 6-10}$$

For Copper:

$$(I_{eff}/A)^2 t = 0.0297 \log_{10}[(T_2 + 234.5)/(T_1 + 234.5)] \qquad \text{Eq. 6-11}$$

where:

I_{eff} = fault current, amperes
t = time of fault, seconds
T_1 = prefault conductor temperature, °C
T_2 = final conductor temperature, °C

Many of the standard texts [37, 73, 74] and manufacturer's manuals [19, 20] have simplified the determination of minimum cable size by providing tables, charts, or nomographs to determine minimum cable size.

Quite often the selection of cable to withstand a short circuit is based on the short circuit momentary or interrupting ratings of the protective devices (e.g., circuit breakers) used to protect the circuits. This is often the case for medium-voltage circuits or low-voltage power cables from distribution switchgear to motor control centers. For low voltage loads such as 460-volt motors, the cable impedance for lengths in excess of 20 to 50 feet is often sufficiently high [75] to limit the short circuit currents to much lower values than if cable impedance is neglected.

On the basis of the design to accommodate short circuits, typical cable sizes are shown in the following table.

Table 6-2
Typical Minimum Cable Size Selection to Withstand Fault Currents

	Insulation		
Power Source	Butyl	EPR	XLPE
Medium-Voltage Switchgear	350 kcmil	4/0 AWG	4/0 AWG
Low-Voltage Switchgear	1/0 AWG	1 AWG	1 AWG
Motor Control Center	l/0 AWG	12 AWG	12 AWG

The use of larger cable sizes to account for short circuit withstand can significantly increase the thermal life of a cable because ohmic heating will be lower due to the lower resistance of the cable than would occur for small conductor sizes based on normal loads. Table 6-4 presents loading data for motor cables that are sized on short circuit currents. For these cable circuits, motor horsepower, full load current, percentage or cable ampacity used, and operating temperature rise percentage versus rated temperature for typical medium-voltage (4000-volt) cables connected to Class 1E (nuclear safety-related) motors is given.

Table 6-3

Typical Characteristics for Cables Connected to Medium-Voltage (4000-Volt) Class 1E Motors

Percentage Temperature Rise

Motor Hp	Full Load Current	PR/XLPE*	Butyl*
250	33	1.4%	0.8%
300	40	2.0%	1.1%
400	53	3.6%	2.0%
500	66	5.5%	3.1%
600	80	8.1%	4.5%
700	93	11.0%	6.1%
800	106	14.2%	7.9%
900	120	8.2%	10.1%
1000	133	22.4%	12.4%
1250	166	34.9%	19.4%
1500	199	50.2%	27.9%

*Ampacity is based on a 100% load factor, three conductor cable in conduit, 40°C ambient, 90°C conductor temperature, 5-kV cable with a copper conductor. The ICEA 46-426, 4/0 AWG ampacity is 281 amperes, for 250°C short circuit rated EPR/XLPE; the 350 kcmil ampacity is 377 amperes for 200°C short circuit rated butyl rubber.

There are older plants, which have used butyl rubber cable for medium-voltage service. These cables have a 200°C short circuit temperature rating resulting in larger conductor sizes than the more modern 250°C rated EPR/XLPE cables. Therefore, the medium-voltage butyl rubber cables used in motor feeds are expected to operate at lower temperatures than their counterpart EPR/XLPE cables.

The above analysis does not mean that all power cables will have low operating temperatures. However, for most power cables, the combined effects of low operating loads, load diversity, and conservatism in ampacity and short circuit determination is such that few power cables are expected to be at temperatures much above 50° to 70°C.

LOCAL THERMAL AND RADIATION HOT SPOTS

Earlier subsections discussed the general conservatism that exists in the aging and design basis accident exposures of cables. The actual environmental exposures for cables are expected to be less severe than the environments simulated during in the qualification program. However, this general condition does not preclude cable damage or failures when cables are installed in environments more severe than the generally anticipated environment. For example, cables that are installed in certain regions in containment such as near the pressurizer of a PWR may experience normal ambients of approximately 200°F [76], and the ends of cables connected to energized solenoid valves may experience temperatures of 263°F in an 150°F ambient environment [77] These are examples of conditions associated with normal operation and are due to equipment breakdown or an accident. However, these conditions clearly deviate from the typical generic conditions that form the basis for traditional cable selection. One of these conditions (the internal temperature of the solenoid valve) led to the issuance of USNRC IE Information Notice 84-68, "Potential Deficiency in Improperly Rated Field Wiring To Solenoid Valves" [78]. Many plants had used "standard" 90°C rated cables for such solenoid valves and expected extremely long life as the normal continuous current of the solenoid may be less than 2 amperes and the rating of a typical No. 12 AWG wire used may be in the order of 20 amperes. Utility personnel had expected negligible ohmic heating of the conductor and had not considered the effect on the end of the cable from the heat generated by the energized solenoid coil. Furthermore, this example can be extended to cable and wiring in the immediate area of a space heater used in a panel or motor operated valve, in the vicinity of a heat traced and insulated housing, or connected to RTDs located on primary process piping.

In addition to the normal plant local environments that may be excessive in regard to traditional cabling, other less easily identifiable hot spot conditions may occur. Cables are installed throughout the plant, sometimes in close proximity to steam pipes, and within rooms with high radiation conditions. Cable failures have occurred, especially in medium-voltage cables that were inadvertently exposed to elevated thermal conditions when thermal insulation was left off of adjacent steam piping. USNRC IE Notice 86-49 [79] describes a condition where the loss of thermal insulation about a pipe led to the direct failure of medium-voltage cabling.

Whenever localized thermal or radiation hotspots are found to have a significant effect on cable materials, appropriate corrective action is necessary to assure that cable function is retained and that the environmental qualification of the cable is not invalidated.

Section 7.0

Record of In-Service Cable Performance

Section 7.0

RECORD OF IN-SERVICE CABLE PERFORMANCE

This assessment of nuclear power plant practices to assure cable operability necessitated a review of in-service cable performance. The operability questions to be resolved were:

- Determination of cable performance to date
- Determination of failure modes for cables
- Determination if reported cable failures were actually:
  (1) cable failures,
  (2) termination rather than cable failures, or
  (3) cable failures induced by installation problems.
- Determination of whether failures were occurring more or less frequently than expected based on experimental data or aging analysis.

Although good performance during normal service does not necessarily indicate that cables will perform satisfactorily during a design basis accident, it does provide a basic indication that gross problems do not exist. Performance during potentially severe accident conditions is addressed by environmental qualification, which is discussed in Section 6.

CABLE PERFORMANCE REPORTED IN NUCLEAR DATA BASES

The performance history of electrical cable in nuclear power plants has been good. Data provided by the United States Nuclear Regulatory Commission's Nuclear Plant Aging Research (NPAR) program [80] concluded the following

> Considering the number of miles of cable and the number of individual circuits in a nuclear power plant, the number of failures that have occurred to date is very low.

The basis of the NRC data was an evaluation of Licensee Event Reports (LERs) regarding cable through February 1984.

A review of LER reports [81-99] that have been issued since the completion of the NPAR review [80] confirmed that cable failures of any kind during operation are rare. The actual reports of cable failures were determined to be due to physical damage after installation, poorly made terminations, or cable abuse during installation.

The LER review results are supported by information available from the Institute of Nuclear Power Operations (INPO) program on Nuclear Plant Reliability. A search of the Nuclear Plant Reliability data base by Duke Power [100] in March 1988 revealed that cable failures reported were primarily related to termination problems, misapplication, and installation errors.

INFORMATION ACQUISITION FROM INDUSTRY PERSONNEL

Information regarding historical cable operability was acquired by structured interviews, discussions, or responses to written questions from more than fifty cable specialists. The cable specialists were utility staff members, cable manufacturers, government and university research personnel, cable-specialty testing personnel, test device manufacturers, A/Es, consultants, and members of professional societies specializing in electrical cables.

Many of the issues in this study were discussed with various professionals participating in the Nuclear Power Engineering Committee (NPEC) of the IEEE Power Engineering Society including principal subcommittees on Equipment Qualification, Operations, Surveillance, and Testing as well as the Insulated Conductors Committee (ICC) Task Force 14-4, "Evaluating Installed Station Cables" and EPRI staff specialists.

The interviews were held with specialists who are involved with and knowledgeable of cable installations in the nation's oldest to the newest plants. The following sections summarize the information acquired.

Confirmation of In-Service Cable Reliability

In each of the interviews, information was sought on actual cable failures due to deterioration over time. The responses of the interviewees were consistent: there are no known failures of low-voltage cable related to deterioration with age, other than those traceable to environments outside design limits (e.g., oil spills), mechanical abuse, misapplication (placement in a high ambient temperature condition), or termination failures. The experts' experience base included cables using butyl rubber, silicone rubber, ethylene propylene rubber, cross-linked polyethylene, PVC, and polyethylene insulation. Similar results were reported for fossil plants that have used older insulation systems of natural rubber, SBR, and varnished cambric. Similar results were reported by cable manufacturers based on their experience with cable failure samples that were returned for evaluation. The results of this study are consistent with that stated by Dr. Ting Ling [101], "The track record of the cable manufacturing industry in the past 100 years has been excellent."

During a three-day EPRI sponsored cable conditioning workshop [102], which drew 103 representatives of 37 utilities, 5 cable manufacturers, 4 testing organizations, 5 universities, and the NRC, it was concluded:

> No serious cable problem exists at present. Fossil and nuclear plant cables should provide continued reliable performance throughout the normal lifetime of the plants.
>
> Power plant cables have been very reliable. Simple in design, cables will cause little trouble during nominal lifetimes if conservatively used, properly applied, and not abused...

MEDIUM-VOLTAGE CABLE FAILURE MODES NOT APPLICABLE TO LOW-VOLTAGE CABLE

Electrical stress for medium-voltage cable is the major design focus as small imperfections in the insulation would be highly stressed and would, and do, lead to cable failure. This concern does not exist for low voltage cable, which is the focus of this research, in which electrical stresses are low.

Industrial, commercial, and utility experience with medium-voltage cable indicates the existence of some failures [103-106], whereas the total failures per cable-mile have been very small [104]. These failures are not traceable to mechanical damage (e.g., damage caused by cable installation abuse) and are generally caused by formation of electrochemical trees, or failure due to corrosion or water intrusion in directly buried cables for underground distribution. This configuration would be an unusual configuration for medium-voltage nuclear safety-related cables. Failures of non-safety-related 4-kV feed cables did occur recently at an 18-year-old plant. These cables had been in conduits that were below grade and were wet. In addition, the cables were energized but unloaded. This condition represents the worst case in that electrical stresses are present but no ohmic heating occurs that would tend to drive moisture out of the insulation. In general, however, the reliability record for nuclear power plant medium-voltage cables remains excellent.

Where failures of medium-voltage cables have occurred [102], they are traceable to overheating due to ambients well beyond the cable design basis or to poor installation. Such conditions would affect any type of cable. For example, the most widely known failure of medium-voltage cable [79] was assessed by the NRC as cable failure most likely due to exposure to a "high-temperature (400°F) feedwater line and pipe flange in the immediate vicinity of the cable."

By comparison to medium-voltage cable, the insulation thickness of low-voltage cable rated at 2000 volts or below (the focus of this study) is driven by the need to meet mechanical stresses during manufacturing, handling, and installation rather than by ability to withstand electrical stress. The nominal source voltage of 120-volt single-phase, 208-volt, 480-volt, or 600-volt 3-phase result in average stresses of 4 to 16 volts per mil. A medium-voltage cable operating on a nominal 4160 volts, 7200 volts, or 13,800 volt 3-phase system results in average stresses of 27 to 46 volts per mil.

The low stress levels of low-voltage cables assure that gas or air trapped in imperfections or small voids will not ionize. Therefore, electrical deterioration that could occur in medium-voltage cable will not occur in low-voltage cable.

Section 8.0

Insulation Fundamentals and Assessment of Industry Test Methods

Section 8.0

INSULATION FUNDAMENTALS AND ASSESSMENT OF INDUSTRY TEST METHODS

The fundamental understanding of cable insulation properties forms the foundation for assessment of cable operability. These same fundamentals (1) provide the basis for evaluating whether various electrical and physical tests and measurements are meaningful, cost-effective, and warranted, and (2) are a basis for evaluation of present or conventional cable test practices against the critical properties of concern for cable operability, life extension, retention of the original environmental qualification, and the adequacy of environmental qualification.

Fundamental insulation properties are discussed in this section in relation to cable factory testing, field testing, and limitations in the present state of the art in cable testing.

GENERAL PROPERTIES OF INSULATION

The electrical properties of concern for cable insulations are dielectric loss properties (resistivity, insulation resistance, dielectric constant and permittivity) and dielectric endurance properties (dielectric strength, breakdown strength, and ability to withstand corona attack). Although these properties are important for higher voltage and other specialty applications, many of them lose their importance for the low-voltage cabling used in nuclear power plants.

The properties of concern regarding the mechanical capability of the insulation systems (e.g., elongation) and thermal capability properties are also reviewed in this section. It is demonstrated that the significance of mechanical and thermal properties depend upon the application of the cable.

Insulation resistance measurements are commonly used to evaluate insulation systems. For shielded cable, insulation resistance is directly related to the volume resistivity of the cable. For unshielded cables, the insulation resistance has a complex relationship to volume and surface resistivity because there is no shield for a return path. The following sections describe volume and surface resistivity and the limitations and uses of insulation resistance measurement.

Resistivity and Resistance

Resistance of a material is the resistance offered by the material's conducting path to passage of electrical current. Resistance is expressed in ohms. For insulating materials, the term "volume resistivity" or simply "resistivity" is more commonly applied. Volume resistivity is the electrical resistance between opposite faces of a unit cube for a given material at a given temperature. Volume resistivity is sometimes called the intrinsic resistivity [107] of the material. The relationship between resistance and resistivity is expressed by the equation:

$$P_v = R_v (A/t) \qquad \text{Eq. 8-1}$$

where:

P_v = volume resitivity, ohm-cm
R_v = resistance between faces (measured or calculated), ohms
A= area of the faces, cm^2
t = distance between faces of piece on which measurements are made, cm

An equivalent expression for volume resistivity when measured per standard practice [108] is determined based on Ohm's law:

$$P_v = R_v A/t = E/I_v \text{ x } A/t \qquad \text{Eq. 8-2}$$

where:

E = applied potential, v
I_v = measured current, amp
A = area of smaller electrode (see Figure 8-1), cm^2

The standard test method measures volume resistivity by sandwiching a flat test specimen, usually a disk, between two electrodes, one of which is electrically guarded to prevent surface leakage around the edges. A voltage, usually 500 Vdc, is applied between the electrodes and the resulting current through the bulk of the specimen is measured by one of a variety of instruments, depending on the resistance value. A schematic of the preferred test setup, ASTM D257, is shown in Figure 8-1 as illustrated in Modern Plastics Encyclopedia [109].

All solid materials conduct electricity to some degree. A representative scale of resistivity for conductors, semi-conductors and insulators derived by Charles A. Harper [46, 110, 111] is presented in Figure 8-2.

Terms modifying resistivity are sometimes used to describe a specific application or condition. One such term is "surface resistivity," which is the resistance between two opposite edges of a surface film 1-cm square (refer to Figure 8-1). The units of surface resistivity are in ohms. Surface resistivity is important when field measuring insulation resistance of unshielded cables. During such measurements, current will flow from the conductor through the insulation and then along the surface of the insulation until it reaches the return path (e.g., conduit or tray). The resistance of the insulation measured in this way will be partially dependent on random parameters such as the amount of direct contact of the cable with the tray or conduit and the amount of dirt or moisture on the surface of the cable.

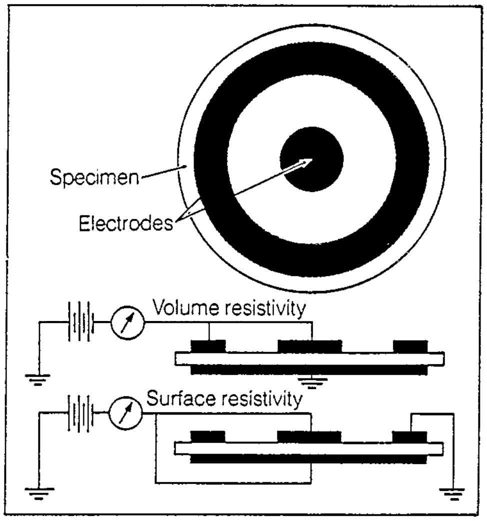


Figure 8-1

Electrode Configurations for Measurement of Volume and Surface Resistivity

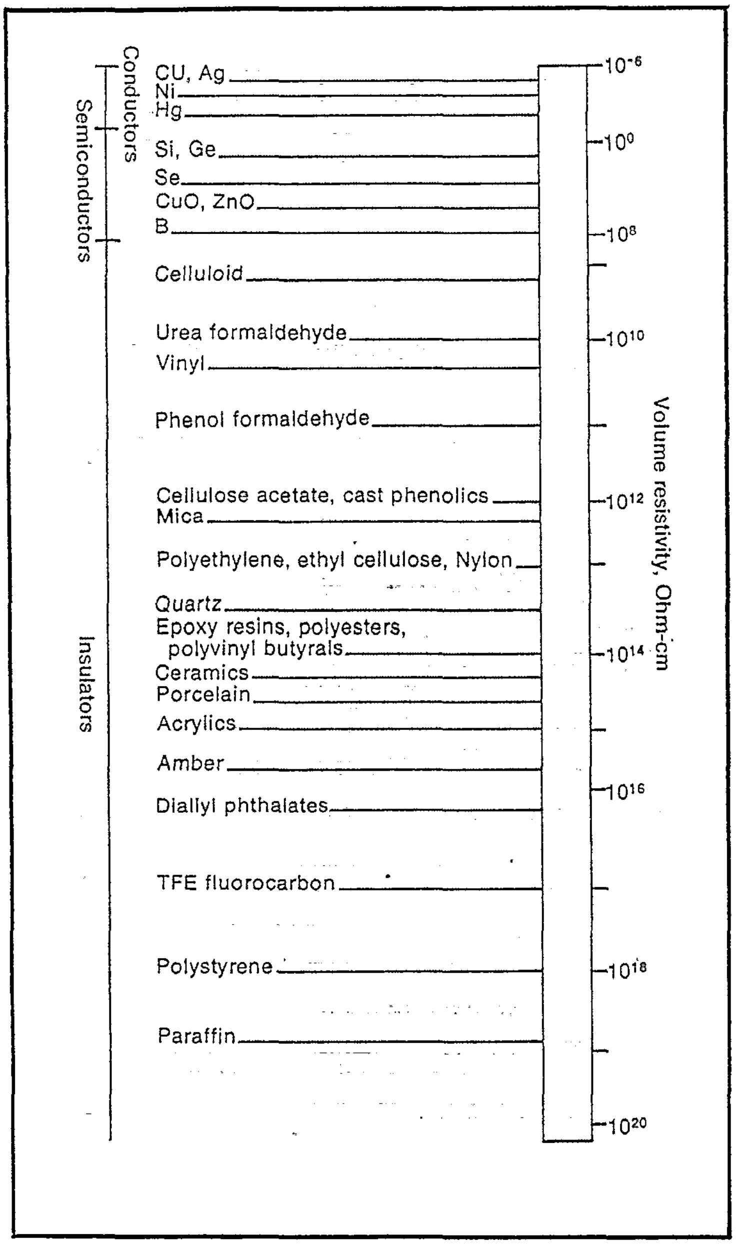


Figure 8-2

Range of Resistivity Values

An important difference between volume and surface resistivity is that surface resistivity must be measured in a humidity-controlled atmosphere. A knowledge of the humidity during measurement is essential to interpretation and use of the electrical test data. As in the case of volume resistivity, calculation of surface resistivity assumes the simple applicability of Ohm's law expressed as:

$$\begin{aligned} P_s &= [(E/I_s)(\text{pi} \times D_m)/g] \\ &= (R_s \times \text{pi} \times D_m)/g \end{aligned} \qquad \text{Eq. 8-3}$$

where:

P_s = surface resistivity, ohms

E = applied potential, V

I_s = measured current, amp

R_s = measured or calculated resistance of the specimen surface, ohms

D_m = mean diameter of the gap, cm

g = width of the gap, cm

pi = value of pi

Surface resistivity is not strictly a material property in the same sense as volume resistivity because the leakage current is carried through a surface layer that includes contaminants on the surface and interacting with adsorbed moisture. It also includes an inescapable volume component through the material just under the surface and is significantly affected by electrode geometry. As a result, measurements of surface resistivity are somewhat variable and are properly regarded as arbitrary measures of the interaction between a variable material surface and a humid environment.

The high resistivity of materials that are designated as insulators is sufficiently great that leakage current may normally be neglected for power and control cables. However, for certain sensitive instrumentation circuits the current through the insulators (generally designated as "leakage current") may be significant enough to induce instrumentation errors. This condition is discussed in depth in this section.

In addition to conductors and insulators, a group of materials designated as semiconductors exists. A semiconductor is neither a good insulator (i.e., it does not have relatively high resistivity) nor a good conductor (i.e., it does not have relatively low resistivity) as shown in Figure 8-2. All three material groups (conductors, insulators, and semiconductors) find application in cable design as discussed in Section 3.

Insulation Resistance

Insulation resistance (IR) is a measurement of the ohmic resistance for a given configuration and environment, and is not a standardized resistivity test or measurement. For example, the insulation resistance of a cable connected to a solenoid coil by means of a terminal block may be significantly different than that of the same cable and coil connected by means of fully insulated butt splices. Insulation resistance values are expressed in ohms. For insulation resistance measurements of cable during normal plant conditions, the values are typically expressed in megohms or gigaohms, due to the high numerical resistance values of insulating cable materials under normal plant conditions.

The resistance of an insulation is the resistance offered to direct current (dc) from one conductor through the solid dielectric and over its surfaces to the return path. Insulation resistance does not provide a direct indication of the dielectric strength or voltage endurance of an insulator.

Insulation Resistance Temperature Dependence

The insulation resistance value for a given cable in its installed configuration depends on a number of factors. Insulation resistance varies inversely on an exponential basis with temperature [108]:

$$R = Be^{m/T} \qquad \text{Eq. 8-4}$$

where:

R = resistance (or resistivity) of an insulating material or system, ohms
B = proportionality constant, ohms
m = activation constant, K
T = absolute temperature, K

The equation is a simplified form of the Arrhenius equation, relating the activation energy of a chemical reaction to the absolute temperature, and the Boltzmann principle, a general law dealing with the statistical distribution of energy among large numbers of minute particles subject to thermal agitation. The activation constant, in, has a value that is characteristic of a particular energy absorption process. Several such processes may exist within the material, each with a different effective temperature range, so that several values of in would be needed to fully characterize the material. These values of m can be determined experimentally by plotting the natural logarithm of resistance against the reciprocal of the absolute temperature. The desired values of in are obtained from such a plot by measuring the slopes of the straight-line sections of the plot. This follows from Equation 8-4 when the natural logarithm of both sides are taken:

$$\ln R = \ln B + m\ 1/T \qquad \text{Eq. 8-5}$$

The change in resistance (or resistivity) corresponding to a change in absolute temperature from T_1 to T_2 , based on Equation 8-5, and expressed in logarithmic form, ie:

$$\ln(R_2/R_1) = m(1/T_2-1/T_1) = m[(T_2-T_1)/T_1T_2)] \qquad \text{Eq. 8-6}$$

These equations are valid over a temperature range for which material properties affecting resistance do not change.

Typical dielectric (insulator) resistivity change with temperature is represented by Figure 8-3 derived from Figure 4-52 of the Standard Handbook of Electrical Engineers [112] and Figure 8-4 representing IR change during the varying high temperature exposure of Loss of Coolant Accidents (LOCA).

Cable Insulation Resistance Change During LOCA Conditions

Figure 8-4 derived from experimental work by the Rockbestos Company [113] provides a plot of insulation resistance versus temperature for cross-linked polyethylene cable during LOCA conditions for thin wall instrumentation cable. Sandia Laboratories, under NRC Contract, has performed substantial research on cable performance under various nuclear power plant environmental conditions. Figure 8-5 presents the variation in insulation resistance with time and temperature during a simulated LOCA for 30-mil wall EPR cables, which have been heat aged, not heat aged, and irradiated to 200 megarads, from NUREG/CR-3263 [114]. Figure 8-6 presents similar data for both EPR (Bostrad^{7}) and silicone rubber (Bostrad^{7S}) small instrument cables (2 conductor, 16 AWG) provided by Boston Insulated Wire and Cable Company [115] again, indicating an orderly change of IR with variation in temperature during LOCA.

The information presented demonstrates that the insulation resistance of a sound insulated cable is primarily dependent (within one order of magnitude) on the insulation temperature regardless of preconditioning, (i.e., during a qualification program, aging degradation has a second order effect when compared to LOCA temperature effects). Figure 8-5, which is derived from Sandia Laboratories data, indicates that the temperature profile and insulation resistance profiles are nearly mirror images (the delay in insulation resistance change with temperature change being a function of the thermal inertia of the cable system).

Humidity Effect on Surface Resistance

Surface resistance changes widely with humidity changes, with a change of 25 to 90% in relative humidity resulting in a factor change of 10^6 or more [108]. Since total insulation resistance measurements during normal plant conditions may be measuring both volume resistance (cable insulation and jacket materials) as well as surface resistance, they are highly susceptible to conditions of measurement. The total impact of differing temperatures and humidity can result in many orders of magnitude difference between IR measurements for the same insulation in the same installed configuration. The ASTM test methods, which are generated to assure consistent testing, report [108] that IR values, "are usually not reproducible to closer than 10% and often are even more widely divergent (a range of values of 10 to 1 may be obtained under apparently identical conditions)."

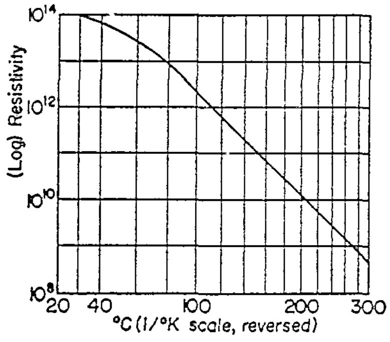


Figure 8-3
Resistivity Vs. Temperature

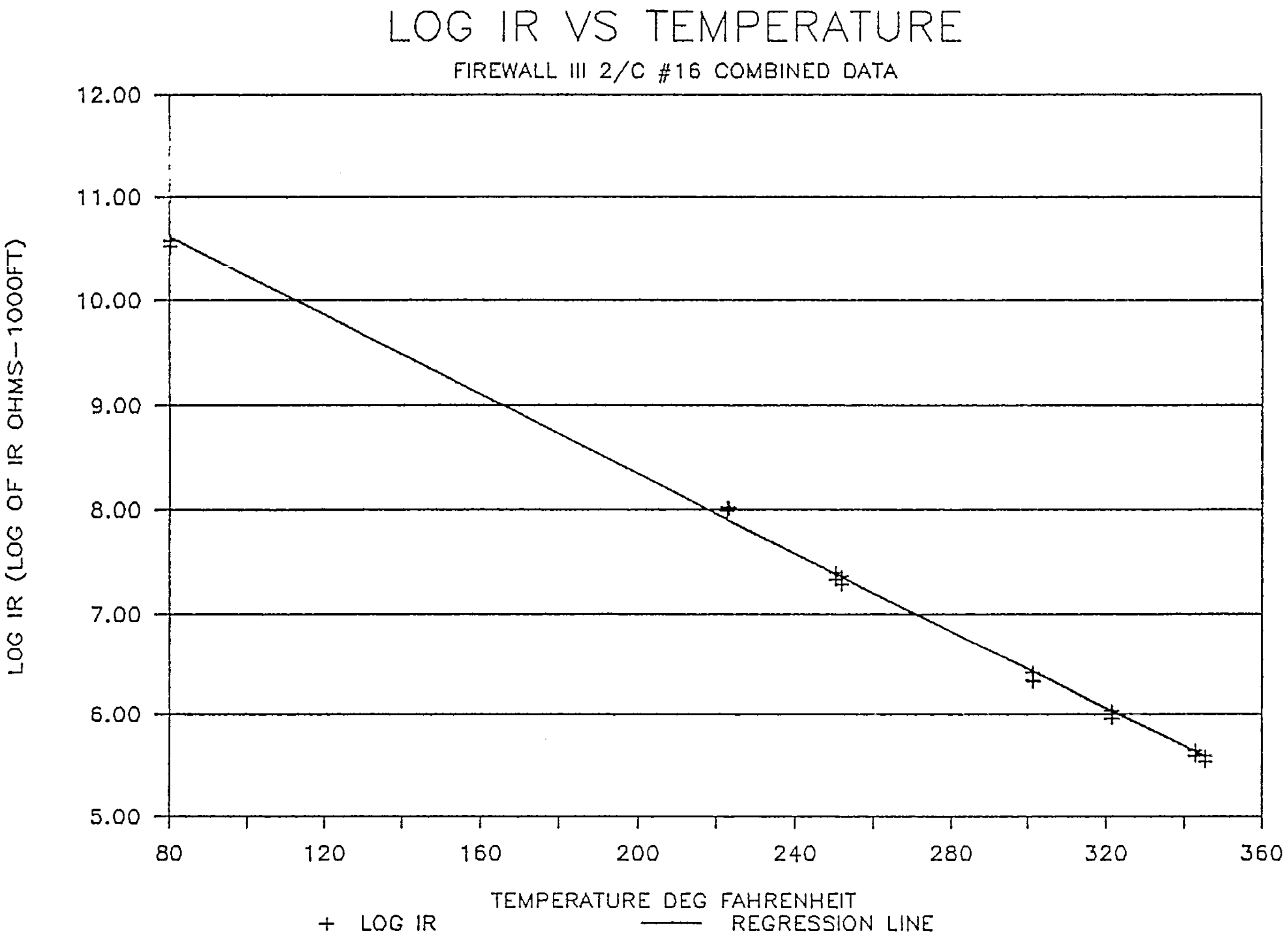


Figure 8-4

Insulation Resistance Vs. Temperature During LOCA

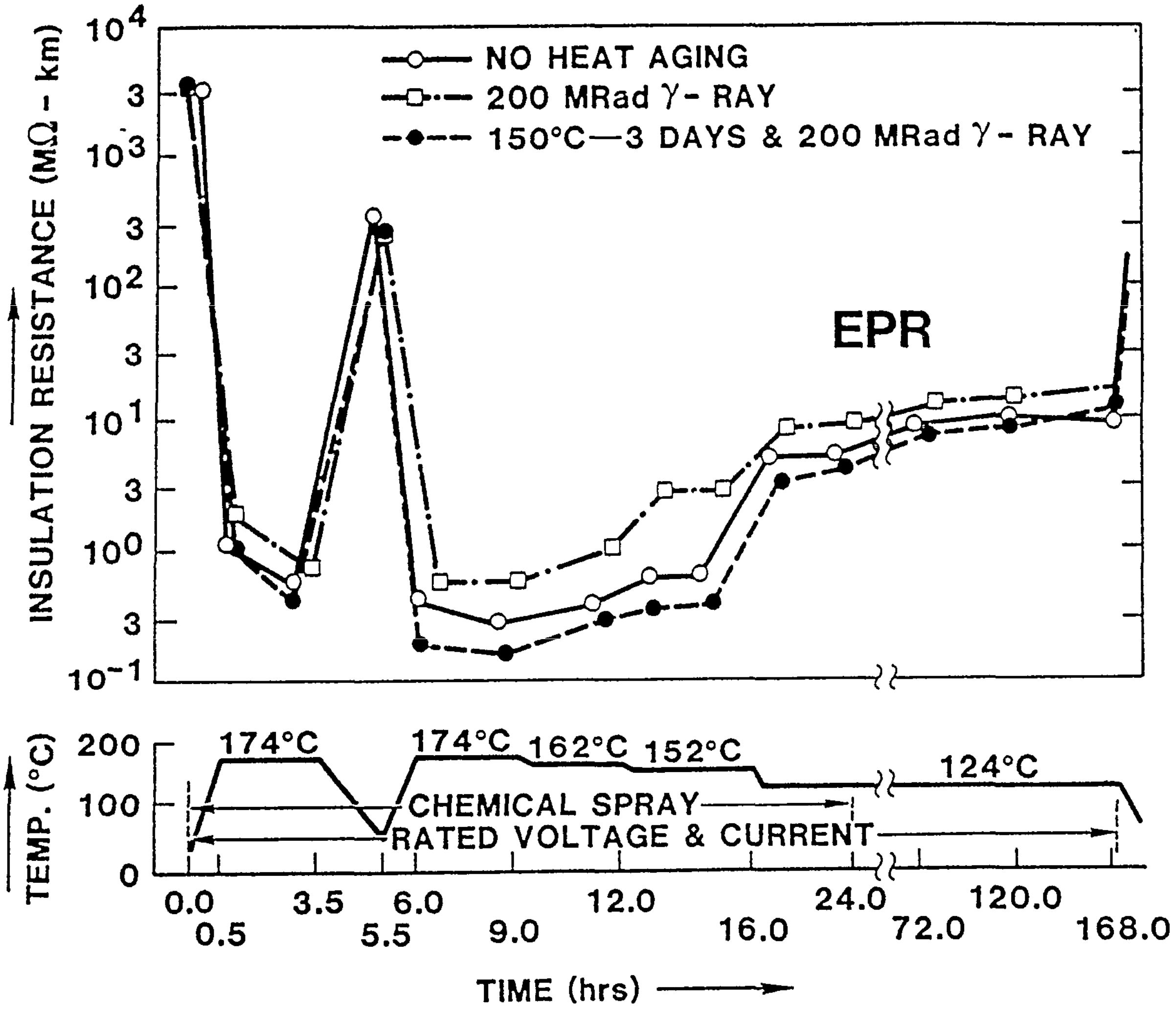


Figure 8-5

EPR Insulation Resistance Values Versus DBA Temperature

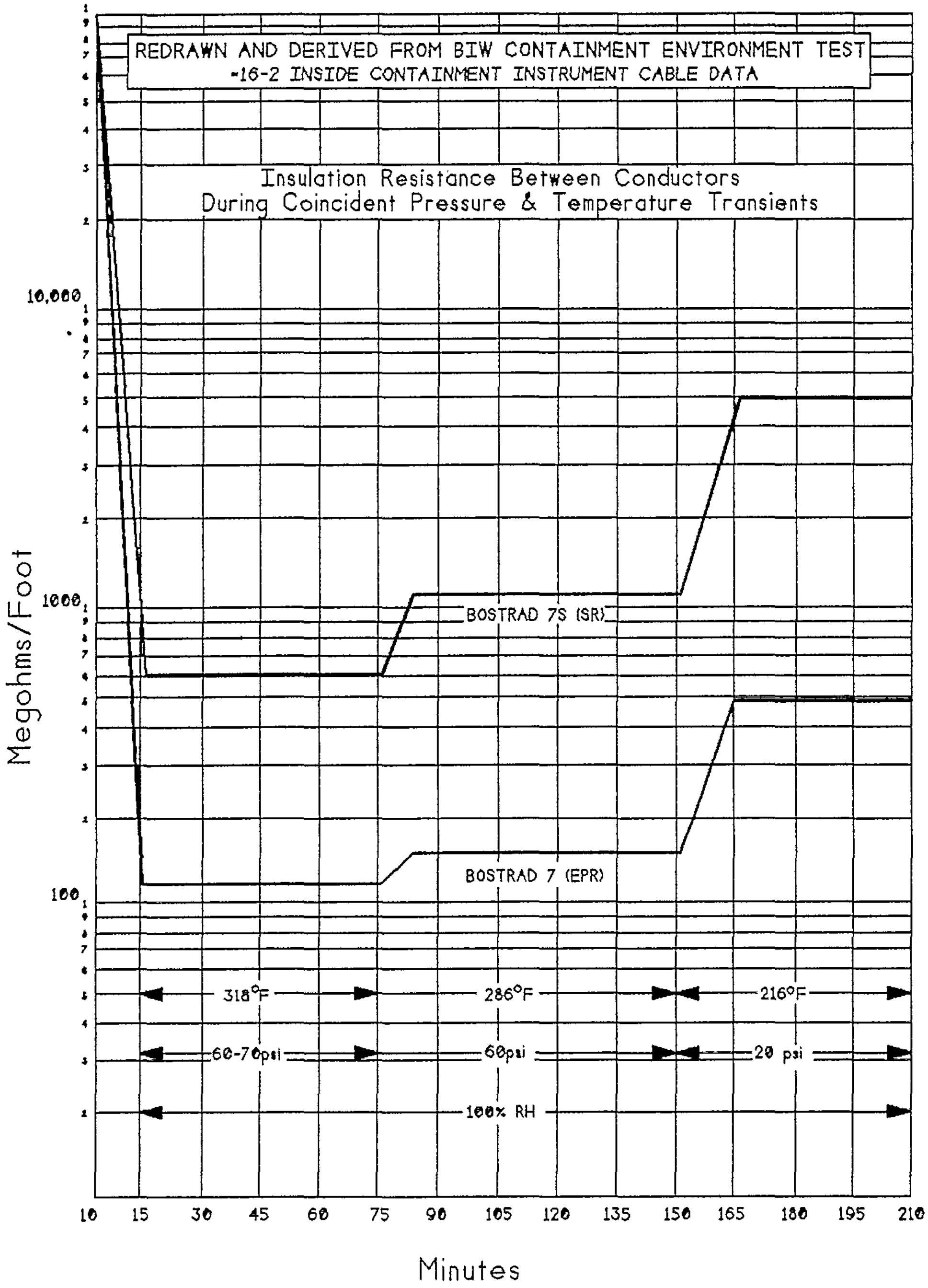


Figure 8-6

Containment Environmental Test IR Values (SR and EPR)

Controlled Factory Insulation Resistance Testing

Insulation resistance of cables is typically measured in the cable factory in a controlled manner in accordance with ASTM D257 [108] at 500 Vdc. These tests are generally performed by immersing the reeled cable in a water bath. Measurement is made between the conductor and water for single conductor cables or between each conductor and all other conductors connected to the shield (when applicable) or to the water electrode. Testing is performed for one minute and corrected to a consistent temperature of 15.6°C (60°F) pursuant to cable industry standards [42-45].

The ICEA cable standards [42-45] provide the following equation for calculating the expected minimum insulation resistance for a typical round cable configuration:

$$R_{ir} = K \log_{10} D/d \qquad \text{Eq. 8-7}$$

where:

R_{ir} = insulation resistance, megohms/1000 ft (305 meters)
K = constant for the grade and type of insulation
D = outer diameter of the insulation
d = inner diameter of the insulation

Values of K based on ICEA minimums [42-45] are as follows:

Table 8-1
Representative ICEA Minimum Values for IR Constants

Insulation	ICEA Minimum
Butyl Rubber	20,000
Silicone Rubber	4,000
PVC (Insulation Grade)	2,000
Cross-Linked Polyethylene (XLPE)	20,000
Cross-Linked Polyethylene (XHHW)	10,000
EPR	20,000

The K factors provided above are minimum values, typical values for actual cables are reported to be 1 to 6 times as great [116].

Field Cable Insulation Testing Under Less Controlled Conditions

As previously described, the industry standard methodology for determining IR measurements in the factory is between conductor and water or conductor and shield. This provides reasonable assurance that IR measurements in the factory or test laboratory are approaching measurement of the true cable insulating material insulation resistance. Field testing of typical unshielded cables for insulation resistance is typically performed between conductor and a ground plane or electrical conducting medium (e.g., metallic raceway such as conduit or grounded enclosure) not immediately surrounding the insulation. A typical configuration of the field condition [116] for an unshielded cable is shown in Figure 8-7.

The measurement of insulation resistance under field conditions effectively results in an insulation resistance measurement actually composed of surface resistance, true insulation resistance, and the insulation resistance of the surrounding air. Furthermore, the cable may be installed in raceway over other cables such that IR measurements are reading a series of insulating materials. In general, when insulation resistance of an individual conductor is taken, it is taken with the remaining conductors in the cable connected to the conduit or tray.

Because of the various influences of installation configuration, the many orders of IR change with testing done at various temperatures and humidity conditions, and the difficulty of screening out various leakage paths during testing, IR measurements for low-voltage cable are of limited value in accurately assessing problems.

Note that measurements of IR after modifications or as a troubleshooting method are not invalidated by its lack of applicability for general condition diagnosis of unshielded power cables. As stated by Stone and Kurtz [107]:

> It is therefore best to use this test as a go/no-go indicator of whether grounding connections have inadvertently not been removed and whether insulation is seriously mechanically damaged or waterlogged. Except under strict controlled circumstances on identical apparatus, the megohm meter test can be extremely misleading when used to judge remaining life or the comparative quality of an insulation system.

P. H. Reynolds [117] indicates that insulation resistance measurements are effective for gross defects only and provide some diagnostic information of the condition of the insulation. His qualitative judgment of the effectiveness of IR measurements under various conditions is presented in Figure 8-8.

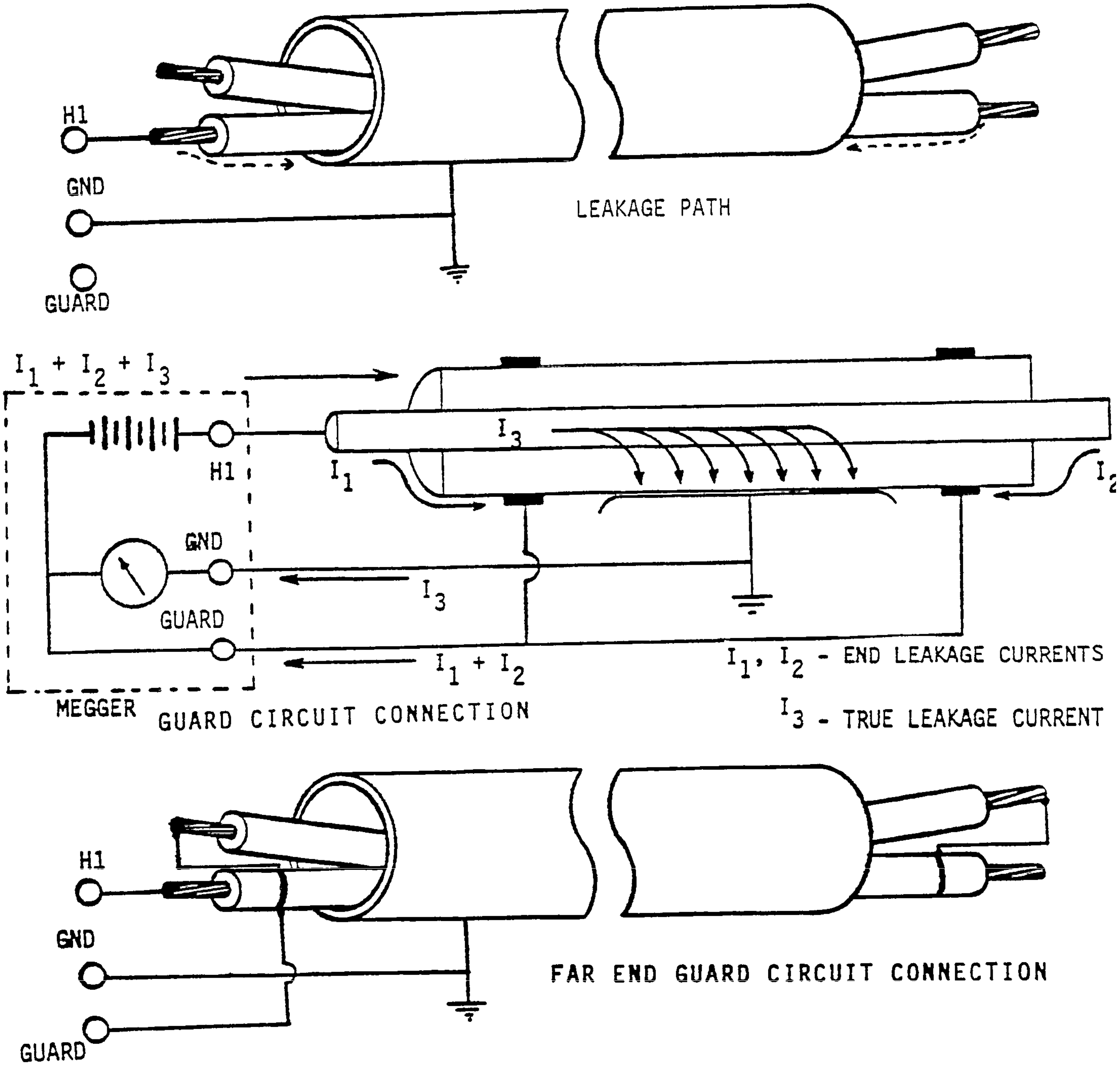
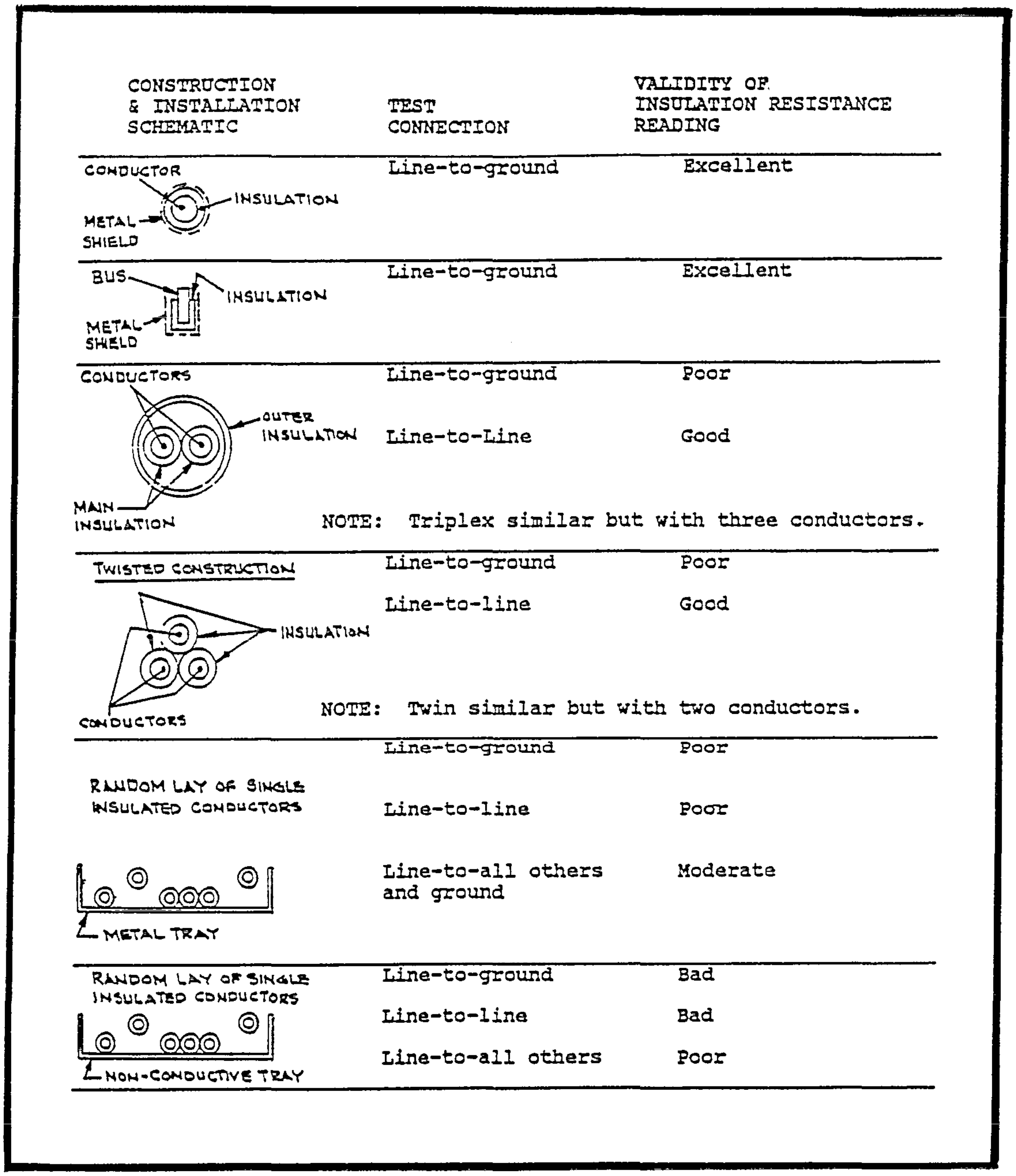


Figure 8-7

Typical Configurations for Field IR Measurement



CONSTRUCTION & INSTALLATION SCHEMATIC	TEST CONNECTION	VALIDITY OF INSULATION RESISTANCE READING
CONDUCTOR INSULATION METAL SHIELD	Line-to-ground	Excellent
BUS INSULATION METAL SHIELD	Line-to-ground	Excellent
CONDUCTORS OUTER INSULATION MAIN INSULATION	Line-to-ground Line-to-Line	Poor Good
	NOTE: Triplex similar but with three conductors.	
TWISTED CONSTRUCTION INSULATION CONDUCTORS	Line-to-ground Line-to-line	Poor Good
	NOTE: Twin similar but with two conductors.	
RANDOM LAY OF SINGLE INSULATED CONDUCTORS METAL TRAY	Line-to-ground Line-to-line Line-to-all others and ground	Poor Poor Moderate
RANDOM LAY OF SINGLE INSULATED CONDUCTORS NON-CONDUCTIVE TRAY	Line-to-ground Line-to-line Line-to-all others	Bad Bad Poor

Figure 8-8

Effectiveness Assessment of Insulation Resistance Measurements

As described in later paragraphs, the typical insulation resistance testing device does not develop sufficiently high voltages to detect even a complete breach of the insulation under normal conditions.

Insulation Resistance and Polarization Index Testing

The Polarization Index (PI) is typically defined as:

$$PI = \frac{\text{IR measurement at 10 minutes}^*}{\text{IR measurement at 1 minute}} \qquad \text{Eq. 8-8}$$

*Some use readings at other intervals (5, 7, 15 minutes) in lieu of the 10-minute reading.

This is a popular test for large motors and very large (typically paper/oil distribution/transmission) cables. To be effective, the time constant of the insulation systems must be relatively long (typically 25 seconds or more). The time constant for an insulation system relates to the period of time required for capacitive and absorptive currents to dissipate. The time constant is composed of both the geometric capacitance of the specimen and the apparent resistance due to the absorption and leakage currents. Refer to Figure 8-9.

The "generally accepted" value of a polarization determination is 1.2 or greater for large motors and generators [118]. Therefore, if a polarization index of 1.2 or greater is measured on a motor it is considered to be in acceptable condition. If a value of 1 is found, severe insulation deterioration will be suspected. Note, that modern insulation treatments may result in very high IR readings (e.g., >10,000 Megohms) such that the IR will not be significantly different at 1 and 10 minute intervals, resulting in a Polarization Index (PI) approaching 1.

However, for components such as low-voltage cables with short time constants, the polarization index determination will be almost always 1. Therefore, measurement of polarization of a low-voltage cable insulation is of little value. Furthermore, Tanaka and Greenwood point out in their text [119] in Section 3.3.1, "Electrical Tests" that "This measure (polarization index)... seems to be ineffective for extruded cable insulation." Nearly all nuclear safety-related cable is extruded (Kapton insulation is a helically applied tape). Therefore, as of this writing, polarization index measurement for low-voltage cables is not a viable troubleshooting technique.

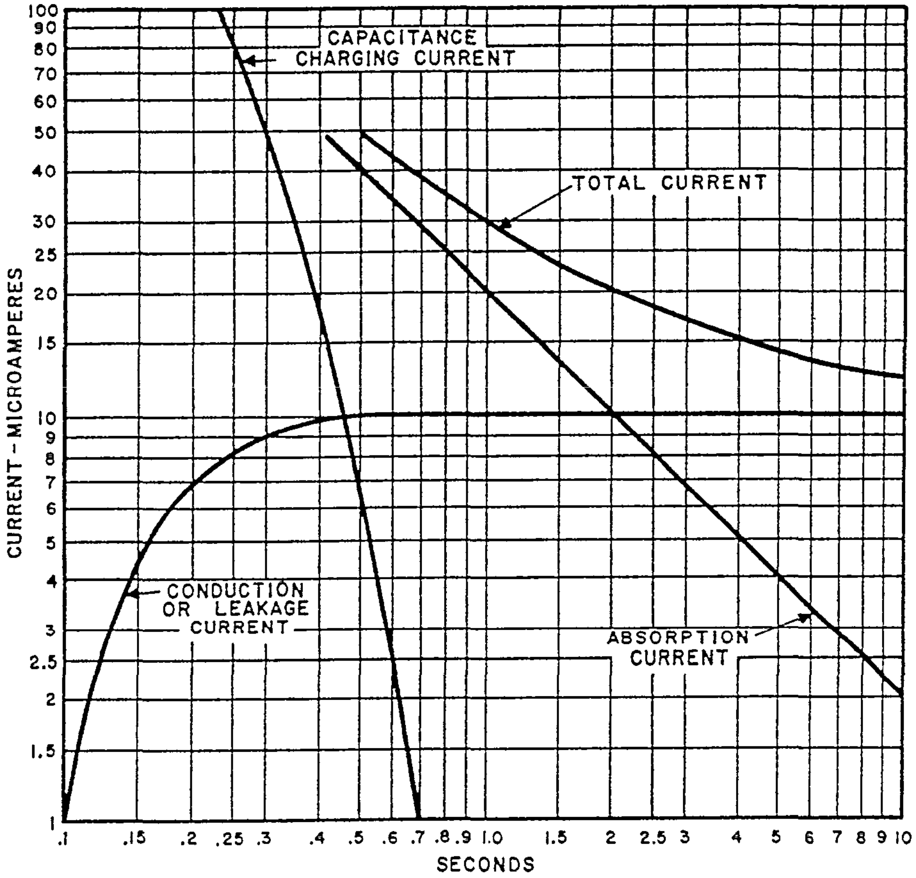


Figure 8-9

Typical Current Values Versus Time Relationship During DC Testing

Industry Standard Acceptance Values for Insulation Resistance for Installed Cables

A new cable tested in the factory to ICEA and ASTM methodology can be expected to have insulation resistance values of 1,000 to 100,000 or more megohms per 1000 feet. These tests are performed between conductor and shield (for shielded cable) or conductor and water tank (with the cable in water) for unshielded cable. After installation, measurements in the field, even for a new cable, can be greater than or less than the factory test values due to the configurational effects of the cable installation.

IEEE Std 422 [16] indicates that the following equation should be used to develop an acceptable minimum insulation resistance for installed power cable:

$$R_{ir} \text{ (in Mohms)} = [\text{rated voltage in (kV)} + 1] \times 1000/\text{length in feet} \qquad \text{Eq. 8-9}$$

The standard's recommended test voltage is 2500 volts for medium-voltage cable and 500 or 1000 volts for low-voltage power cables. As previously described, it is possible for insulation resistance test values derived for unshielded, low-voltage cables with a 500- to 1000-volt insulation resistance tester to exceed the acceptance criteria while the insulation has a complete breach of integrity. Therefore, the use of such acceptance criteria are of limited value.

IEEE Std 422 goes on to state that insulation resistance "should be performed on signal cables if circuit performance is dependent on insulation resistance." The existing standard specific to the nuclear industry, IEEE Std 690 [17], is similar to IEEE Std 422. The acceptance criteria for a typical 5-kV, 600-V, and 300-V rated cable for a typical plant cable run of less than 500 feet, with typical operating voltage to ground, result in the following insulation resistances and leakage currents:

Cable Rating	Length	Min. IR*	Nominal 3Ph Operating Volts System Volt	Nominal 3Ph Operating Volts to Ground	Leakage Current
5000 V	500'	12 Mohms	4160 V	2402 V	0.200 mA
			2400 V	1386 V	0.120 mA
600 V	500'	3.2 Mohms	600 V	346 V	0.110 mA
			480 V	277 V	0.087 mA
			208 V	120 V	0.038 mA
300 V	500'	2.6 Mohms	-	120 V	0.046 mA
			-	50 V	0.019 mA
			-	30 V	0.012 mA

*On basis of Equation 8-9

Dielectric Properties

The dielectric constant of an insulating material is the ratio of the capacitance of a capacitor containing that particular material to the capacitance of the same electrode system with air or vacuum replacing the insulation as the dielectric medium. The dielectric constant is sometimes defined as the property of an insulation that determines the electrostatic energy stored within the solid material. The dielectric constant of solid electrical insulating materials ranges from a low of about 2 or less for materials with lowest electrical loss characteristics, up to 10 or so for materials with highest electrical losses.

Low dielectric constant materials are preferred for insulations to achieve low electrical losses. The dielectric constant for air or vacuum is approximately 1. The dielectric constant of a given insulating material varies as a function of frequency and temperature. The most common method to determine the capacitance of the insulating material is derived from ASTM D150 [120], as illustrated in Figure 8-10. The test measures the capacitance of the insulating material in the form of a disk in a standard electrode fixture and then measures the capacitance of air in the same fixture and calculating the ratio. The same test yields both the capacitance required to calculate the dielectric constant and the dissipation factor, which is defined below.

The dielectric constant is a fundamental property of a material. It defines the ability of a material to store charge, i.e., act as a capacitor, when used to separate regions of different electrical potential, which inherently is the case with all electrical insulators. The mechanism of charge storage involves the alignment of dipoles within the insulation in the direction of the applied electric field. A dipole is a molecule or group of molecules that has a different electrical charge at each end. Such dipoles come from a variety of sources including polar groups in or attached to polymer chains, dielectric inhomogeneities due to crystallinity and unsymmetrical molecules, polar additives, pigments, plasticities, lubricants, and fillers.

In an ac circuit, the insulation dipoles oscillate to the extent that they can as the electric field polarity changes during each cycle. As a result of this oscillation, an irreversible power loss (dielectric relaxation) occurs which is dissipated as heat in the material. The current-voltage relationships in a typical test circuit are shown in the vector diagram in Figure 8-10. The complex resultant current, I, lags the capacitive current, I_C, by angle delta, called the loss angle, due to the relaxation current, I_R. The tangent of the loss angle is the dissipation factor and is a measure of the power dissipated as heat.

Total power loss in an ac circuit is represented by the following equation:

$$P = DC \times DF \times E^2 \times f \times V \times 5.556 \times 10^{-13} \qquad \text{Eq. 8-10}$$

where: P = power loss, w

DC = dielectric constant
DF = dissipation factor
E = voltage gradient, V/cm
f = frequency, Hz
V = insulation volume, cc

The material property governing power loss is the product of dielectric constant and dissipation factor. This product is the dielectric loss index or loss factor.

At 60 Hz, the voltages, cable sizes, and relatively short cable lengths in use at nuclear power plants cause the electrical losses related to the dielectric constant to be considered insignificant for modern insulators. The important aspect of dielectric constant is the role it plays in distorting the electrical stresses in a system of different or dissimilar insulation. This is discussed later in this section under AC Dielectric Circuits.

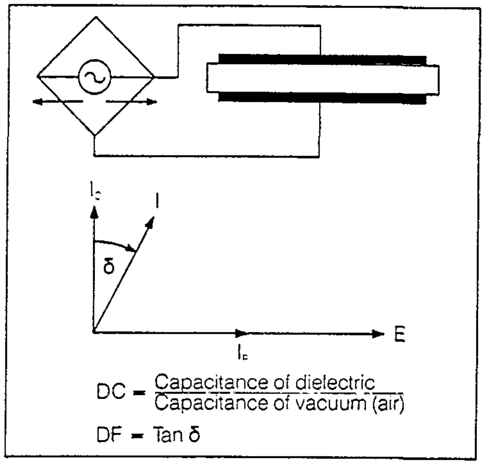


Figure 8-10

Electrode Configuration and Test Circuit for Measurement of Dielectric Constant and Dissipation Factor; Vector Diagram Showing Current-Voltage Relationships in a Typical Test Circuit

Dielectric Breakdown

Dielectric breakdown may result from an electron avalanching in the dielectric. Each avalanche results from the acceleration of a few electrons by the electric field, which gives rise to the generation of secondary electrons from impact of the first set of electrons with atoms or molecules. Each of these produces other electrons by the same process. A few free electrons are believed to be present in all materials. Although dielectric strength appears to be an intrinsic property of a dielectric, macroscopic imperfections and the presence of low-resistance contaminants in all materials contribute to failure at lower field intensities than expected [121]. In fact, electrical stress failure is typically dominated by imperfections. However, the discussion of Paschen's Law later in this section indicates that low-voltage cables may have no practical electrical stress failure mechanism due to the benign electrical stresses imposed on these cables.

U.S. [122] and international standards [123] establish limits on allowed imperfections in extruded insulations for cables rated 5 kV or greater as imperfections are critical to dielectric performance [119].

Dielectric Strength

The dielectric strength is the voltage an insulating material can withstand before dielectric breakdown occurs. Dielectric strength is measured through the thickness of the material and normally is expressed in voltage gradient terms, such as volts per mil.

In testing for dielectric strength, two methods of applying the voltage are used: short-time and step-by-step. The short-time test is performed by increasing the voltage from zero at a predetermined rate (100 to 3,000 V/sec) until breakdown occurs. The step-by-step test differs in that an initial voltage of 50% of the short-time voltage is applied to the material, and then the voltage is increased in equal increments and held for periods of time set by the investigator.

Dielectric strength is influenced by specimen size, temperature, humidity, voids or foreign materials in the dielectric, electrode configuration, frequency, and test specimen geometry. Because of this, it often is difficult to compare breakdown data from different sources unless all test conditions are known. The method of voltage application, the temperature, and any preconditioning of the test specimen must be known. The volts per mil at which breakdown occurs varies with thickness of tests pieces. Normally, breakdown occurs at a much higher volts-per-mil values in very thin test pieces (a few mils thick) than in thicker sections (0.125 inch thick for example). See Figure 8-11 from Harper [111].

As stated in Appendix XI, "Significance of the Direct Voltage Dielectric Strength Test" of ASTM D149 [124] and ASTM D3755 [125], "Experience has shown...the dielectric strength varies inversely as a fractional power of the specimen thickness and there is a substantial amount of evidence that for relatively homogeneous solids, the dielectric strength varies approximately as the reciprocal of the square root of the thickness."

It is necessary to understand this phenomenon such that breakdown values for thin materials are not linearly extrapolated to determine expected breakdown values for thick materials.

In testing of shaved insulation wall silicone rubber cables from three manufacturers reported by TVA [126] subsequent to a LOCA simulation, cable walls with minimum dimensions of 4 to 11 mils had a minimum dielectric strength from 2000 to greater than 10,000 Vdc/mil. New cable with wall dimensions of 45 mils from the three vendors had dielectric strengths ranging from 667 to 2222 Vdc/mil. The greater dielectric strength even after LOCA simulation is in agreement with the concept that there is an increase in strength per mil with a decreased insulation wall thickness. It is not expected that LOCA simulation is actually improving the electrical properties of the material.

For operating equipment, the terms "voltage breakdown" and "voltage endurance" are used. Voltage breakdown refers to the voltage at which electrical breakdown of the components materials occurs. Voltage endurance refers to the time to voltage breakdown when a material is exposed to an elevated voltage that would not cause immediate breakdown.

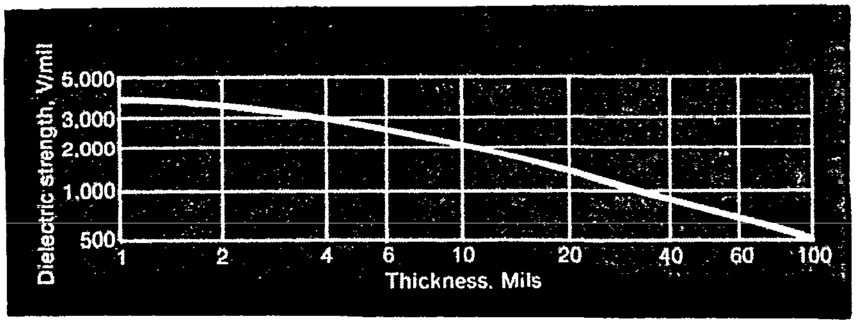


Figure 8-11

Dielectric Strength Versus Thickness [111]

<u>Voltage Endurance Time Curves and Ratings of Insulation</u>

The most useful voltage rating of an insulation system is the voltage at which the life approaches infinity on a voltage endurance or voltage time curve. In this context, only electrically induced damage is being considered, not such conditions as mechanical damage that could lead to more rapid deterioration. Representative work from Ralph Lee [103], Graham Lee Moses [127], and Perkins [l28] is shown in Figures 8-12(a), 8-12(b), and 8-12(c). These curves illustrate the exponential relationship of life versus voltage for voltages in excess of the corona (partial discharge) inception level. As pointed out by Perkins the true voltage rating is, "the voltage at which the curve becomes asymptotic with the time axis." For the maximum 600-volt limit of a low-voltage system, which operates at 346 volts to ground or less [(600-volt nominal three-phase system)/($3^{1/2}$)] and less than an average of 12 volts/mil stress (< 11.6 v/mil for a 30-mil wall insulation), the voltage life is expected to approach infinity.

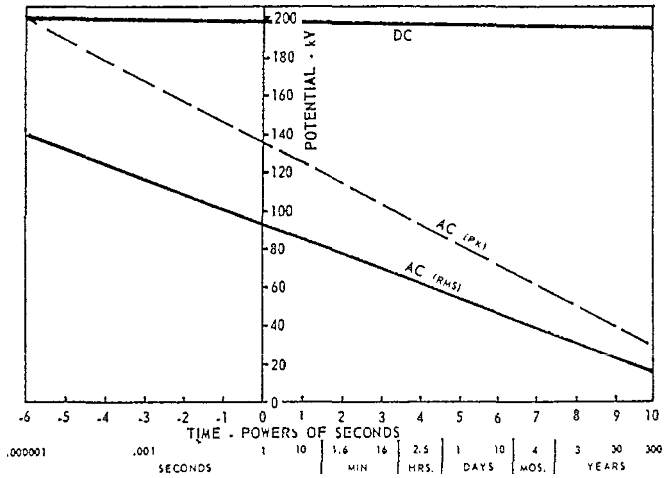


Figure 8-12(a)

Apical Voltage Endurance Curve for 15-kV Insulation from Lee and Moses

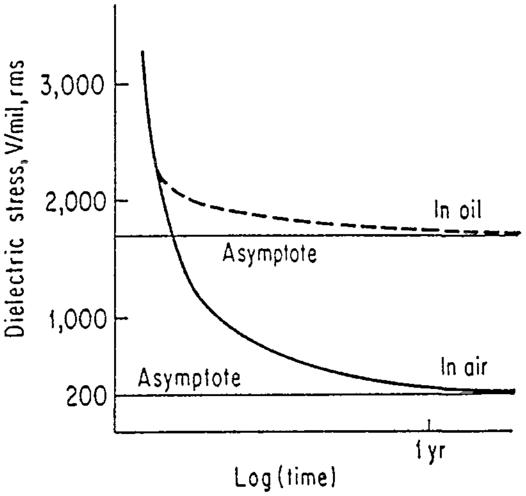


Figure 8-12(b)

Typical Voltage Time Curve from Perkins

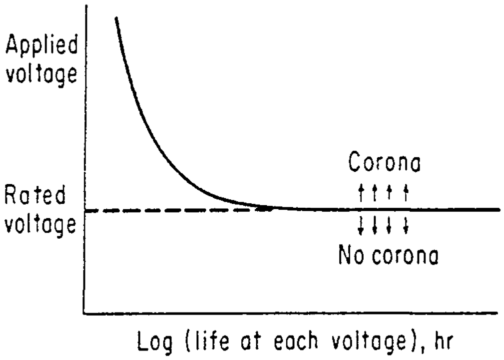


Figure 8-12(c)

Voltage Endurance Relationship to Corona

AC Dielectric Circuit

In coaxial configurations, the electrical stress in an insulation system does not change linearly across the material. To determine the electric stress in a cable which has a coaxial geometry with inner and outer radii R_1 and R_2 at any distance from the axis as defined by "r" (in centimeters) for a given applied voltage V may be determined by the following equation [129]:

$$E = V/[r\ (\ln R_2/R_1)] \qquad \text{V/cm} \qquad \text{Eq. 8-11}$$

A more convenient-to-use form of this equation is as follows:

$$S = E/X\ \text{In}\ (R/r) \qquad \text{Eq. 8-12}$$

where:

S = electrical stress, V/mil
X = distance from center of the conductor to point of stress calculation, mils
r = radius of center conductor, mils
R = radius of outer surface of the insulation at the inner surface of the outer conductor, mils
E = voltage between inner conductor and outer conductor

Two or more insulations in series between a conductor and ground result in the stress in each material (volts per mil) being inversely proportional to the dielectric constant of each insulation [130]. With a solid insulation and air in series, at the solid/air interface, the stress is always higher in the air because air has the lower of the dielectric constants. First, a one-dimension geometry will be considered. As illustrated in Figure 8-13 from work by Perkins [128], the insulations have dielectric constants K_1 and K_2, and air has a dielectric constant of 1. Thicknesses are t_1 and t_2 for the solid insulation and t for the air gap. V_a is the voltage across the air gap.

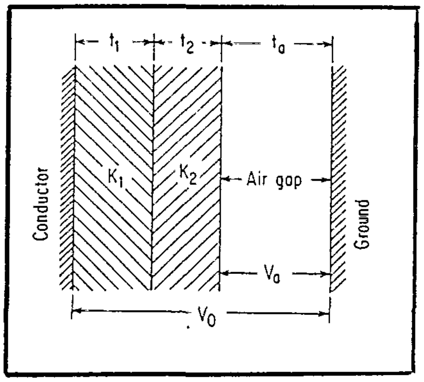


Figure 8-13

Series Dielectrics - Parallel Electrodes, ac

Effectively there are three capacitors in series and the voltage divides inversely with the capacitances .

If V_1 and V_2 are voltages across insulations 1 and 2, then:

$$V_1/(t_1/K_1) = V_2/(t_2/K_2) = V_a/(t_a/1) \qquad \text{Eq. 8-13}$$

$$V_o = V_a/(t_a/1)[(t_a/1)+(t_1/K_1)+(t_2/K_2)] \qquad \text{Eq. 8-14}$$

This results in:

$$\frac{\text{Stress in insulation 2}}{\text{Stress in insulation 1}} = \frac{(V_2/t_2)}{(V_1/t_1)} = K_1/K_2 \qquad \text{Eq. 8-15}$$

The term t/K can be considered as "electrical equivalent thickness," meaning that for stress distribution a solid is less effective than a gas.

Figure 8-14 represents the more complex coaxial condition in which electrical stress does not vary linearly in the insulations. When there is an air layer between the outside of the insulation and the inside of the outer conductor (e.g., a conduit), the voltage across each material and the air are series capacitors; and the voltage across insulation 1 is given by:

$$V_1 = \ln[(r_2/r_1)/K_1] \times V_0/[(\ln(r_2/r_1)/K_1)+(\ln(r_3/r_2)/K_2)+(\ln(r_4/r_3)/1)]$$

Eq. 8-16

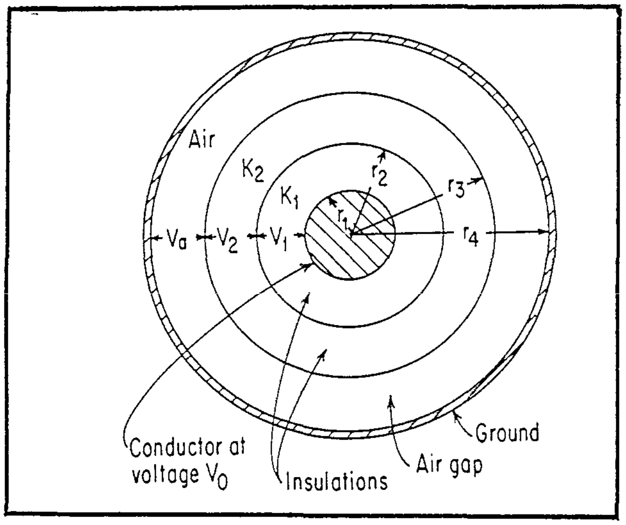


Figure 8-14
Cable (Coaxial Structure)

Similarly, the voltage across the air gap is

$$V_a = \ln[(r_4/r_2)/1] \text{ x } V_o/[(\ln(r_2/r_1)/K_1)+(\ln(r_3/r_2)/K_2)+(\ln(r_4/r_3)/1)]$$

Eq. 8-17

The stress is not constant across insulation 1. At the inner surface of insulation 1, the stress is:

$$\text{Stress, volts/unit thickness} = V_1/[(r_1 \ln (r_2/r_1)]$$ Eq. 8-18

while the stress just within the outer surface of insulation is:

$$\text{Stress, volts/unit thickness} = V_1/[(r_2 \ln (r_2/r_1)]$$ Eq. 8-19

At the same time, the stress in insulation 2 just across the interface from insulation 1 is

$$\text{Stress, volts/unit thickness} = K_1/K_2 \text{ x } V_1/[(r_2 \ln (r_2/r_1)]$$ Eq. 8-20

In this condition, the bulk of the stress will be across the air gap, and a smaller portion of the voltage drop will be across the insulations.

<u>DC Dielectric Circuit</u>

A one-dimensional representation of a set of dielectrics is shown in Figure 8-15 where the t's are the layer thickness, the p's are the volume resistivities, and the V's are the voltages. Under dc stress conditions, the controlling property for voltage distribution is related to resistivity and not dielectric constant. The voltage across insulation 1 is given by:

$$V_1 = V_o[(p_1t_1)/(p_1t_1+p_2t_2+p_3t_3)]$$ Eq. 8-21

and the stress across this layer is

$$\text{Stress, volts/unit thickness} = V_1/t_1 = V_o[(p_1)/(p_1t_1+p_2t_2+p_3t_3)]$$ Eq. 8-22

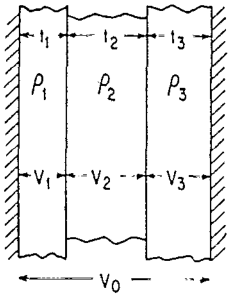


Figure 8-15

Series Dielectrics, Parallel Electrodes

If one layer is air, the resistivity of air, when it is not over-stressed, is very high. This resistivity is high compared with the best solid insulations, and thus essentially all the voltage can be across the air gap. If the air gap is overstressed (i.e., over about 75 V/mil for a large gap at atmospheric pressure), ionization of the air will occur. This is a significant cause of concern in testing of unshielded cables under high voltage DC without an intimate ground plane. As the applied voltage is raised beyond the ionization level of the air, the voltage drop across the air gap will tend to remain approximately at the level at which ionization began and the increase in voltage across the system will appear across the solid insulation.

For insulating materials, p decreases with an increase in temperature (temperature coefficient of resistance). Resistivity also varies with voltage stress (volts per distance) and, in general, drops as stress rises (voltage coefficient).

Data derived from Durham, Boyer, and Beer [131] in Figure 8-17 illustrates the exponential increase in leakage current under do testing with an increase in temperature. Consequently, dc testing when performed must be at known and constant temperatures to have valid results. The increasing leakage current with temperature is simply the equivalent of the inverse plot of insulation resistance versus temperature previously discussed in the paragraphs dealing with resistivity and insulation resistance.

For the coaxial or cable type system shown in Figure 8-16 under dc stress, the voltages are controlled by the series resistances, which depend now not only on resistivity, p, but also on the voltage across the insulation. V_1 across insulation 1 is given by:

$$V_1 = p_1 \ln(r_2/r_1) \text{ x } V_o/[p_1(\ln(r_2/r_1)+(p_2 \ln(r_3/r_2)+(p_3 \ln(r_4/r_3)] \qquad \text{Eq. 8-23}$$

The average stress across insulation 1 is:

$$\text{Average stress, volts/unit thickness} = V_1/(r_2-r_1) \qquad \text{Eq. 8-24}$$

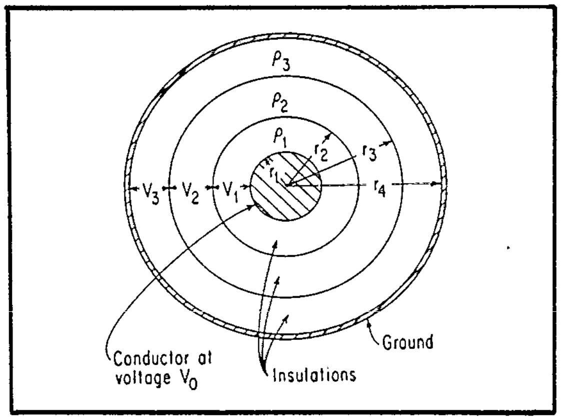


Figure 8-16

Coaxial Structure, DC Dielectric Circuit

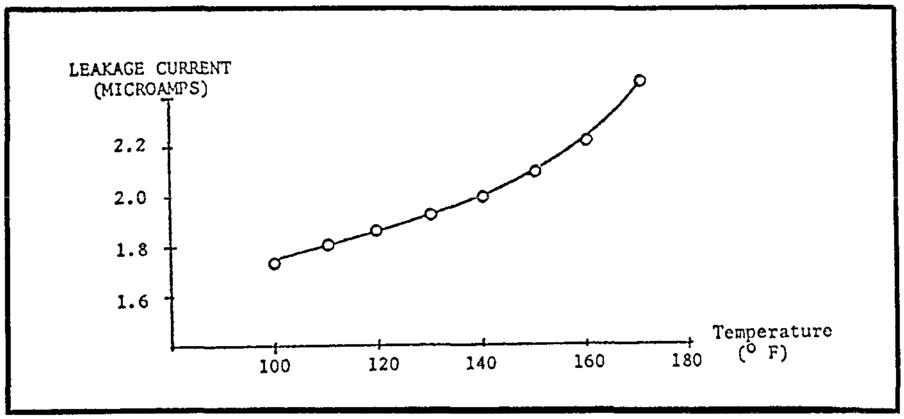


Figure 8-17
DC Test Leakage Current Versus Cable Temperature

The stress at the conductor is given by

$$\text{Stress, volts/unit thickness} = V_1[\ln (r_2/r_1)] \times 1/r_1 \qquad \text{Eq. 8-25}$$

The stress at the interface between insulation 1 and 2 changes as one goes from insulation 1 to insulation 2. In insulation 1, the stress is

$$\text{Stress, volts/unit thickness} = V_1[\ln (r_2/r_1)] \times 1/r_2 \qquad \text{Eq. 8-26}$$

whereas in insulation 2, the stress is

$$\text{Stress, volts/unit distance} = V_2[\ln (r_3/r_2)] \times 1/r_2 \qquad \text{Eq. 8-27}$$

$$= V_1[\ln(r_2/r_1)] \times (1/r_2) \times [(\ln(r_3/r_2)/(\ln r_2/r_1)) \times (p_2/p_1)]$$

These equations show that there are sudden changes in electrical stress at the interfaces between insulators and that the stress in each insulator can be quite different if the volume resistivities are significantly different.

Paschen's Law and Its Importance to Low- and High-Voltage Testing

The technical literature [128, 132, 133] describes Paschen's work as establishing two facts.

1. The breakdown voltage of a gas in a uniform electric field varies with the product of the pressure and the distance (spacing).

2. For each gas there is a minimum value of breakdown voltage (the Paschen minimum) below which no combination of pressures or spacing will result in breakdown. This value is reported [128] to be approximately 240 V rms or 350 Vdc with the spacing for minimum breakdown about 0.2a to 0.3 mils.

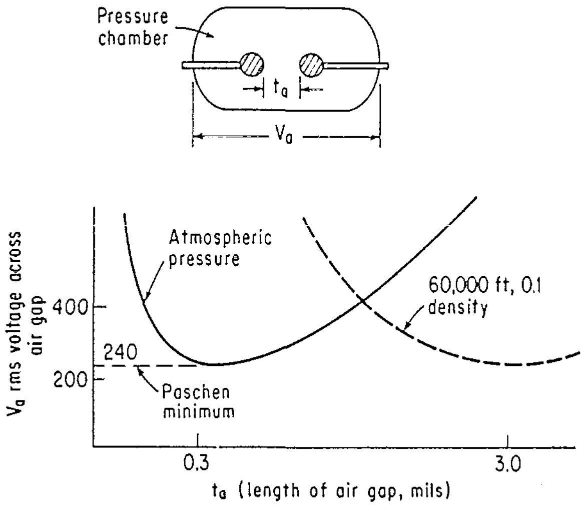
Table 8-2 and Figure 8-18 were prepared by Perkins [128].

Table 8-2

Paschen Curve-Data Points at Atmospheric Pressure*

Spacing t_a mils	**Breakdown Voltage, rms**
0.30	250
0.50	270
0.75	300
1.00	330
1.50	390
2.00	445
3.00	555
5.00	700
7.50	1,000
10.00	1,175
15.00	1,550
20.00	1,900
30.00	2,575
50.00	3,800
75.00	5,350
100.00	7,000
150.00	10,000

*Data from J. R. Perkins [128]



Paschen curve—for air (not to scale).

Figure 8-18
Paschen's Curve for Air (from Perkins)

The data reported by Perkins [128] was compared to work reported by the French [132] and Dakin [133] that summarized international data [134, 135]. The data plots of the Paschen curves are provided as Figures 8-19 and 8-20.

The Paschen minimums are very significant as they demonstrate that even if an insulation is breached as long as a minimum gap is maintained at the operating voltages of low-voltage cable (over all feasible operating pressure and temperature ranges), gaseous ionizations of air will probably not occur and the gap will not breakdown. This is especially true for low-voltage, nuclear safety-related cable in containment whose voltage to ground (for a maximum nominal three-phase system voltage of 600 V) would be 346 V [600 V/($3^{1/2}$)]. Greater than 90% of all nuclear plants use 480 V three-phase nominal systems with stress in volts to ground of only 277 V [480 V/($3^{1/2}$)]. Breakdown will not occur for any insulation wall, whether it is breached or not, with a thickness above approximately 1.5 mils from data in Table 8-2 assuming dry air conditions.

Experimental work reported by Durham, Boyer, and Beer [131] described an investigation of field testing of cable to correlate the arc over voltage versus distance. Experimental results using standard insulation resistance and dc test equipment are shown in Figure 8-21. The cable was tested as described below:

> A single conductor of the cable had a 3/16 inch hole drilled through the insulation material to the surface of the wire. A curved grounded metal plate was then positioned over the hole and clamped to the insulating material. DC voltage was applied and Increased until the sparkover level between the conductor and ground plate was reached.

The recorded values are plotted in Figure 8-21. Both plots of voltage to arcing versus distance are linear functions and roughly parallel. The arcing voltage across the hole in the insulation is substantially lower than in free air. The reasons for this difference are summarized by the experimenters as probably due to the limited air space which ionizes more quickly, or a conductive path formed along an insulation surface. This data indicates that if a crack or void is directly adjacent to a return path (conduit), a somewhat lower breakdown voltage would occur in the air gap than indicated by Table 8-2. However, the breakdown voltages are still well above the 346 V maximum voltage expected on 600 V rated cable.

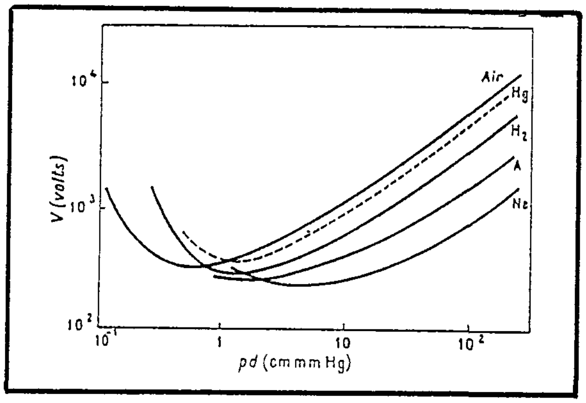


Figure 8-19

Paschen Curves (A. von Engel)

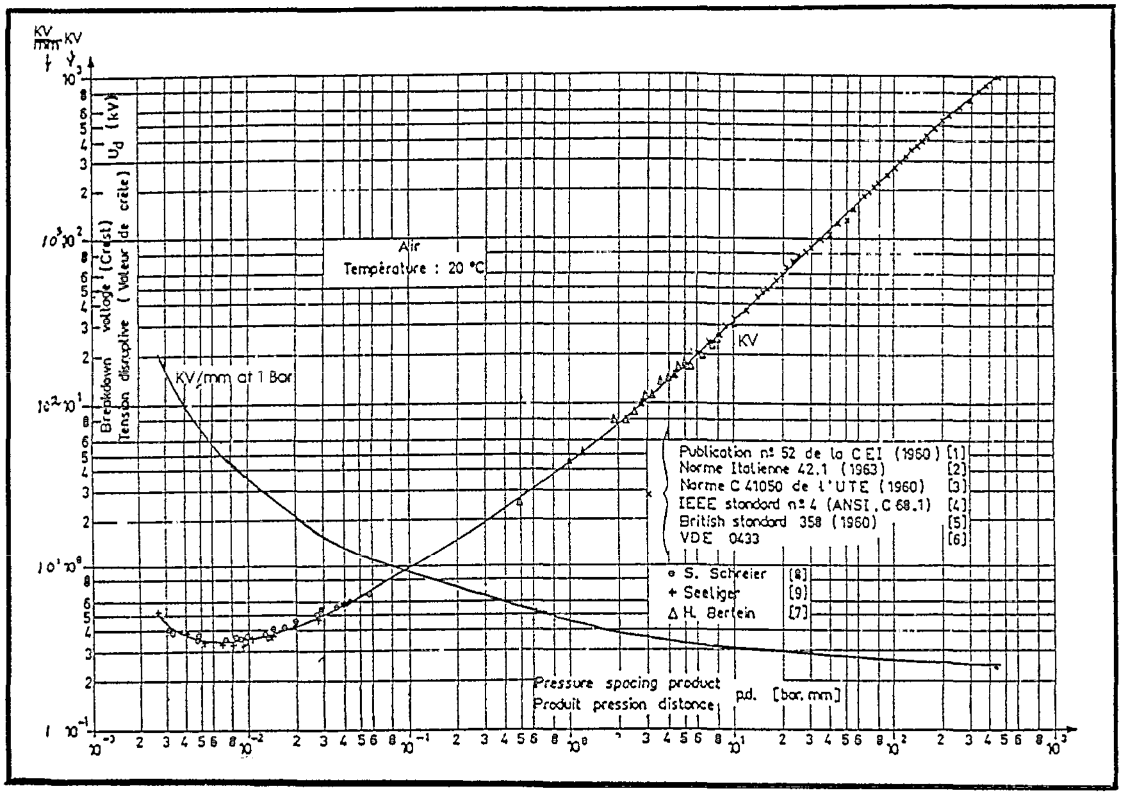


Figure 8-20

Paschen's Curve of Gases Reported by Dakin

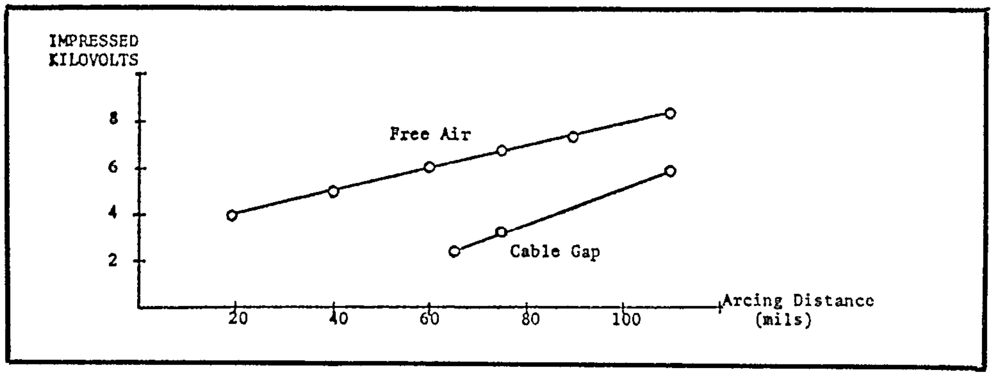


Figure 8-21

Arcing Versus Distance Under DC Testing

Gaseous Ionization Potential for High-Voltage Testing of Unshielded Cables

Figure 8-22 illustrates a typical low-voltage unshielded, insulated conductor that has varying spacings between the insulation surface and the ground plane. The cable is under high-voltage test conditions. The ground plane in this case would be a typical metallic conduit, cable tray, or wireway. For firm contact with ground, all the voltage appears across the solid insulation and none across the air, and hence no ionization occurs. At a location where the cable is far from the ground plane, essentially all the voltage drop is across the air gap and very little occurs in the insulation. The stress in the air, because of the great distance, is very low and no ionization occurs. However, under the high-voltage test condition, there can be gaps between the insulation and ground plan of the proper length to allow ionization of the air in the gap. Figure 8-23 shows that ionization may also occur radially a short distance from the point of contact with the conduit. There is concern that corona attack may damage cable surfaces and that the discharge currents may cause localized heating that could increase the discharge and eventually lead to insulation breakdown.

Figure 8-24 from Perkins [128] provides a method to determine corona initiation or ionization starting voltage for unshielded cable. It is reported to be accurate within 5% of experimental data. The equivalent electrical thickness of each insulation is the actual thickness in mils divided by the relative dielectric constant of that insulation. The total equivalent electrical thickness is the sum of the values for the number of insulations.

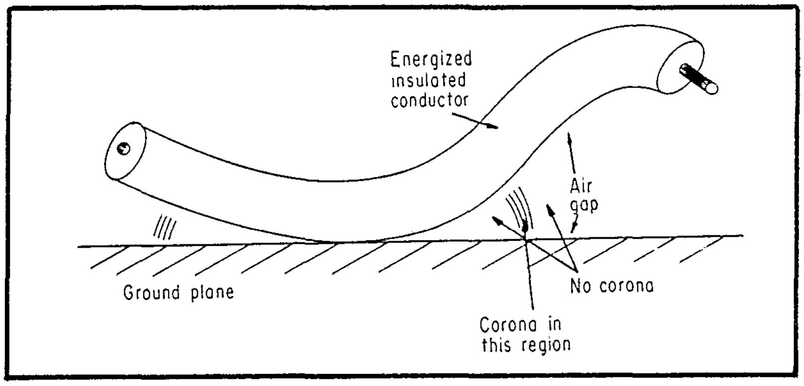


Figure 8-22

Corona Location-Round Wire Adjacent to Ground

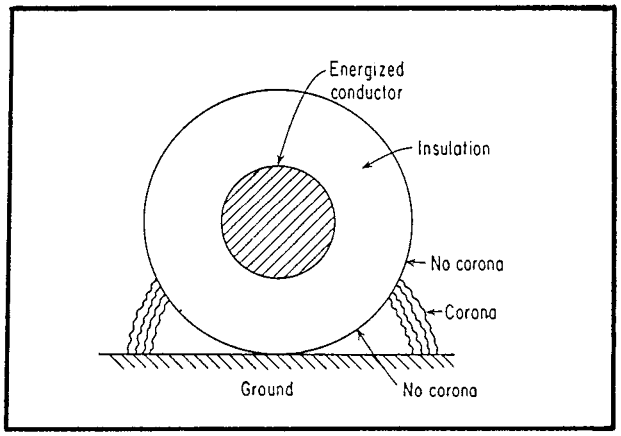


Figure 8-23

Corona Location, Round Wire in Contact with Ground Plane

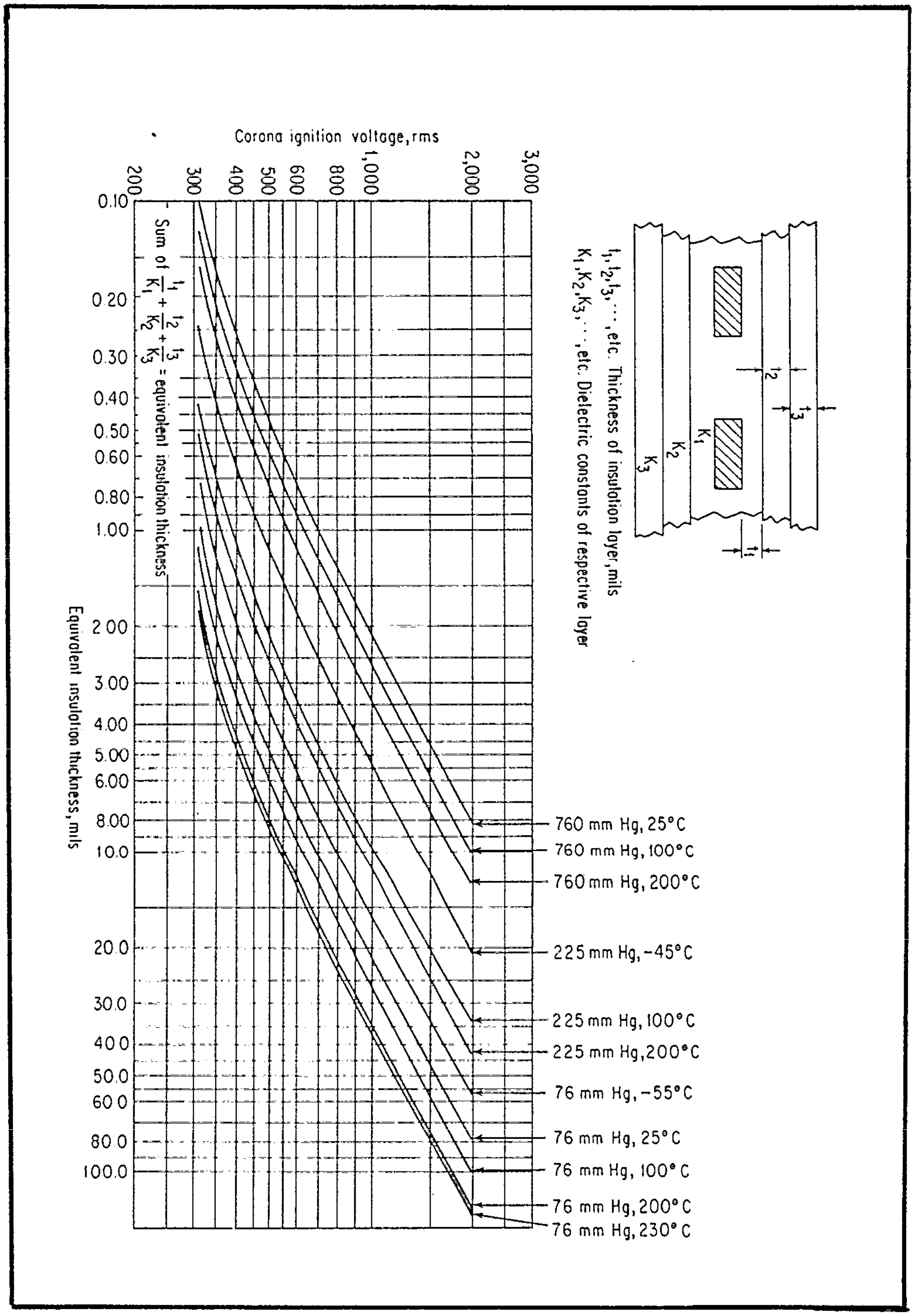


Figure 8-24

Corona-Starting Voltage, rms, Versus Equivalent Electrical Thickness of Insulation System

CABLE TESTING OR CABLE CONDITION MONITORING TECHNIQUES

Section 6 discusses the cable qualification aspects indicating the general conservatism believed to exist in qualification. Section 7 indicated the overall good performance record of cable during normal operation. However, both aspects of sound cable performance are based on cable installations that are not suspected of being damaged or having suffered age-related degradation. When suspect installation exists or an assessment of cable condition is required, an in-situ non-destructive cable testing or cable monitoring technique is desirable. A universally acceptable simple in-situ cable test or cable condition monitoring method that directly indicates the cable condition or its capability to withstand accident conditions does not exist. Cable testing or cable condition monitoring techniques currently under development must be perfected and field evaluated before they can be useful.

In earlier sections of this report, much data is presented which indicates that no significant cable operability concern exists for the general cable population. However, a simple and cost-effective technique to validate or verify the acceptable status of cable would be of value to the industry. Although much of the data presented in this report can be of use to provide a foundation for cable life extension for license renewal, an overall assessment tool based on testing and condition monitoring may well be useful. And, for suspect installations which may exist or be discovered, cable testing and monitoring may well be prudent in lieu of replacing the suspect installation.

The terminology associated with cable testing or cable conditioning monitoring techniques continues to evolve. Two main concepts related to cable condition have been developed [136]: bulk property changes and point physical defects. Bulk properties relate to mechanical (e.g., elongation, modulus, and tensile strength), electrical (e.g., dielectric strength, resistance, and capacitance), or physical (e.g., density) attributes of the cable insulation and jacket. Some of the changes in bulk properties can be correlated to aging of the cable materials. If the aging of the material adversely affects cable function under normal or accident conditions, the ability to monitor the bulk property changes would be desirable.

Point physical defects are defects or damage that occur at a specific location on the cable and represent specific locations where cable integrity may be suspect. Some point defects may occur during manufacturing others may be produced by damage from installation or handling; still others may occur as the result of degradation of bulk properties (e.g., cracks in embrittled insulation).

Condition monitoring techniques measure either bulk properties or detect point defects. The techniques are "global" if they are applied to an entire circuit and "local" if they examine a portion (small or large) of a cable run. Note that both a global technique and a local technique can measure bulk properties and/or detect point defects. The techniques can also be "remote" (e.g., require only access to one or both ends of a run) or "hands-on" (require access to the portion under examination). A test can be an "acceptance" test (applied once with a pass/fail, go/no-go criterion) or a "trending" test (applied successively over time to track bulk properties or overall condition, usually without pass/fail criteria). Techniques can be applied either in-situ or in a laboratory. In-situ tests must be non-destructive. Laboratory tests can be destructive (performed on "sacrificial" specimens of cable removed from a plant circuit) or non-destructive (performed on tiny samples of insulation material removed non-destructively from a plant cable).

To illustrate use of this terminology, the following examples are offered:

Hi-pot:	A global, remote, in-situ, acceptance test that <u>attempts</u> to monitor overall condition (it does not measure bulk proprieties nor will it detect point defects not close to a path to ground)
Indenter: [1]	A local, hands-on, in-situ, (or laboratory) test that measures (or trends) bulk properties
Preionized Gas: [2]	A global, remote, in-situ, acceptance test that <u>attempts</u> to monitor overall condition (it is intended to be a more effective hi-pot test whose acceptance criteria can be correlated with ability to function in LOCA environments)
Elongation, etc.:	Local, hands-on, laboratory tests that measure bulk proprieties

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1. The Indenter is an in-situ test device that pushes a small probe against the side of a cable to determine the compressive modulus of the insulation system. This modulus changes in an orderly manner with thermal age for many insulation systems. The Indenter was developed under an EPRI research program.

2. Preionized gas testing places an ionizable gas in a cable conduit to provide a ground plane during high-voltage testing. The ionizable gas provides similar results to that when water is used to surround the cable. The test method is being developed under an EPRI program.

In summary, condition monitoring tests can be categorized as:

1. Relating to a bulk property or a point defect,
2. Evaluating a circuit globally or locally,
3. Being applied remotely (at terminations) or hands-on (in the run of the cable),
4. Being used acceptance criteria or trending basis, and
5. Being used in-situ or in a laboratory.

Criteria for a Desirable Cable Testing/Monitoring Technique

The desirable attributes [136-138] of testing/monitoring techniques are:

- Methodology should minimize intrusiveness or be nondisruptive.
- Evaluation should be possible at time of normal operation.
- Disconnection of circuits or long equipment outages should not be required.
- Testing should be possible from readily accessible and convenient locations such as one end of a cable (e.g., from MCCs, and outside of containment termination boxes).
- The application of the test should minimize exposure of plant personnel to elevated radiation and temperature levels.
- When the process uses trends, the process should provide and allow appropriate storage of baseline data on parameters significant to operability such that trends can be analyzed.
- Test methodology should be applicable to wide variety of cable types (power, control, and instrumentation).
- Test methodology should be applicable to differing cable constructions (single conductor, multiconductor, unshielded cable, shielded cable).
- Test methodology should be applicable to different installation configurations (trays, conduits).

- Special training needs should be minimal.
- The need for high levels of expertise, special tools, and specialized calibration systems should be minimized.
- The need for specialized safety precautions should be minimized.
- The cost of testing should be significantly less than the cost of replacement of the cable.
- Results should be based on evaluation of direct rather than inferred data.
- Special test connections and configurations should be minimized.
- The need for post-test return to service functional testing should be minimized.
- For cables potentially subject to harsh environments (e.g., LOCA), measured parameters and acceptance criteria should be correlatable with expected performance under accident conditions.
- The condition evaluation instrument must be portable or allow for permanent non-intrusive installation.
- The technique should be sensitive to subtle changes in insulation that are significant to operability without being sensitive to conditions of test (such as humidity, temperature, cable position in the plant, and electrical noise).
- The technique should provide a means to discriminate between significant degradation of bulk properties and point defects.
- Implementation of the test should not require significant movement of installed cable.
- The test should not be detrimental to cables adjacent to the cable being assessed.

- Acceptance criteria should be clear without requiring specialized engineering knowledge or interpretational skills.

- Acceptance criteria should be traceable to recognized industry standards or defendable research programs.

- The results should be repeatable.

The following sections describe existing condition monitoring test methods that exist or are under development. None of these test methods fulfill all of the desirable attributes listed above. Very few are directly applicable to low-voltage unshielded cable. Some are more suited to testing of shielded, medium-voltage cable.

High-Voltage Testing of Cables

The application of high voltage to a cable insulation is used as a proof test. If the cable withstands the voltage for a specific period of time, it is considered free from significant flaws and degradation sites, and suitable for continued operation. High-voltage testing is typically not performed for low-voltage cables except for factory proof tests. Some utilities use high-voltage proof testing on in-plant medium-voltage cables as a means of verifying continued ability to function. Generally, the cable is tested with its load (e.g., large motor) connected, giving an overall indication of the circuit's ability to perform. These utilities believe that failure at a time when repairs can be readily implemented (i.e., during a plant maintenance outage) is preferable to an in-service failure. Other utilities believe that the effects of high-voltage testing are detrimental by comparison to the benefits and do not espouse use of such tests.

For medium-voltage cable, there are many types of high-voltage tests in use. Typical tests are impulse or surge tests, direct current tests, rapid rise ac tests, step voltage tests, and voltage endurance tests. The most popular high-voltage tests are described in this section.

Factory Testing

High potential (typically designated "hi-pot") testing can be conducted with either ac or dc test equipment. Under controlled factory test conditions, cable manufacturers [139] have historically favored ac high potential testing due to its high-stressing character, which offers a greater searching ability: significantly lower ac than dc voltages may be used to detect flaws. In addition, the "ac hi-pot test stresses all portions of the cable insulation, terminations etc. in exactly the same manner as encountered in normal service, except at a higher level" [140].

In factory testing, the average ac stress is approximately 100-130 V/mil for low-voltage cable and 125-160 V/mil for medium-voltage cable. These values are much lower than the dielectric withstand capability of the cable, but the intent is to detect significant weak spots in the insulation, not cause failure of the sound insulation by taking it to the limits of its capability. The purpose is to identify defects that would eventually affect operation of the cable while in service. The factory test voltage value for low-voltage cable (100-130 V/mil) is generally ten or more times greater than operating average stress of a low-voltage cable, which is typically less than 12 V/mil for power cable, and less than 5 V/mil for 120 V control cable. Through empirical testing, use of do testing generally requires that the dc test voltage be approximately 3 times the rms voltage level of an equivalent ac test. The specific ratio of ac to dc test values depends on insulation type and wall dimension. Representative values for factory testing (at 100% insulation levels) for low- and medium-voltage EPR [141], silicone rubber [142], and cross-linked polyethylene [143-145] cable follows:

Table 8-3

Representative High-Voltage Test Values

Rated Voltage	Insulation Wall	ac Test (V/mil)	dc Test (V/mil)
	Ethylene Propylene Rubber		
600 V	30 mils	4 kV (133)	12 kV (400)
	45 mils	5.5 kV (122)	16.5 kV (367)
	56 mils	7 kV (127)	21 kV (382)
5 kV	90 mils	13 kV (144)	35 kV (389)
8 kV	115 mils	18 kV (156)	45 kV (391)
	Slicone Rubber		
600 V	45 mile	4.5 kV (100)	13.5 kV (300)
	60 mils	6 kV (100)	18 kV (300)
5 kV	155 mils	13 kV (84)	35 kV (255)
	170 mils	13 kV (75)	35 kV (206)
	Cross-linked Polyethylene		
600 V	30 mils	3 kV (100)	9 kV (300)
	45 mils	4.5 kV (100)	13.5 kV (300)
	55 mils	5.5 kV (100)	16.5 kV (300)
5 kV	90 mils	13 kV (144)	35 kV (389)
	15 mils	18 kV (116)	45 kV (391)

High Potential Voltage Field Testing for Medium-Voltage Cable

The application of high potential testing of medium-voltage cables in the field on a periodic maintenance basis has been debated in the commercial, industrial, and utility industry for at least 30 to 40 years. To put this debate into perspective, it is appropriate to clarify the test purpose. The purpose of the test is to apply a suitably high voltage to cause the failure of "weak" insulation at a convenient time rather than during service.

Field testing typically is dc testing, as do test equipment is lighter, smaller, and generally less expensive than ac. However, as previously indicated ac testing is more representative of actual ac service conditions and should provide a greater correlation to actual in-service stress. The reader is referred to the literature [34, 130, 139, 140, 146-148] for a discussion of the pros and cons of ac versus dc testing.

It has been reported that high-voltage testing reduced in-service medium-voltage cable failure in an industrial company by as much as 90 percent [34]. On the other hand, cable experts do not recommend application of hi-pot testing on a routine basis. In addition, the appropriate voltage limit (acceptance criteria) for such tests is in conflict in various standards. As reported by Nobile and LaPlatney [146], the following differing dc test voltage values are found for 5 kV, 8 kV, and 15 kV rated cable.

Table 8-4
Comparison of Recommended Test Voltages

(kV)	Test Voltage				
	Rated Voltage			Installation	
Maintenance (kV)	ICEA/NEMA	AEIC	IEEE 400	AEIC	IEEE 400
5	25	28	35	28	20
8	5	36	40	46	25
15	55	56	55	46	40

The debate about use of hi-pot testing was summed up more than 30 years ago in the 1957 Underground Systems Reference Book Section 11 [149] as follows:

> Some companies do proof test cables on a routine basis and show evidence of increased service reliability. Some of the leading cable manufacturers not only recommend such routine tests, but actually sponsor them by making available a

the majority, believe that such tests not only cannot be economically justified, but cause service failures that would not otherwise occur.

The facts probably lie somewhere between these extremes. It is possible that any damage to good cable insulation caused by a do proof test, and resulting in increasing service failures, may have been one due to testing techniques which caused unnecessary stresses.

Previously, the criteria for a desirable cable testing/monitoring technique were described. High-voltage field dc testing meets few of these criteria. The following summarizes part of the test procedure necessary to complete a high-voltage dc test:

- The desired minimum industry test level of 20 kV for the typical Class 1E 5 kV, medium-voltage cable IS much greater than the allowable test level for the connected equipment (i.e., 20 kV for the cable versus motor/generator factory hi-pot level of 9 kV. A typical 4 kV motor test voltage is based on twice rated voltage plus 1 kV or 9 kV.).

- To perform a cable hi-pot, cabling must be disconnected and sufficiently isolated from other equipment unless the test voltages are limited to that appropriate to the connected equipment. Disconnection entails system shutdown, untaping of stress cones, cable movement and isolation for test, re-termination, and post-maintenance system checkout and functional testing.

- Hi-pot testing employs potentially lethal voltage levels necessitating great care in performance of the test such that personnel safety is maintained. Both ends of the cable must be controlled for safety purposes.

- A highly experienced test crew is required.

- Care must be taken to assure power cables are not tested while at elevated operating temperatures to prevent "dc stress inversion," a condition where the highest test stress is at the shield due to resistivity induced changes in potential distribution due to operating temperature gradients.

- Post-testing discharge of residual high voltage remaining on the cable is necessary.

With respect to do testing of repaired, aged 15 kV cross-linked polyethylene cable, a research program performed by Detroit Edison for EPRI indicates that do high-potential testing substantially reduces the remaining life of the cable [178]. The research program also indicated that do high-potential testing did not identify significantly weakened cable. In the program, water-trees were induced in 15 kV cross-linked polyethylene cable by accelerated means (150 V/mil ac, with daily load cycles to 90°C while bathed in water and having a wet conductor). After the first electrical failure occurred during the accelerated aging under ac stress, the failed section was removed and the remaining cable was cut in half. Each half was spliced to a new section of cable. One of the two resulting test specimens was subjected to a 40 kV, 15-minute high-potential test; the other specimen was not electrically tested. Both test specimens were then subjected to the accelerated aging conditions. In each case, the specimen that was dc high-potential tested failed well before the associated specimen that was not high potential tested. Failures of the high potential tested cable occurred in as little as 13 minutes. The associated specimen that had not been high-potential tested did not fail until the 581st day. For the other sets of specimens, the specimen that was not high-potential tested survived between 1.2 and 22 times as long as the high-potential tested specimen. In none of the tests did dc high-potential testing cause the immediate failure of the spliced cables (i.e., do high potential testing was insensitive to the degraded condition). However, when restored to ac service following the high-potential test, failures occurred in as few as 13 minutes. These tests provide a strong basis for discouraging dc high-potential testing of medium voltage cross-linked polyethylene cable that may contain water trees, especially those with spliced repair segments. Other experiments in the same program indicate that do high-potential testing of new cable does not appear to cause any reduction in service life.

Recent research and use of a resonant ac power supply and partial discharge detector by Ontario Hydro [140] confirms the superiority of ac versus dc testing for shielded 5 kV to 15 kV cables when combined with partial discharge testing. As reported by testing at Ontario Hydro's Bruce B and Darlington Nuclear Generating Stations from 1983 to 1988 that included 97 cable circuits (291 cables), all but two of the cables survived both the ac and dc hi-pot. Hi-pot cable testing detected only gross flaws, such as "a nail through the cable." Partial discharge (corona or micro-sparking) will occur in medium-voltage cable and terminations which contain voids, contaminants, or interruptions in the insulation shield. As described in other sections of this report, medium-voltage cable operating voltages are such that electrical stress at voids or other imperfections will likely be susceptible to corona discharge that can ultimately lead to failure.

Partial discharge testing that determined if discharges were occurring above normal working voltage indicated problems (e.g., detection of discharges at 4 to 5 kV for a nominal 4.16 kV system voltage) in 10% of the medium-voltage cables that were tested. Most of the problems found were traceable to poorly made splices or damage to the shield which occurred during installation.

These recent research programs indicate that do high-potential testing will not necessarily identify severe deterioration, and will tend to shorten the life of aged cross-linked polyethylene having water-trees. Ac high-potential testing also may not identify severe deterioration, but does not appear to cause loss of remaining life on aged cables. Partial discharge testing appears to be the most promising for detecting flaws in 4.16 kV cables.

Recommendation Against Routine High-Voltage In-Plant Testing of Low-Voltage Class BE Cables

It is not recommended that high-voltage in-plant testing Class 1E cables be undertaken as a condition monitoring or routine maintenance task, especially for low-voltage, unshielded cable This recommendation is based on the current state of the art of high-potential testing. The basis of this recommendation is as follows:

- The service history of properly designed and installed cable systems under normal nuclear plant environments has been excellent indicating no significant need for high-potential testing of low voltage cable.
- There is a significant potential for human error due to complex testing procedure that could induce electrical breakdown of cables without commensurate benefit.
- A true acceptance criterion for high-voltage testing does not exist as failure may be test induced and not related to cable operability. In addition, multiple acceptance criterion values exist leading to confusion concerning the appropriate test value.

Application of High-Voltage Testing for Installations of Medium-Voltage Cables

As previously described, suspect installations require special attention. The failure mechanisms of a suspect installation of medium-voltage cable may lead to discontinuities in the cable cross-section. At the discontinuities and under operational voltage stress, areas of localized corona discharge between the insulation and the conductor, or the insulation and the shield leading to insulation deterioration and cable failure. Where cable replacement is under consideration, high-voltage cable testing may be prudent to demonstrate relative cable soundness.

OTHER ELECTRICAL TEST/CONDITION MONITORING METHODS

Other electrical test methods beyond insulation resistance testing and high-voltage testing are under review and development by industry. The following provides brief summaries of the techniques.

Partial Discharge Testing

This test, performed in the factory on medium-voltage cables, is very useful as it can detect latent defects in cable that are much smaller than gross imperfections. The test measures small electrical discharges that occur in voids in the insulation or in gaps between the insulation and the conductor or shield. These discharges are called partial discharges. Partial discharges (also called corona and sometimes micro sparking) in voids in the insulation may cause progressive damage leading to the breakdown of the insulation. The damage is caused by localized overheating at the site of the discharge. These discharges can occur during each cycle of the ac voltage wave under normal conditions if the stresses in the voids are high enough. Deterioration leading to failure may occur over a number of years. The partial discharge test acceptance requirements for shielded power cable tested at time of manufacture typically comply with the maximum partial discharge limits in picocoulombs specified in the AEIC standards [122].

Partial discharge testing in the field is not currently practical within the commercial state-of-the-art as a field test because of several limitations. For medium-voltage cables, a high-voltage ac source of large capacity is required. Factory tests are performed in a shielded facility to eliminate extraneous electrical noise that could erroneously interpreted as partial discharge currents. Such a shield can not be used in the field. Therefore, extraneous noises and spurious discharges could be picked up by the corona detection equipment making it very difficult to obtain adequate detection sensitivity.

Currently, this test is not applicable to low-voltage cable without shields. However, research continues [136, 150-152] in regard to development of practical tools for partial discharge measurements in the field.

Time-Domain Reflectometry (TDR)

Time-Domain Reflectometry (TDR) has been in use for 20 to 30 years. It is based on sending a "radar liken signal into a transmission line while the voltage is displayed as a function of time [153]. Discontinuities in the transmission path cause a voltage change, which is displayed at a time corresponding to the round trip time between the origin and the site of the discontinuity. In recent years, TDR data has been combined with other electrical circuit characterization test methods in an automated test such that resistance, impedance, capacitance, inductance, TDR signature, phase angle, and quality factor data are measured and stored to provide a baseline of circuit characteristics and assist in circuit assessment [154, 155].

This system does provide useful data for evaluating series impedance changes for troubleshooting, determining termination problems, and evaluating other impedance and gross changes in the circuit. Research [5. 156] has led to the conclusion that the present stage of this system's development does not support the evaluation of cable insulation degradation of sufficient precision for cable operability assessment.

Time-Domain Spectrometry (TDS)

Time-Domain Spectrometry is a relatively new technique for determination of the frequency spectrum of the dielectric loss of material from its measured time behavior in response to a step-voltage excitation [156]. The National Institute of Standards and Technology is leading a research effort including establishing a data base providing a correlation between aging and dielectric loss. This new methodology requires a ground plane (a shield) and may have little potential usefulness for the low-voltage, unshielded cable, which is of major concern in nuclear power plants.

Ground Plane Enhancement Techniques

Various ground plane enhancement techniques are presently being investigated such that conventional testing of unshielded low-voltage cable Drill be enhanced. As described previously, a major shortcoming with the traditional testing of cables by insulation resistance or high potential is the lack of a consistent ground plane about the cable sheath.

Consequently, various research projects [136] are presently underway to ionize gas about the cables under test by electric ionization, charged particle ionization, and ultraviolet-assisted ionization or to provide a metallic ground plane (metallic blankets) about the cables. The development of ionized gas methodology may allow use of voltage withstand and partial discharge testing on unshielded, low-voltage cable.

Improved Polarization Index Evaluation

Currently, Biddle Instruments, in conjunction with an EPRI/Ontario-Hydro cable research program [157], is developing a new insulation resistance test device that will determine low-voltage cable polarization indices during the first seconds on the test. It is hoped that the test device under development will capture low frequency dielectric response of the insulation. Changes in low frequency dielectric response should be indicative of aging. As of this writing, laboratory experimentation with the prototype is underway.

MANUFACTURING TESTS AND THEIR APPLICABILITY TO CABLE MONITORING

Typical industry standards [42-45, 122, 142-145, 158, 159] include factory tests that are used to primarily confirm the physical and electrical characteristics of cable. As such, these tests are not intended to provide evidence of cable operability. For nuclear safety-related cable, long-term operability to date has been demonstrated by design and type testing. Many tests are used in the factory to evaluate the as-manufactured cable, such as conductor resistance, conductor diameter, insulation and jacket thickness, tensile strength tests for jacket and insulations, thermal aging tests for jacket and insulation, contaminant and porosity tests, insulation stripping tests, accelerated water absorption tests, heat distortion of insulation tests, voltage tests, and insulation resistance. For medium-voltage cable, partial discharge (previously described), void determination, conductor shield projection, and volume resistivity for semi-conducting shields tests are also performed.

The subset of tests that may prove to be useful for evaluating cable operability are described herein.

Tensile Strength and Elongation Testing

Tensile strength and elongation are measured by placing specimen ends of the material (e.g., insulation) in the jaws of a tensile test machine. The jaws withdraw until specimens break with the strength expressed as pounds of load per square inch of sample cross-section (psi) while elongation is the increase in length at fracture between two sample gage marks on the sample. An increase from 2 inches to 6 inches represents an elongation at break of 200%. These tests are primarily a check on quality control of the insulation material. For many insulation materials, elongation-at-break can be used as an indication of the age of the insulation in that elongation-at-break tends to change in an orderly manner with the degree of thermal aging. With regard to its use as a condition monitoring technique, it is destructive in nature and would require cables to be permanently removed from service in order to get specimens for testing.

Factory Thermal Aging Tests

Factory testing for thermal aging is also a control tool for verifying the adequacy of as-produced insulation. For typical 90°C rated cross-linked polyethylene and EPR cables, insulation specimens are exposed to 121°C and for 168 hours per the ICEA standards [43, 44]. Following this aging, the specimens are subjected to elongation and tensile tests and must meet minimum requirements of the standards. These are not the equivalent of qualification aging tests and are far less severe than the thermal aging exposures used for qualification (150°C for 504 hours or more) [160].

Water Absorption Tests

Water absorption test are essentially a quality control tool. Two tests exist [43, 44]. One test, designated the electrical method, places 10 feet of sample in water at 75°C. The capacitance is measured at 80 V/mil after 1, 7 and 14 days, whereas the power factor is measured after 1 and 14 days, at 80 and 40 V/mil. The dielectric constant of water is approximately 80, while popular cable insulation materials (EPR, XLPE, SR) have dielectric constants of approximately 2 to 4. Therefore, moisture absorption would cause a marked change in capacitance-based measurements. This is considered a quality control check only due to the short duration of the test as the water immersion stability of sound modern insulation is very high and significant changes would take months or longer to occur.

The second test method is designated the gravimetric method as it is typically based on immersing the sample for 168 hours in 70°C distilled water. The water is shaken off after 168 hours and weighed in milligrams. The weight is divided by the total sample surface area to give a reading of milligrams per square inch. The results do not relate to electrical functionality and vary markedly between acceptable different materials. It is a quality control check only. With respect to condition monitoring and evaluation, these tests are not expected to provide meaningful data.

EVOLVING RESEARCH TEST METHODS FOR MONITORING AGING

Another series of condition monitoring methods being developed or used by research organizations [4, 161, 162] that evaluate physical and chemical properties of insulations and jackets that relate to cable aging. These methodologies are briefly covered. The reader is directed to the reference literature for in-depth coverage. These descriptions of the evolving methods for cable assessment do not indicate the advocacy of use of these techniques for the general cable population. However, these tools may become of significant value for validating conservatism in qualification and evaluating cables that have been damaged by localized hot spot conditions.

Cable Indenter

EPRI is developing a cable insulation aging monitor that evaluates the compressive modulus of insulation and jacket materials to determine the relative age of the materials. Research has determined that compressive modulus shows good correlation with elongation-at-break measurements that have classically been used as an indication of polymer age. The monitor is called an "Indenter." The technique uses a hand-held test rig that presses an instrumented anvil against the cable surface under a controlled rate and measures displacement and force. It is a non-destructive test for in-plant use. This device could be used to assess the status of cable "aging" at a certain location or to validate the degree of conservatism inherent in the simulated aging used for cable qualification. Trial use of this method is expected to be available during the second half of 1991 [136]. Acceptance criteria that are indicative of a cable's ability to withstand an accident environment are to be developed by taking Indenter measurements on cables that have been subjected to the equivalent of the radiation and thermal aging from the environmental qualification program.

Differential Scanning Calorimetry

Differential Scanning Calorimetry provides a melting curve for insulation material which can reveal the maximum operating temperature a cable has seen in service [163]. To a limited extent, the method allows determination of the duration of the elevated temperature condition.

Oxidation Induction Time

Oxidation induction time (OIT) testing determines the period of time before an exothermic reaction occurs in a small sample of insulation material when it is subjected to a constant temperature on the order of 180°C. The time at which the exothermic reaction occurs is indicative of the amount of remaining anti-oxidants remaining in the material. OIT has shown a reasonably valid experimental correlation with elongation values, because elongation does not significantly decrease until the insulation's anti-oxidant is depleted. Measurement of the oxidation induction time may be of use in trending insulation degradation. The samples that are used for these tests are small enough that they could be removed from operating cables although a patch such as heat shrinkable tubing may have to be placed over the site.

In-Plant Aging Study

An ongoing EPRI program [61] is underway in which specimen bundles of widely used cable types (and other electrical components) have been placed in the containment buildings of operating nuclear plants. The specimens are expected to be removed from the plants at approximately 5-year intervals for up to 40 years. Utility personnel will remove the specimen bundles and environmental monitors during planned outages. Researchers will measure physical properties of the materials and compare the degradation of the naturally aged materials with that of identical specimens aged artificially under equipment conditions as they would be in a qualification test program. Specimen locations were selected to give a reasonably wide range of environments. Natural age degradation appreciable enough to construct models and compare against artificial aging is expected to occur in 1995 or later, some 10 years after program initiation.

Section 9.0

Electric Circuit Performance Characteristics

Section 9.0

ELECTRIC CIRCUIT PERFORMANCE CHARACTERISTICS

Electric equipment that is located in areas that may be subject to a harsh environment and performs a safety function must be capable of functioning under harsh environmental postulated conditions. This is an inherent aspect of the definition of cable operability found in Section 2.

The verification of the ability of a component to function under normal and harsh conditions are documented in qualification files. These files demonstrate that components can withstand the rigors of normal life and at any time during that life be able to withstand harsh environment conditions for as long as the component is required to be functional. Additional coverage of cable qualification is found in Section 6. A key part of cable qualification is evaluating the electrical performance of the cable under normal and accident environment conditions. The following sections describe performance attributes and requirements for cables that are considered during the qualification process.

Performance Attributes for Power Cables

Each cable environmental qualification report includes a description of the testing or a combination of testing supplemented by analysis which demonstrates that cables will remain functional during and after exposure to accident environments.
Since 1974, voltage testing of cables using 80 Vac/mil (or 240 Vdc/mil) of insulation has been the standard cable qualification test following the harsh environment exposure [58]. Manufacturers have tended to use a minimum wall thickness for the insulation of 30 mils. Therefore, these tests are generally performed at 2400 Vac or higher, depending on the wall thickness. These values are consistent with a minimum wall thickness for 600 V class cross-linked polyethylene, ethylene propylene, and silicone rubber cables used by industry that have been manufactured to ICEA standards [42-45, 158]. Tests are performed by straightening the cables and bending them around mandrels that have diameters that are 40 times the diameter of the cable. The cable is then immersed in water and the voltage is applied for 5 minutes between the conductor and the water tank.

Without considering the extra protection of cable jacket or braid, 600 V power cable having a minimum of 30 mils of insulation can successfully withstand testing to 80 Vac/mil (or equivalent 240 Vdc/mil). The typical operational electrical stress for this power cable is 4 to 12 V/mil, which is significantly lower than the test values. The applicable qualification standard, IEEE Std 383, states:

> The post-LOCA simulation test demonstrates an adequate margin of safety by requiring mechanical durability (mandrel bend) following the environmental simulation and is more severe than exposure to two cycles of the environment.

The post-LOCA bend and high-voltage test demonstrates that the combination of normal life and accident simulations has not embrittled a cable to the point where it has cracked or deteriorated significantly and demonstrates that the cable insulation has remaining margin between the required and actual capability.

In recent years, concerns related to low insulation resistance of cables during nuclear design basis accidents have arisen. While low insulation resistances may occur during accident simulations, they are not significant to power cables applications where leakage currents would still be small by comparison to load currents. For power circuits, as long as the insulation retains its basic ability to insulate conductors from one another and ground, the function is adequate.

As pointed out by Sandia Laboratories under NRC research [Reference 165, Part II, Paragraph 3, "Comment on Circuit Failure"], leakage in a power cable circuit of up to 200 mA "is unimportant." As described later in this section, typical power cables at typical plants will have a leakage current far less than 200 mA (actually less than 5 mA) at the worst-case cable temperatures.

Large power cables for medium-voltage, safety-related loads are all located outside of the drywell or containment and are not exposed to worst-case LOCA or MSLB conditions. These power cables actually have two walls of isolation between phases and typically have current limiting resistance in the ground circuit path to limit ground faults under line to ground short circuit conditions.

Insulation resistance values expected for these cables in lengths over 250 feet exposed to limiting ambient environments outside containment should be in excess of 1 megohm. Even for the full nominal system voltage of 4160 V (not considering the actual line to ground voltage of 2400 V), the largest power cable used will experience a leakage current of about 4 mA (i.e., $I = 4160/1 \times 10^6 = 4.16 \times 10^{-3}$ amperes). This value is 50 times less than Sandia accepts as a non-problem.

Similarly, a 1-megohm minimum insulation resistance would be expected for outside of containment 460 V circuits. For the 460 V motors circuits, the leakage currents would be less than 0.5 mA (i.e., $I = 460/1 \times 10^6 = 4.6 \times 10^{-4}$ amperes). These leakage current values will have no impact on circuit function as even fractional horsepower loads have normal load currents of 1 ampere or more at 480 V nominal system voltage. The smallest overload element in a motor control center starter would not respond to a less than 1% increase in nominal motor current [100 x (4.6 x 10^{-4} /1) = 0.046%)].

The discussion above for power cables is also generally applicable to control cable. The minimum insulation thickness for control cables used by manufacturers of control cable (if rated 300 volts) is generally in the range of 20 to 25 mils. Under a nominal 120 Vac, the stress would be 6 V/mil for a 20-mil wall.

Control cables do not normally have insulation resistance degradation to the extent that control circuit performance is of concern. However, to demonstrate that these concerns are not generally pertinent to cable operability, further evaluation of insulation resistance is provided later in this section for typical devices at nuclear power plants.

Furthermore, as previously indicated, many plants use control cables rated at 600 volts or greater for control. Analysis of 300V rated cable, when 600V cables have actually been used, provides additional margin in the demonstration of adequacy.

Environmental qualification testing for instrument cable has been equivalent to that for control cables. The application voltage for typical 4- to 20-mA instrument circuits is less than 50 volts. The nuclear industry typically uses such instruments as Rosemount, ITT Barton, and Foxboro transmitters which have a maximum operation voltages of 40 V [166], 42 V [167], and 50 V [168]. The actual applied voltage for many plants is 30 Vdc and 24 Vdc, whereas the cable test specimens typically are operated at 120 Vac or 140 Vdc during qualification testing. This difference between as-tested and as-operated voltages adds to the conservatism in qualification practice for instrument cables.

SYSTEM CONSIDERATIONS RELATED TO CABLE INSULATION RESISTANCE

This section addresses cable insulation resistance as it relates to typical plant circuit applications. Insulation resistances under normal and accident environment conditions are considered.

Instrument Current Loop Operation Principles

As illustrated in Figure 9-1, instrument transmitters are used to produce electrical signals that are proportional to a measured process condition (e.g., pressure, differential pressure, and level). Two transmitter loop current ranges are standard for instrument loops in the United States: 4 to 20 milliamperes and 10 to 50 milliamperes. The most common output range is 4 to 20 milliamperes. The instrument loop's resistance and supply voltage are related, which describes the power supply versus load (resistance) capability. Specific values for transmitters by three manufacturers are given in Table 9-1.

Table 9-l

Specific Instrument Loop Critical Parameters

	Rosemount*	ITT Barton**	Foxboro***
Minimum Voltage (Vdc)	3.5	15	30
Maximum Operating Voltage (Vdc)	40	50	42
Maximum Series Resistance	1325	1750	1150
Minimum Series Resistance	0	0	600

* Reference 200
** Reference 202
*** Reference 201; Vendor "Area B" data.

An electronic transmitter functions as the equivalent of a variable resistor with the resistance value proportional to the process condition being monitored. Transmitters are supplied from 24 to 50V power sources, and range in resistance values from approximately 1000 ohms to 12,500 ohms. The exact values are manufacturer dependent.

Effect of Insulation Resistance on Instrument Current Loops Under Normal (Mild) Conditions

Under normal plant operating conditions, cable and termination insulations for instrument current loops have high values of insulation resistance (i.e., greater than 100 megohms and up to 10,000 megohms or more). The lumped insulation resistance for the loop appears electrically in parallel with the transmitter. With such high values of insulation resistance, the instrument signal is essentially unaffected by termination and cabling insulation resistance. That is, 100 megohms or more in parallel with 1000 to 12,500 ohms resistance of the transmitter has essentially no effect on the signal. The complete instrument loop has various elements and terminations as shown in Figure 9-1. However, for an initial screening review, these elements may be neglected and the effect of the insulation resistance on signal can be evaluated in terms of leakage current through the insulation.

For a rather low insulation (shunt) resistance, R_s , during normal plant environmental conditions, (e.g., a 100 megohms/1000 feet insulation resistance value in a 1000-foot-long circuit), the leakage or shunt current, I_s (conservatively assuming no voltage drop through the instrument cable series lead wires) at maximum voltage V_s (from Table 9-1) for a 4- to 20-mA current loop would be only 0.0005 mA as determined below:

$$I_s = V_s / R_s \qquad \text{Eq. 9-1}$$
$$50/1 \times 10^{8}$$
$$5 \times 10^{-7} \text{ amperes}$$

This increase in total circuit current above the transmitter current (I_t) even at the zero percent of full scale or 4-mA output (see Table 9-2) results in only an approximate 0.01% increase in apparent measurement. The worst-case signal error (e) is the ratio of the shunt leakage current (I_5) to the minimum transmitter signal current (I_t) of 4 mA.

$$e = I_s / I_t \qquad \text{Eq. 9-2}$$
$$= (5 \times 10^{-7})/(4 \times 10^{-3})$$
$$= 0.000125$$

Equation 9-2 can be used to demonstrate that the worst-case error is associated with the 4- to 20-mA current loop rather than the other industry standard current loop value of 10 to 50 mA for the same cable length and cable IR circuit values.

A maximum V_5 of 95 volts [167] is found for the transmitters of the three vendors [166-168] for a Foxboro 10- to 50-mA circuit. The error for this circuit is as follows:

$$e = (V_s / R_s)/I_t \qquad \text{Eq. 9-3}$$
$$=(95/1 \times 10^{8})/10 \times 10^{-3}$$
$$= 0.000095$$

where:

R_s = minimum shunt IR, 1×10^{8} Ohms
I_t = minimum loop current, 10 mA
V_s = maximum voltage, 95 vdc

Consequently, screening analysis of the worst-case 4- to 20-mA circuit must always envelop the worst-case 10- to 50-mA circuits for the same shunt resistance and worst-case currents (minimum) and voltage (maximum). Therefore, as a screening mechanism, the utility may use 4- to 20-mA current loop circuits to evaluate worst-case conditions on all transmitter loops.

Harsh (High Temperature) Environment Insulation Resistance Effects on Transmitter Current Loops

During a postulated accident, the ambient temperature rise resulting from a pipe break area can be appreciable (i.e., up to 340°F (superheated) in the drywell of a BWR or 440°F superheat in containment of a PWR). In such environments, the insulation resistance of cable and associated splices or terminations will be reduced, as insulation resistance is inversely proportional to temperature as described in Section 8. Erroneous readings can occur in current-loop circuits due to increased leakage currents through the cable insulation. Figure 9-2 illustrates the severe error that can result from low insulation resistance values based on Sandia Laboratories research [169]. Plots of Sandia Laboratory data are shown for shunt insulation resistance values of 5 kohms, 10 kohms, 60 kohms, and 500 kohms at different transmitter outputs. Independent work by Sandia indicates that cable and terminal block low IR behavior is similar for similar configurations and insulation systems regardless of specific vendor [165, 169]. To evaluate the effect of low insulation resistance, the insulation resistances of the cable, terminations and electrical penetration must be parallelled and the effect on leakage current determined. The resulting error must be evaluated against instrument loop requirements. The effect of this error can be evaluated against the safety function requirements of the circuit. If the error drives the signal in a safe direction, the error may still be acceptable. Also, larger errors may be acceptable for indications that have no trip function.

Technical Data for IR Evaluation

This section provides technical data that can be used as a screening mechanism to determine the worst-case error caused by a low IR value in a circuit. When the screening value shows that the error is excessive, specific analysis may be performed by the utility to determine acceptability of data.

Variable Nature of IR

As described in Section 8, insulation resistance is an effect that depends on temperature. For example, the temperature influence on cable insulation resistance is such that the insulation resistance of cabling of most concern (i.e., instrumentation) may change as much as a 5 to 7 orders of magnitude when exposed to the worst-case accident environment. The insulation resistance value returns to near normal values (within 1 to 2 orders of magnitude) when the ambient returns to near normal.

Likewise, terminal block low insulation resistance for "bare or uncoated" termination facilities is moisture dependent with a return to near normal values when the moisture source is removed. (A detailed discussion of terminal blocks is outside the scope of present cable research.) The temporary nature (e.g., recovering after normal temperatures are restored) of the low values is shown in Sandia Laboratories and vendor data as illustrated in Figures 8-5 and 8-6.

The calculations performed in this section are only for the leakage currents caused by low insulation resistance. These calculations do not represent the accuracy of the complete instrument circuit or loop, which may be affected by errors induced by other causes. The accuracy of each circuit depends upon the circuit's specific elements. It cannot be specifically determined by a generalized model. However, this calculation provides a reasonable basis to describe the low insulation resistance induces error. The specific service of each cable is not identified in this section except in selected cases. This allows generalized models based on a worst-case 50 Vdc instrument loop to be used for calculations. (50 Vdc for a 4 to 20 mA loop is a worst-case or highest instrument loop voltage used in this study, as described above.)

Basis for Comparative Analysis

The time-temperature profiles for many plank include significant superheat conditions, whereas vendor testing generally is at saturated temperature conditions. The basis for the IR screening value consideration is determined from the review of test insulation resistance results from cable vendors or laboratories at the worst-case saturation temperature. These values are then extrapolated to the expected cable operating temperature.

Error calculations were performed for an appropriate range of instrument loop resistances (e.g., 250 ohms, 500 ohms, 600 ohms, 900 ohms, 1000 ohms, 1150 ohms, 1250 ohms, 1325 ohms, and 1750 ohms) and seventeen different signal current (4 mA to 20 mA in 1 mA increments). Note that actual instrument loop resistances must be within the parameter values described in Table 9-1. Furthermore, operation at lower than maximum voltages requires a check to verify minimum voltage is available at the transmitter. Worst-case examples are included in this report.

In operation, the instrument circuit is scaled such that an electrical signal of 4 mA corresponds to an input process value of 0 units, whereas the 20-mA electrical signal level corresponds to a 100% process value. Table 9-2 provides the correlation of transmitter current to percent of process value.

Table 9-2
Transmitter Signal Vs. Process Condition Value

Instrument Transmitter Signal Level	Process Condition (% full Scale)
4 mA	0%
8 mA	25%
12 mA	50%
16 mA	75%
20 mA	100%

Consistent with typical and "good practice" setpoint selection, an instrument is typically set to operate between 30% and 70% of span to allow for instrument inaccuracy, calibration uncertainty, and instrument drift. Therefore, this evaluation includes not only the entire range of signal currents, 4 mA to 20 mA, but various intermediate points. For example, the 30% and 70% of span corresponds to instrument transmitter (I_t) output current values as follows:

$$I_{x\%} = (\text{Span\%}) \times \text{Span} + 0 \text{ Process Input Current Value} \qquad \text{Eq. 9-4}$$

$$I_{30\%} = 0.3 \times (20 \text{ mA} - 4 \text{ mA}) + 4 \text{ mA}$$
$$= 8.8 \text{ mA}$$

$$I_{70\%} = 0.7 \times (20 \text{ mA} - 4 \text{ mA}) + 4 \text{ mA}$$
$$15.2 \text{ mA}$$

Specific determination of error caused by shunt resistance values of cable, can be calculated for an actual set point considering worst-case cable length and voltage as described in this section. For convenience in this study, determination is based on graphical plots of error versus signal level.

Cable Circuit Lengths for Error Analyses

Tables may be developed for different cable length applications such that a reasonably accurate and conservative value of error (e) can be determined without calculation by the application engineer. Examples are presented to be representative of typical BWR/PWR containments. In general, this data envelopes outside containment applications.

BWR Data

A representative diameter of a BWR drywell is approximately 80 feet, and a screening value for instrument cable length may be established as follows: The circumference is equal to pi times the diameter, or (3.14 x 80) 251 feet. Conservatively, a maximum cable length is selected as a value 10% greater than the circumference. Therefore:

Maximum cable length (C1) = drywell circumference + 10% = 276 ft

The maximum cable length represents a complete circumferential traverse of the drywell and a 10% allowance for change in elevation.

The instruments inside drywell or primary containment are typically RTDs and thermocouples. No known installation locates transmitters in drywell. Cable analysis conservatively assumes that cable is exposed to primary containment accidents without benefit of protective raceways which would tend to limit the effects of short-term temperature transients (i.e., reduces the peak temperature). Other ranges of cable lengths used in the analysis are as follows:

Length C2 = 100% of circumference = 251 feet
Length C3 = 75% of circumference = 0.75 x 251 = 188 feet
Length C4 = 50% of circumference = 0.50 x 251 = 126 feet
Length C5 = 25% of circumference = 0.25 x 251 = 63 feet

In general, for instrument circuits, a minimum acceptable loop insulation resistance for screening purpose is 10^6 ohms.

PWR Data

A representative diameter of a PWR containment is approximately 140 feet (circumference = 440 feet), and a screening value may be established, as follows:

Length C1 = maximum cable length
= containment circumference + 10%
= 484 feet

The length C1 represents a complete circumferential traverse of containment and a 10% allowance for change in elevation. The instruments inside PWR containments are RTDs, thermocouples, and transmitters. Again, the analysis should conservatively assume that cable is exposed to containment accidents without benefit of protective raceways, which would cause thermal inertia. Intermediate ranges used in the evaluation are:

Length C2 = 100% of circumference = 440 feet
Length C3 = 75% of circumference = 0.75 x 440 = 330 feet
Length C4 = 50% of circumference = 0.50 x 440 = 220 feet
Length C5 = 25% of circumference = 0.25 x 440 = 110 feet

Outside Drywell or Containment Cable Lengths

In general, cables servicing transmitters, RTDs, and other devices in the reactor building of a BWR or the reactor auxiliary building of a PWR range in length from 25 feet to 650 feet. For simplicity, maximum cable lengths are specified as follows for this illustrative evaluation:

Length C1 = 650 feet
Length C2 = 530 feet
Length C3 = 410 feet
Length C4 = 290 feet
Length C5 = 170 feet

Use of these lengths, as if the entire cable run is exposed to the accident environment, is conservative, and may be overly conservative. When the results of this screening process are unfavorable, a specific circuit analysis should be performed that determines if the outside of containment section of the cable is exposed to elevated temperature as a result of the accident environment.

Analysis Approach - Current Loop Instrument Circuits

Sandia National Laboratories, in Section 8.1 of NUREG/CR-3691 [169], described a reasonable basis for determining low-insulation-resistance-induced error in instrument transmitter circuits. The equivalent equation for expressing instrument error is given by:

$$e = (V_s - R_e I_T)/(I_T(R_{TB} + R_e)) \qquad \text{Eq. 9-5}$$

The Sandia report dealt with the concern for low-insulation resistance associated with terminal blocks as represented by the expression R_{TB} Replacing that with R_c for the insulation resistance of the cable, results in:

$$e = (V_s - R_e I_T)/(I_T(R_c + R_e)) \qquad \text{Eq. 9-6}$$

where:

e = error
V_s = source voltage
R_c = equivalent series resistance of loop instrument and cable to the low insulation resistance region (e.g., containment)
I_T = transmitter loop current
R_e = insulation resistance of the cable (including adjustment for length and circuit configuration)

In the Sandia Report, a representative 1000 ohm R_e (loop resistance) and 45 Vdc for V_5 (source voltage) were used. Figure 9-2 reflects the Sandia data to validate the calculation methods used. The results using the same input are the same in the Sandia report [169] and in the error determination in this report. Note that these severe results are not applicable to the typical plant, as the shunt IR values at the plant (not using uncoated terminal blocks exposed to moisture) should be much higher for typical plant cabling than the values used in Figure 9-2. An exception may be PVC insulated cables, as the basic volume resistivity of PVC is substantially lower than EPR, cross-linked polyethylene, silicone rubber, and other traditional insulation systems.

In this analysis, a worst-case (i.e., highest) voltage of 50 Vdc (V_s) for the 4 to 20 mA current loop is used, consistent with the worst-case application transmitter (ITT Barton) as show in Table 9-1. Instrument transmitters at most plants include Rosemount 1153 series and Foxboro E11 and E13 series that operate at lower voltages. The maximum qualified voltage is 40 V for the Rosemount transmitter and 42 V for Foxboro transmitters (for a 4 to 2 mA configuration).

Equation 9-6 demonstrates that the error is largest at maximum V_s. Therefore, error calculations at 50 volts envelope errors for the 4 to 20 mA loops with power supply voltages below this value. A range of equivalent loop resistances (R_e of 250 to 1750 ohms for ITT Barton; 250 to 1325 ohms for Rosemount; 600 to 1150 ohms for Foxboro), a range of typical instrument loop currents (I = 4 to 20 mA) and cable lengths would be used to envelop the typical plant applications. Using these different values allows the utility to determine error impact for a range of applications enveloping their needs. Note that the present tabular results in the generic worst-case tables of this effort are conservative.

The worst-case tables for representative cable insulation types for a plant and longest representative cable length in the plant should be provided as a first screen. In addition, a series of plots of error results may be presented. This series would provide sufficient detail to allow determination of errors for specific transmitters and signal levels. Representative results of the error calculations are at the end of this section.

Power source voltage values less than 50 volts (i.e., 30 volts or 24 volts) would reduce every error determined to no more than approximately 60% of the generic values indicated on the basis of the ratio of actual to maximum V_s values. The series voltage drop in the loop circuit, as shown in Equation 9-6, for lower V_s values results in a more conservative error determination using the ratio of actual to generic V_s values.

Determining Applicable Temperature Rise Associated with Accident Conditions

The typical field run instrumentation cable is a No. 16 AWG cable, which is rated by the National Electrical Code at 24 amperes for a 90°C conductor temperature in a 30°C ambient. The operating temperature of a cable is a function of both the ambient temperature and load current induced temperature rise. The specific temperature rise can be determined by methods such as those found in ANSI/IEEE 242 [73].

For a typical instrumentation application, the temperature rise from ohmic heating is negligible as determined below, using the industry accepted equation from Chapter 11 of ANSI/IEEE 242:

$$T_x = T_a + (T_n - T_a)(I_n/I_a)^2 \qquad \text{Eq. 9-7}$$

where:

T_x = temperature at loading current

T_a = temperature at rated ambient

T_n = temperature at rated normal current

I_x = current at maximum application load

I_n = rated normal current load corresponding to Tn

Therefore: $T_x - T_a$ equals temperature rise

$$T_x - T_a = (T_n - T_a)(I_x/I_n)^2 \qquad \text{Eq. 9-8}$$

where:

I_x = 20 mA maximum for instrument current loop

$T_x - T_a = (90°C - 30°C) \times [2 \times 10^{-2})/24]^2$

$= 4.17 \times 10^{-5}$ °C rise

The temperature rise from current in the loop is negligible.

Determining Typical Test Cable Operating Temperature Rise

An actual test cable specimen in an accident environment simulation may be energized during the simulation with a current of 10 amperes. Typical qualification testing by vendors is represented by testing of cross-linked polyethylene cable [160, 170], testing of silicone rubber cable [171], and EPR cable [172]. Temperature from ohmic heating during vendor testing (no credit being taken for other test cables producing heat in close proximity) would be determined using the same formula as Equation 9-8, but with the load current values from the harsh environment test:

$$T_x - T_a = (T_n - T_a)(I_x/I_n)^2$$

where the terms have been previously defined:

$$T_x - T_a = (90°C - 30°C) \times [10/24]^2$$
$$= 10.4\ °C \text{ rise}$$

This indicates that the actual insulation temperatures in the harsh environment can be 10.4°C higher than the test chamber ambient temperature. This heating will cause a further insulation resistance drop than that from the test chamber environment alone. Therefore, there is conservatism in test insulation resistance measurements when these values are used for instrument loop evaluations. (Note: It is necessary that simulated accident qualification envelop all requirements including ambient and application temperature rise. The above equation can be used for comparison purposes only. Use of this equation to obtain absolute temperatures values is inappropriate without correction for thermal resistivities and other factors.)

Determining Cable Comparison Temperatures

To determine the realistic comparison cable temperatures for vendor and generic testing as well as typical plant requirements, a comparison may be made at saturated steam temperatures when properly supported by analysis. Because cable testing is in a steam environment [160, 170, 171, 173, 174], the saturation temperature may be reasonably used. The use of saturated steam during testing may in fact be a bit more severe than superheated steam. Recent testing by Sandia [175] states the following in Conclusion 3 of its Executive Summary:

> Since the same results occurred using either superheated-steam or saturated-steam at the start of the accident simulation, it does not appear that saturated-steam

conditions forced moisture into the cable causing the cable to fail prematurely. (Superheated- steam only delayed the electrical degradation of the cables slightly.)

The use of the saturation temperature in an analysis may also be justified on the basis of the laws of physics. The rate of heat transfer at the cable surface for superheated steam appears to be only slightly higher than for saturated steam. In addition, actual expected interposing raceway about the instrument cable will cause condensation of the superheated steam until temperatures equalize. As established by heat transfer studies [176], the temperature value for saturated steam at accident superheated pressure may reasonably and conservatively be used for the qualification of the instrument cable.

Substantial confirmation testing by Sandia Laboratories has established a range of expected insulation resistance values for EPR and XLPE. Sandia generic data is therefore used, when appropriate, in this analysis in addition to available specific data. For silicone rubber cable, data from a typical vendor is used [171].

Applicability of ICEA Standard Methods for Insulation Resistance Evaluation

ICEA Standard publications [42-45, 158] are the basis for the manufacture and production test of cables. The insulation resistance of manufactured cable is measured and corrected to a standard temperature (60°F) using a reference length of 1000 feet. This method, used in conjunction with a temperature correction factor derived from ICEA methodology, allows extrapolation from test data at a specific temperature to another specific temperature within a small temperature interval (typical ICEA data does not extend beyond 85°F).

Temperature correction factor values or an appropriate equation for extrapolation of insulation resistance values to the accident environment temperatures are generally unavailable. Consequently, a technically supportable basis to find expected insulation resistance values at the peak accident temperatures for the cable is not readily available through standard ICEA methodology.

Insulation Thickness Sensitivity Analysis for Insulation Resistance

Certain cables are tested with minimum insulation wall thickness that meets industry standards for instrument service. In cases where the test specimen thickness directly corresponds to a specific application thickness, insulation resistance data can be derived directly from the vendor insulation accident simulation test results. In some cases, testing may have been performed with minimum 30-mil wall cable test specimens while the applied cable may have a 25-mil or 20-mil wall (typical wall dimension for 300-V rated cable). During demonstration of adequacy of circuit performance, a qualification engineer or cable engineer may be required to demonstrate the adequacy of a wall thickness which deviates from the as-tested configuration. This subsection provides a method to determine insulation resistance for different wall dimensions.

The following is an example of such an evaluation for a 25-mil insulation wall insulation when a 30-mil test specimen was used. To verify that a nominal wall thickness of 25 mils versus 30 mils is not significant with respect to insulation resistance, the ICEA standard equation for expected insulation resistance from ICEA S-19-81 [42] is used for a sensitivity analysis:

$$R = K \log_{10} (D/d) \qquad \text{Eq. 9-9}$$

where:

R = insulation resistance in megohms/1000 ft
K = constant for the grade of insulation
D = outer diameter of the insulation
d = inner diameter of the insulation

An analysis of the sensitivity to the wall thickness indicates that the insulation resistance (R in this equation) would be expected to change only 14% for a 5-mil wall increase from the 25-mil specified wall thickness as follows:

<u>25-mil wall</u>

$R = K \log_{10} (D/d)$ for a 25-mil wall
R and K are constants described before
d = 0.058-inch conductor outside diameter from ICEA S-19-81 [42]
Table 2-2.

$$D_{25} = d + (\text{wall thickness}) \times 2$$
$$= 0.058 \text{ inch} + (2 \times 0.025 \text{ inch})$$
$$= 0.108 \text{ inches}$$

The variable is the expression:

$\log_{10}(D/d)$
Substituting values from above:
$\log_{10}(0.108/0.058) = 0.2699$

<u>30-mil wall</u>

All data is the same as the 25-mil wall case except that the wall thickness changes from 25 to 30 miles The variable expression is:

$$\log_{10}(D/d)$$

Substituting values:

$$\log_{10}[(0.058 + (2 \times 0.030))/(0.058)] =$$
$$\log_{10}(0.118/0.058) = 0.3084$$

$$R_{30mil}/R_{25mil} = \frac{\text{30-mil wall variable expression}}{\text{25-mil wall (base) variable expression}} \qquad \text{Eq. 9-10}$$
$$= 0.3084/0.2699$$
$$= 1.14 \text{ per base unit}$$

Therefore, when the wall thickness changes from 25 mils to 30 mils, the change in insulation resistance should theoretically increase by approximately 14%. For insulation resistances of cables under normal ambient conditions, such a change would be in the noise of the measurement.

Using the same technique, the change in insulation resistance when comparing a 20-mil wall with that of a 30-mil wall results in approximately a 35% increase in insulation resistance under normal ambient conditions.

Correcting IR Values for Various Cable Lengths

As shown in Figure 9-1, the parallel shunt insulation resistance of the cable designated Rc is the resistance from one conductor to the other conductor, not the conductor to shield resistance. During qualification testing, the insulation resistance measurement is taken between conductor and shield or ground. Consequently, using this value for the shunt resistance of a typical ungrounded instrument loop does not take credit for the two insulation walls between the positive and negative signal paths of a current loop. The insulation resistance analysis (including verification of ungrounded positive and negative leads) may take credit for the actual configuration such that twice the insulation resistance measured during the qualification test may be used.

As the insulation resistance is a parallel or shunt resistance, its value decreases in direct proportion to cable length. The equation for the actual Rc to use in the analysis is determined below.

Rc_{Test} = resistance of specific length of test cable corrected to a single foot value

Rc = resistance of actual plant cable corrected for length

$Rc = (Rc_{Test})/$ (actual cable length in feet)

Note: The following values represent cables installed in typical BWRs or PWRs outside drywell or containment. The insulation values used represent cables with different insulation materials. The results found here are solely illustrative of the methodology. The reader is cautioned not to use these results in determining the suitability of any specific installation. Only actual lengths and worst-case application specific insulation resistance values from accident environment portions of qualification tests should be used in evaluating a particular application.

Cross-Linked Polyethylene (single wall credit only)

$Rc_1 = Rc_{650'} = (1.8 \times 10^9)/650'$

$= 2.77\ 10^6$ ohms

$Rc2 = Rc_{530'} = (1.8 \times 10^9)/530'$

$= 3.40 \times 10^6$ ohms

$Rc_3 = Rc_{410'} = (1.8 \times 10^9)/410'$

$= 4.4 \times 10^6$ ohms

$Rc_4 = Rc_{290'} = (1.8 \times 10^9)/290'$

$= 6.20 \times 10^6$ ohms

$Rc_5 = Rc_{170'} = (1.8 \times 10^9)/170'$

$= 1.06 \times 10^7$ ohms

Ethylene Propylene Rubber (single wall credit only)

$Rc_1 = Rc_{650'} = (3.28 \times 10^9)/650'$

$= 5.05 \times 10^6$ ohms

$Rc2 = Rc_{530'} = (3.28 \times 10^9)/530'$

$= 6.19 \times 10^6$ ohms

$Rc_3 = Rc_{410'} = (3.28 \times 10^9)/410'$

$= 8 \times 10^6$ ohms

$Rc_4 = Rc_{290'} = (3.28 \times 10^9)/290'$

$= 1.13 \times 10^7$ ohms

$Rc_5 = Rc_{170'} = (3.28 \times 10^9)/170'$

$= 1.93 \times 10^7$ ohms

Silicone Rubber (single wall credit only)

$Rc_1 = Rc_{650'} = (8.55 \times 10^9)/650'$

$= 1.31 \times 10^7$ ohms

$Rc2 = Rc_{530'} = (8.55 \times 10^9)/530'$

$= 1.61 \times 10^7$ ohms

$Rc_3 = Rc_{410'} = (8.55 \times 10^9)/410'$

$= 2.08 \times 10^7$ ohms

$Rc_4 = Rc_{290'} = (8.55 \times 10^9)/290'$

$= 2.95 \times 10^7$ ohms

$Rc_5 = Rc_{170'} = (8.55 \times 10^9)/170'$

$= 5.03 \times 10^7$ ohms

Evaluation of Worst-Case Instrument Circuit Sensors for Normal Environment Insulation Resistances

In the following analyses, the worst-case 50Vdc loop configuration is used for a 4 to 20mA current range that results in instrument loop resistance ranges from 250 to 1750 ohms. The analyses consider the insulation resistance from only one thickness of insulation. As previously described, the actual circuit configuration for the shunt cable insulation resistance Rc includes the insulation barriers of both the positive and negative leads. Consequently, the outside of containment insulation resistance values calculated above have a margin of approximately 100%. Should the following results be deemed too conservative for a specific application, a specific analysis should be used to verify that the circuit is isolated from ground such that the insulation resistance value to be increased by an appropriate factor to account for the two cable walls.

Sample calculations for worst-case, maximum screening value cable lengths under 4-mA signal conditions (which is the worst-case as the leakage current impact on the circuit reduces with increased signal current) are included here. It is highly unlikely that any circuit will be at worst-case voltage, worst-case current, worst-case length, worst-case operation during temperature transient conditions such that these results are conservative and appropriate for screening purposes.

The tables and graphs shown in Figures 9-3 through 9-8 indicate the percent error for the different transmitters, cable insulation resistance and transmitter loop resistance on a worst-case basis. Using the equation previously presented in this section:

$$e = (V_s - R_e I_T)/(I_T(R_c + R_e))$$

where:

e = error

V_s = 50 Vdc

I_T = 4mA

R_c = 2.77 x 10^6 ohms (worst case for 650 feet of XLPE insulation outside of containment)

R_e = equivalent series resistance of the instrument loop

A) R_e = 250 ohms

$e = [50 - 250(0.004)]/[0.004[(2.77 \times 10^6) + 250]$

$e = 0.0044$

Percent Error = 0.44%

B) R_e = 500 ohms

$e = [50 - 500(0.004)]/[0.004[(2.77 \times 10^6) + 500]$

$e = 0.0043$

Percent Error = 0.43%

C) R_e = 1000 ohms

$e = [50 - 1000(0.004)]/[0.004[(2.77 \times 10^6) + 1000]$

$e = 0.0042$

Percent Error = 0.42%

D) R_e = 1250 ohms

$e = [50 - 1250(0.004)]/[0.004[(2.77 \times 10^6) + 1250]$

$e = 0.0041$

Percent Error = 0.41%

E) R_e = 1750 ohms

$e = [50 - 1750(0.004)]/[0.004[(2.77 \times 10^6) + 1750]$

$e = 0.0039$

Percent Error = 0.39%

If the worst-case errors are unacceptable, the data presented can be applied consistent with the following example of a specific setpoint:

Cable run outside drywell or containment = 359 ft
Minimum current, I_T = 7.66 mA for setpoint of a transmitter
Circuit resistance = 1100 ohms
Power source, V_S= 30 volts (corresponding to expected value)

The application-specific analysis may be performed with the use of the basic equation that was previously described (Equation 9-6):

$$e = (V_s - R_e I_T)/(I_T(R_c + R_e))$$

where:

$Rc_{Test} = 1.8 \times 10^9$ ohms/foot
$Re_{application} = (Rc_{Test})/359$ foot application
$= 5.01 \times 10^6$ ohms
Re = 1100 ohms as stated
I_T = 7.66 mA as stated
V_s = 30 volts as stated

$$e = \frac{[30 - (1100 \times 7.66 \times 10^{-3})]}{[(7.66 \times 10^{-3})(5.01 \times 10^6 + 1100)]}$$

$= 0.00056$
Percent Error = 0.056%

This sample-specific calculation demonstrates the conservatism in the typical tabular and graphically plotted values and their usefulness as a screening mechanism. Any value determined acceptable by use of the tables need not be specifically calculated. Furthermore, all circuits with power supply values, V_S. below the screening value of 50 volts will have a potential error that is reduced at least proportionally.

The above analyses are for normal temperature insulation resistances. If R_c were to fall to 500 kohms due to accident temperature conditions, the resulting worst-case error for R_e = 250 ohms would be:

$e = [50 - 250(0.004)]/[0.004[(0.5 \times 10^6) + 250]$
$e = 0.022$
Percent Error = 2.2%

This error due to insulation resistance drop resulting from an accident environment could be significant to an actual application. Therefore, users of the equations must use circuit insulation resistances derived from the actual accident simulation data from the qualification test.

Insulation Resistance and RTD Accuracy

This subsection analyzes the effect of decreased insulation resistance on RTD accuracy. For demonstration purposes, a temperature of 150°C (302°F) will be used. This temperature typically exceeds the saturation temperature corresponding to the peak accident pressure for most incontainment accident conditions. This analysis is provided to demonstrate circuit performance will not be significantly degraded for the application if cable circuit insulation resistances remain at or above 1 megohm. In addition, sufficient data is presented to allow an engineering assessment and extrapolation (when adequately justified) to other applications. Other considerations such as the accuracy of the RTD itself and basic design of the system are not covered in this review.

Several RTD constructions are available to industry. Four of the most common types will be analyzed on a generic basis. Their construction and electrical characteristics are listed below:

Resistance Value (ohms)

Material	O°C	150°	ohms/ohm/°C	Alpha Comment
Platinum(1)	100	158.090	.003902	US Standard
Platinum(2)	100	157.310	.003850	Intl'l Standard
Copper	10	14.828	.004274	US Standard
Nickel/ Copper	150	248.950	.006720	US Standard

150°C Effective Resistance*

Material	Element (ohms)	Cable IR (ohms)	Eff. Res (ohms)
Platinum(1)	158.090	1×10^6	158.070
Platinum(2)	157.310	1×10^6	157.290
Copper	14.828	1×10^6	14.828
Ni/Copper	248.950	1×10^6	248.890

*The effective resistance is calculated using the standard parallel resistance formula $Re = (R_1 \times R_2)/(R_1 + R_2)$

The effective resistance value from the paralleling of the element and the cable insulation resistance is translated into a relative temperature using the typical RTD tables and interpolating, as appropriate. The results are shown below.

Material	Effective Resistance	C Resultant Temperature (°C)	Difference Temperature (°C)
Platinum(1)	158.070	149.95	0.05
Platinum(2)	157.290	149.95	0.05
Copper	14.828	150.00	0.00
Ni/Copper	248.890	149.94	0.06

Percent Error is calculated using the following formula:

% Error = [(Actual-Required)/Required] x 100%

where Required = 150°C, and Actual = °C Resultant Temperature

Material	Percent Error
Platinum(1)	-0.033%
Platinum(2)	-0.033%
Copper	-0%
Ni\Copper	-0.04%

As can be seen from the Percent Error values above, the largest error is 0.04% less than the required value of 150°C (e.g., -0.06°C for a resultant temperature of 149.94°C). It should be noted that larger errors will result if insulation resistances drop below 1 megohm. Such errors may be significant for specific applications. The high temperature portion of an accident temperature profile is transient in nature. As the temperature drops, the insulation resistance will improve and the induced error will decrease.

LOW INSULATION RESISTANCE CONSIDERATIONS FOR OTHER APPLICATIONS

Thermocouple Extension Lead Considerations

Thermocouples generate millivolt outputs that are proportional to the difference in temperature between the measuring junction and a reference junction. Because the voltages are very low, leakage currents will be very small. As such, thermocouple circuits are not very sensitive to relatively low insulation resistance values. Vendors have stated [177] "that an insulation resistance as low as 1 x 10^3 ohms will not significantly affect the ability of the probe to accurately sense temperatures."

Coaxial Cable

The review of the operability of coaxial cables is much the same as that for standard cable. The acceptance criteria established for testing of standard cables includes a voltage withstand test of 80 volts/mil for 5 minutes after a 40x diameter bend. This criteria also applies to coaxial cables. Actual application voltages are generally far less than the test voltages used in qualification testing.

Assessments of the operability of coaxial cables are directly related to their affects on the accuracy of their associated circuits. Typical applications for coaxial cables in nuclear power plants are in the radiation monitoring and acoustic valve position monitoring systems.

The following assessment of accuracy is based on actual insulation resistance data from the applicable qualification reports. An analysis of the affect of the worst-case coaxial cable insulation resistance requires consideration of the insulation resistance of the other components of the system. These include the in-containment coaxial connector, and the penetration assembly. It must be demonstrated that the reduction of insulation resistance in the combination of the coaxial cable and the associated components is within instrument acceptable limits.

An analysis considering the circuit components must be performed to determine the appropriate insulation resistance value for the circuit. A minimum insulation resistance value of 2.34 x 10^6 ohms is established as the acceptance criteria. This value is based on criteria typically recommended by manufacturers of the monitoring systems described above.

The total circuit analysis considers the insulation resistance of the cable, its connectors, and the penetration assembly. The insulation resistance of the cabling (pigtails and feedthroughs) at the penetration is conservatively enveloped by assuming it is equivalent to a 10-foot cable.

The minimum insulation resistance measurement for coaxial connectors is typically a value of 9.0 x 10^8 ohms at 340°F. The worst-case insulation resistance values for coaxial cables is based on minimum values found in representative test reports. Typical values are conservatively as low as 1 x 10^8 ohms-1000 feet.

The contribution of penetration pigtail leads is considered along with the circuit length of the coaxial cable. Assuming a maximum drywell signal cable length of 30 feet, plus a 10-foot allowance for the penetration leads, a 40-foot total circuit length results. Based on a typical 1×10^8 ohms-1000 ft. this results in an equivalent IR value of:

$$1 \times 10^8 \text{ ohms}/1000 \text{ ft} \times (1000 \text{ ft}/40 \text{ ft}) = 2.5 \times 10^9 \text{ ohms}$$

Using the worst-case IR value of 9.0×10^8 ohms for the connector and 2.5×10^9 ohms for the cable and penetration lead, the total insulation resistance of the circuit components is evaluated as follows for the parallel circuit:

$$1/R_{comb} = 1/R_{cable} + 1/R_{con} + 1/R_{con}$$

where:

R_{comb} = total resistance of coaxial cable and connector combination

R_{cable} = insulation resistance of coaxial cable and the penetration leads (2.5×10^9 ohms)

R_{con} = insulation resistance of the coaxial connector (9.0×10^8 ohms for the connector at each end of the cable)

Therefore: $1/R_{comb} = 1/2.5 \times 10^9 + 1/9.0 \times 10^8 + 1/9.0 \times 10^8$

$$R_{comb} = 3.81 \times 10^8 \text{ ohms}$$

This conservatively determined IR value meets the previously stated minimum specified IR value of 2.34×10^6 ohms stated by the vendor.

Splice Considerations

Power and control cables that are spliced together using qualified heat shrinkable tube or tape splices effectively are reinsulated at the point of connection with an insulation system built up to a dimension equal to or greater than the minimum cable wall it is reinsulating. Standard electrical practice requires that the tape buildup be at least 50 percent greater than the insulation. Furthermore, the lineal length of the splice or reinsulation area is 1 to 6 inches. Therefore, it is a small fraction of the cables length. Consequently, the insulation resistance impact of the splice is generally not significant.

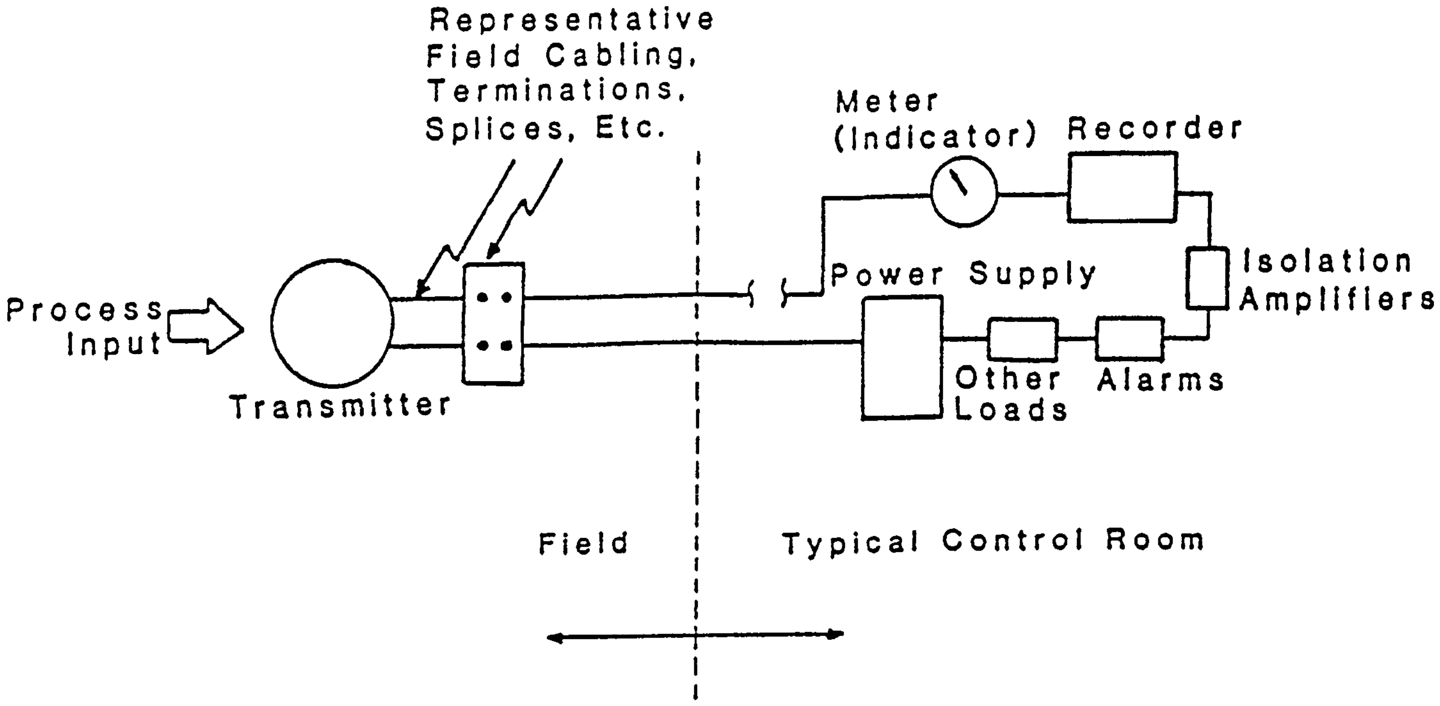

Figure 9-1

Typical Instrument Transmitter Loop

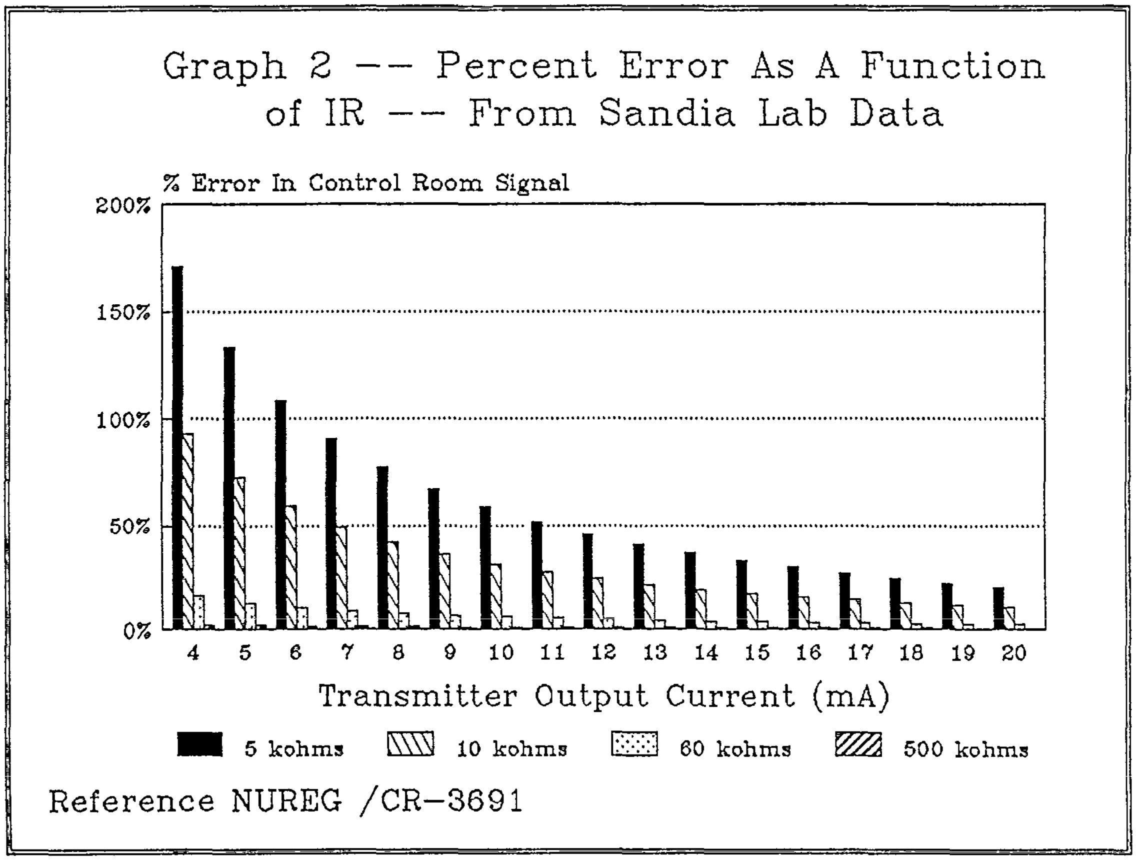

Figure 9-2

Check Against Sandia Data

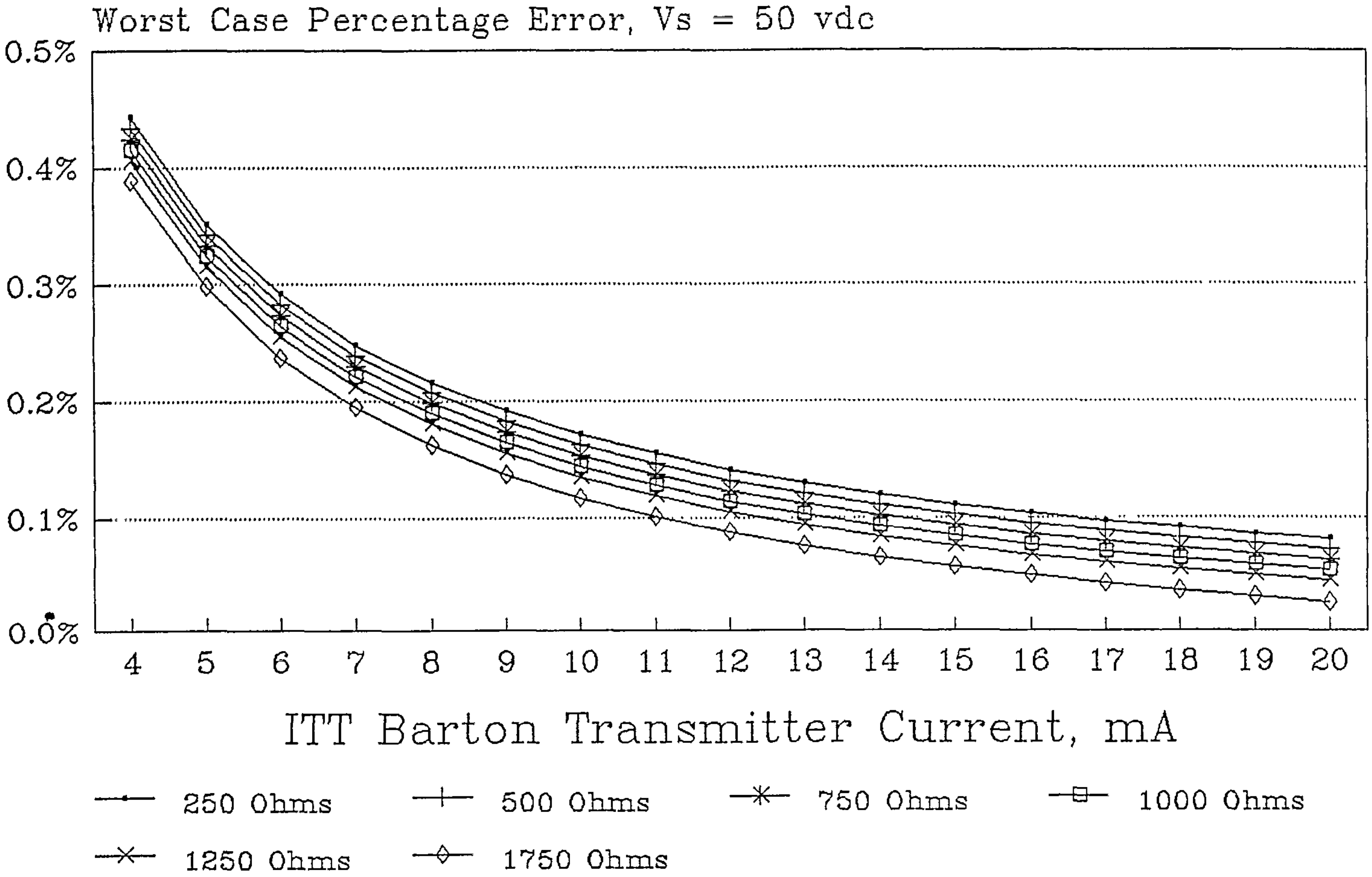

Figure 9-3

% Error due to Insulation Resistance of 650 ft XLPE Insulated Instrument Circuit under Normal Environments as a Function of Signal Current

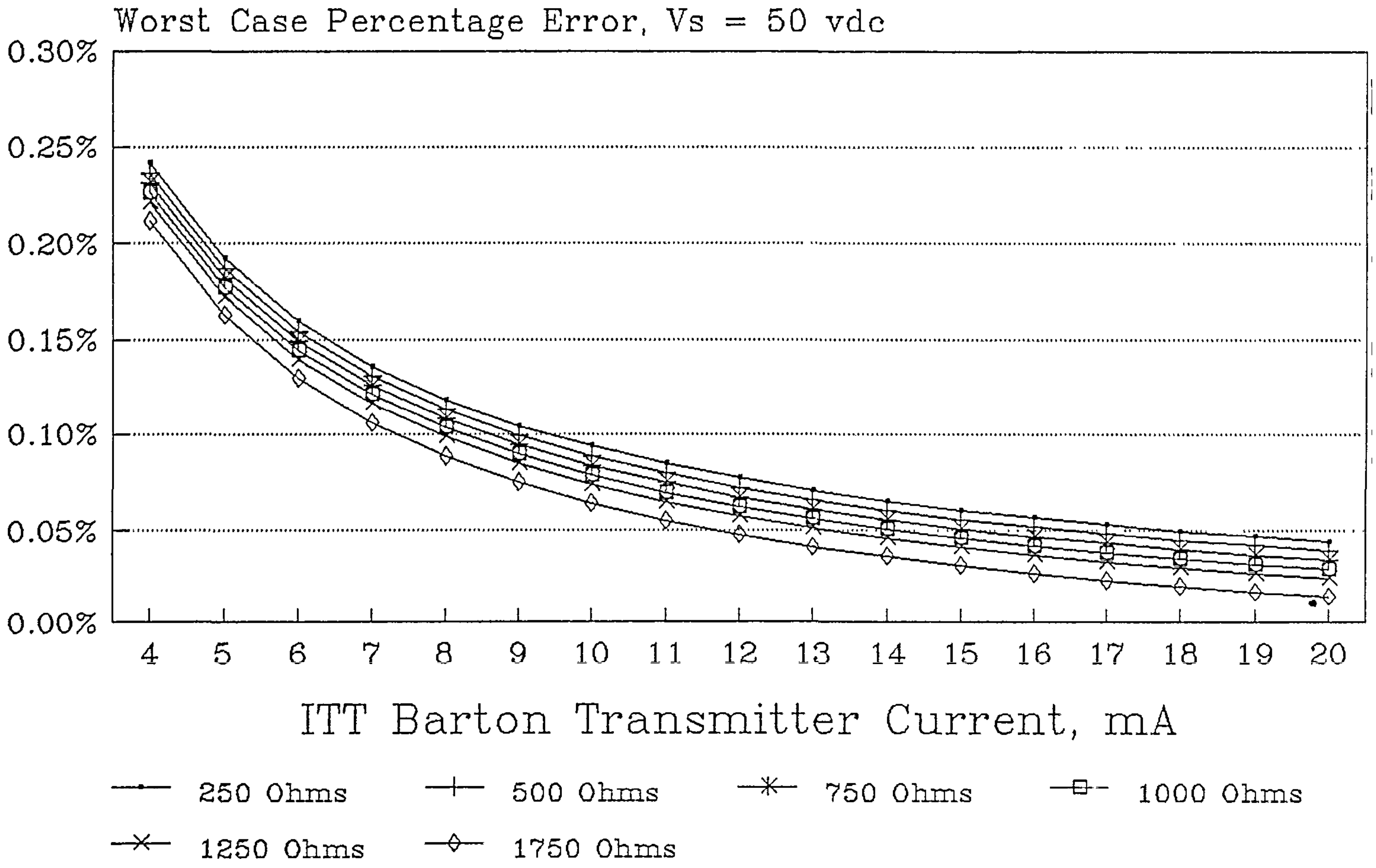

Figure 9-4

% Error due to Insulation Resistance of 650 ft EPR Insulated Instrument Circuit under Normal Environments as a Function of Signal Current

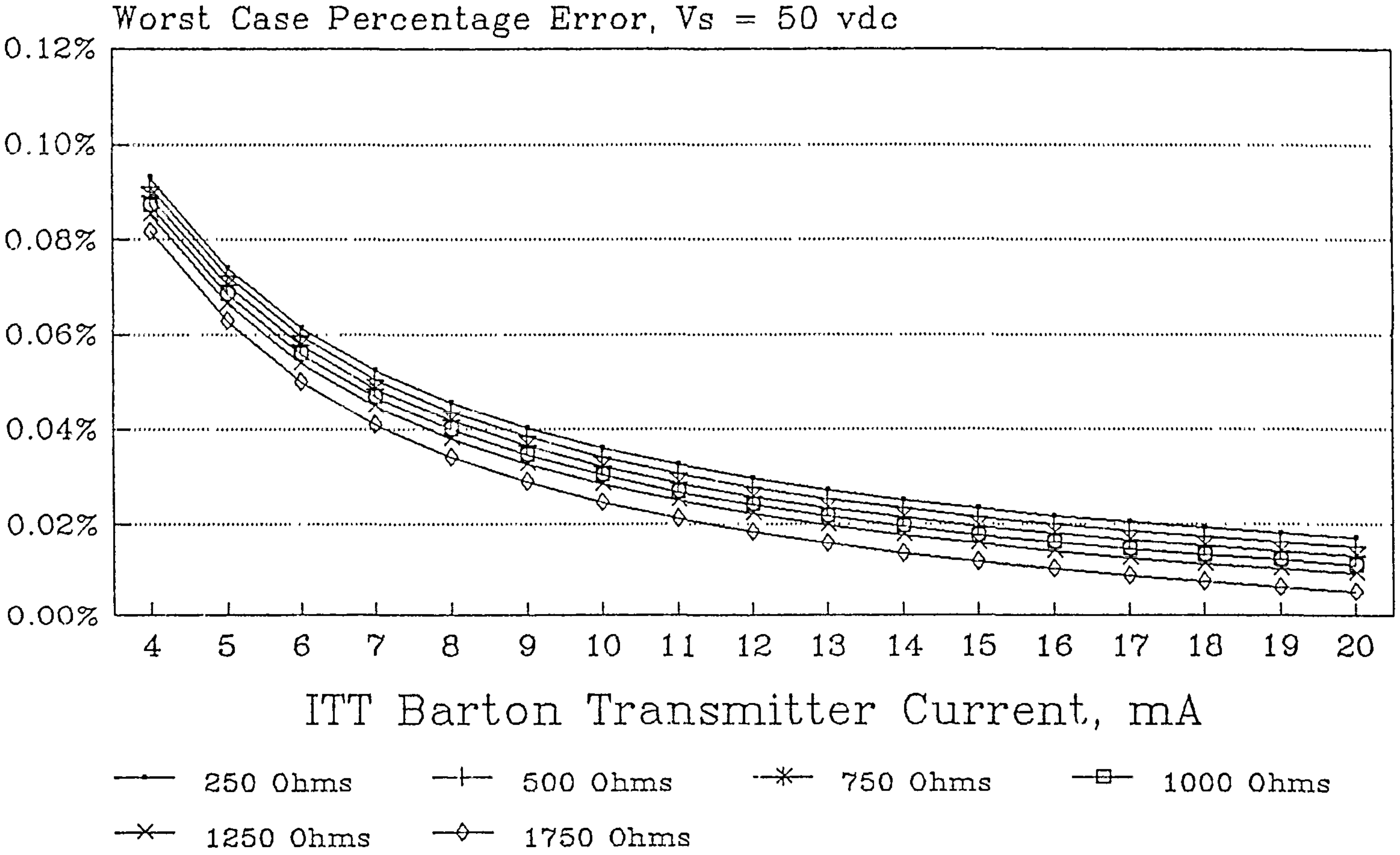

Figure 9-5

% Error due to Insulation Resistance of 650 ft Silicone Rubber Insulated Instrument Circuit under Normal Environments as a Function of Signal Current

Transmitter Current mA	Error for Re Value of 650' CKT LENGTH					
	250 Ohms	500 Ohms	750 Ohms	1000 Ohms	1250 Ohms	1750 Ohms
4	0.442%	0.433%	0.424%	0.415%	0.406%	0.388%
5	0.352%	0.343%	0.334%	0.325%	0.316%	0.298%
6	0.292%	0.283%	0.274%	0.265%	0.256%	0.238%
7	0.249%	0.240%	0.231%	0.222%	0.213%	0.195%
8	0.217%	0.208%	0.199%	0.190%	0.180%	0.162%
9	0.192%	0.183%	0.173%	0.164%	0.155%	0.137%
10	0.172%	0.162%	0.153%	0.144%	0.135%	0.117%
11	0.155%	0.146%	0.137%	0.128%	0.119%	0.101%
12	0.141%	0.132%	0.123%	0.114%	0.105%	0.087%
13	0.130%	0.121%	0.112%	0.103%	0.094%	0.076%
14	0.120%	0.111%	0.102%	0.093%	0.084%	0.066%
15	0.111%	0.102%	0.093%	0.084%	0.075%	0.057%
16	0.104%	0.095%	0.086%	0.077%	0.068%	0.050%
17	0.097%	0.088%	0.079%	0.070%	0.061%	0.043%
18	0.091%	0.082%	0.073%	0.064%	0.055%	0.037%
19	0.086%	0.077%	0.068%	0.059%	0.050%	0.032%
20	0.081%	0.072%	0.063%	0.054%	0.045%	0.027%

ITT BARTON
Vs = 50 vdc

Figure 9-6

% Error due to Insulation Resistance of 650 ft XLPE Insulated Instrument Circuit under Normal Environments as a Function of Signal Current

Transmitter Current mA	Error for Re Value of					
	650' CKT LENGTH					
	250 Ohms	500 Ohms	750 Ohms	1000 Ohms	1250 Ohms	1750 Ohms
4	0.241%	0.236%	0.231%	0.226%	0.222%	0.212%
5	0.192%	0.187%	0.182%	0.177%	0.172%	0.162%
6	0.159%	0.154%	0.149%	0.144%	0.139%	0.130%
7	0.136%	0.131%	0.126%	0.121%	0.116%	0.106%
8	0.118%	0.113%	0.108%	0.103%	0.098%	0.089%
9	0.104%	0.100%	0.095%	0.090%	0.085%	0.075%
10	0.094%	0.089%	0.084%	0.079%	0.074%	0.064%
11	0.085%	0.080%	0.075%	0.070%	0.065%	0.055%
12	0.077%	0.072%	0.067%	0.062%	0.057%	0.048%
13	0.071%	0.066%	0.061%	0.056%	0.051%	0.041%
14	0.065%	0.060%	0.056%	0.051%	0.046%	0.036%
15	0.061%	0.056%	0.051%	0.046%	0.041%	0.031%
16	0.057%	0.052%	0.047%	0.042%	0.037%	0.027%
17	0.053%	0.048%	0.043%	0.038%	0.033%	0.023%
18	0.050%	0.045%	0.040%	0.035%	0.030%	0.020%
19	0.047%	0.042%	0.037%	0.032%	0.027%	0.017%
20	0.044%	0.039%	0.034%	0.030%	0.025%	0.015%

ITT BARTON
Vs = 50 vdc

Figure 9-7

% Error due to Insulation Resistance of 650 ft EPR Insulated Instrument Circuit under Normal Viromnents as a Function of Signal Current

	Error for Re Value of					
Transmitter	650' CKT LENGTH					
Current mA	250 Ohms	500 Ohms	750 Ohms	1000 Ohms	1250 Ohms	1750 Ohms
4	0.093%	0.091%	0.089%	0.087%	0.086%	0.082%
5	0.074%	0.072%	0.070%	0.068%	0.067%	0.063%
6	0.061%	0.060%	0.058%	0.056%	0.054%	0.050%
7	0.052%	0.050%	0.049%	0.047%	0.045%	0.041%
8	0.046%	0.044%	0.042%	0.040%	0.038%	0.034%
9	0.040%	0.038%	0.037%	0.035%	0.033%	0.029%
10	0.036%	0.034%	0.032%	0.030%	0.029%	0.025%
11	0.033%	0.031%	0.029%	0.027%	0.025%	0.021%
12	0.030%	0.028%	0.026%	0.024%	0.022%	0.018%
13	0.027%	0.025%	0.024%	0.022%	0.020%	0.016%
14	0.025%	0.023%	0.021%	0.020%	0.018%	0.014%
15	0.023%	0.022%	0.020%	0.018%	0.016%	0.012%
16	0.022%	0.020%	0.018%	0.016%	0.014%	0.010%
17	0.020%	0.019%	0.017%	0.015%	0.013%	0.009%
18	0.019%	0.017%	0.015%	0.014%	0.012%	0.008%
19	0.018%	0.016%	0.014%	0.012%	0.011%	0.007%
20	0.017%	0.015%	0.013%	0.011%	0.010%	0.006%

ITT BARTON
Vs = 50 vdc

Figure 9-8

% Error due to Insulation Resistance of 650 ft Silicone Rubber Insulated Instrument Circuit under Normal Viromnents as a Function of Signal Current

Section 10.0

Cable Aging Management and Maintenance

Section 10

CABLE AGING MANAGEMENT AND MAINTENANCE

MAINTENANCE ACTIVITIES FOR CABLE

Nuclear plants are required to develop a surveillance and maintenance program that relates to the continuing qualification of safety-related electrical equipment. An appropriately implemented surveillance and maintenance program assures that environmental qualification is preserved. That is, the equipment will be able to withstand an accident condition on a continuing basis and will not be adversely affected by age-related deterioration. This subsection assesses present generic requirements and concepts and relates them to cable operability.

As part of the demonstration of qualified life in equipment qualification programs, equipment evaluations are prepared identifying equipment or components with a potential for age-related degradation. These evaluations include appropriate plant cabling. Whenever testing and analysis for any safety-related equipment shows that the demonstrated qualified life is less than the life necessary to reach plant retirement, replacement of the equipment or critical component is scheduled under the preventive maintenance program for the plant. In addition, the manufacturers' recommended maintenance, if any, is incorporated into the preventive maintenance program. Deviations from the manufacturer's recommendations are specifically evaluated and justified. For cables, there generally are no recommended maintenance requirements. However, cables in certain applications may have relatively short qualified lives due to local elevated stress conditions. Cables in these applications, such as those near a PWR's pressurizer, have to be replaced periodically (e.g., on 5- to 20-year interval) to assure their ability to function through an accident environment. Most cables in less severe normal environments will not require replacement before 40 years and, in addition, many can be expected to operate indefinitely.

CABLE CONDITION AWARENESS CONCEPTS

While manufacturers do not require any specific maintenance to be performed for low-voltage cables and periodic high-potential testing is inappropriate, cables can deteriorate when subject to adverse conditions. It is difficult to postulate and protect against all adverse conditions. On occasion, unexpected adverse conditions are identified, such as localized hot spots. To help identify adverse conditions and unexpected deterioration, equipment maintenance personnel could inspect the visible portions of leads, terminations and field cables at the time of maintenance of electrical equipment. These visual inspections would attempt to identify discolorations, crazing and cracks that would be indicative of significant deterioration. When cable and leads must be moved during maintenance, a rough indication of the degree of hardening, if any, could also be observed. If an insulation or jacket that is normally pliable when not severely aged is found to be stiffened or cracked during maintenance of the associated component, appropriate actions to evaluate and correct the condition would be taken. Conversely, if no deterioration were noted, the lack of deterioration would be documented on the maintenance procedure form.

The incorporation of inspection of cables at component terminations is appropriate for those components that are connected to or in close proximity to hot process systems or that place a heavy electrical load on the cable (i.e., cause significant ohmic heating of the insulation). Inspection of cables at component terminations is also appropriate for components located in high normal radiation areas (i.e., those having total integrated doses greater than 10 megarads). The types of components for which leads and cables should be inspected include:

- PWR primary loop RTDs that experience significant heating from circulating reactor water
- Motor operators for valves on hot piping systems
- Continuously energized solenoid valves
- Main steam isolation valve limit switches
- Motors that run for long periods during normal operation.

The section of cable near the terminations to these components has a high likelihood of being subjected to significant thermal aging levels. As such if they are not experiencing deterioration, the inference can be drawn that cables that are subject to less severe thermal aging will also not be experiencing deterioration.

The effort required to perform the evaluation of the leads should not extend the duration of a maintenance effort significantly. However, maintenance personnel would have to be provided training regarding conditions that are indicative of deterioration. In addition, engineering personnel would be needed who are capable of evaluating any abnormal cable condition found during these visual inspections. It should be noted that such inspections will not provide a direct indication of the future operability of the cables; however, they will be useful in identifying unexpected deterioration, and will help identify and control hot spots.

Section 11.0

Conclusions and Recommendations

Section 11.0

CONCLUSIONS AND RECOMMENDATIONS

This section provides conclusions and recommendations of the research effort.

CONCLUSIONS

1. Significant operational problems do not exist with the general population of power plant cable. The number of failures has been low in proportion to the amount of installed cable. Those cable insulation problems that have occurred have predominantly been limited to the effects of localized hot spots resulting in premature aging of insulation systems. A review of reported cable failures listed in the nuclear industry (contained in the Licensee Event Reports (LERs) and Nuclear Plant Reliability Data System (NPRDS)) databases and discussion with industry experts indicates that the bulk of the reported cable failures are primarily termination failures. Whereas the majority of such failures are random in nature (i.e., use of wrong crimp tool, etc.), a recurring problem was recognized. This problem relates to the use of poor cable-to-connector terminations (solder joints) at coaxial and triaxial cable connections. The total quantity of such cable/ connector applications is rather limited as these cables/connectors typically service only ex-core or out-of core detectors and radiation monitoring instrumentation. Therefore, this problem appears to be significant and deserves further attention (See Recommendations below).

2. As indicated in Section 8, electrical application stresses on low-voltage cable are such that electrical breakdown under normal conditions is all but precluded. Even substantial reductions in the insulation wall thickness of low voltage cables will not cause cable failures under normal conditions. Essentially, if the integrity of the insulation is retained (i.e., no punctures or cracks), the insulation will continue to perform its electrical function. On the other hand, medium-voltage cable and its terminations have a potential for electrical stress-induced failure if significant cable insulation voids and imperfections exist.

3. The substantial theoretical basis indicating that only a thin insulation wall is required for low voltage cabling, coupled with design basis accident simulation testing, reasonably assures the capability of low-voltage cable to withstand electrical operating stress.

4. With regard to environmental qualification:

   a. Environmental qualification practices, including qualification margins, provide an adequate basis for assuring that common-mode-failure mechanisms from aging and accident conditions do not exist.
   b. Conservative design practices provide further assurance that cables will function adequately under accident conditions. In many cases, design conservatisms (e.g., use of larger ampacity cables than necessary for the application, use of 600 V rated cable for 125 V and less applications) provide additional conservatisms beyond the built-in qualification margins because the actual application of the cables does not stress the cables to the extent that they were stressed in the qualification tests.
   c. Current environmental qualification practice is based on the assumption that cables are properly installed. Wide spread cable installation damage would invalidate this assumption and require remedial action. Unavoidable random installation damage to a limited number of cables in a plant would not invalidate this assumption because redundancy built into the plant design would assure safety function.

5. With regard to condition monitoring and troubleshooting of low-voltage cables:
   a. Industry standards have not previously addressed condition monitoring of low-voltage cable as (a) there has been no historical need, (b) no completely cost-effective method exists, and (c) the need for proving cable capability after more than 40 years of service is new.
   b. Electrical high-voltage or insulation resistance tests without a conductive medium (shield, water, conductive gas) surrounding the insulation cannot reliably indicate even gross cable insulation degradation except for extreme cases (e.g., dead short).
   c. High-voltage testing methods are undesirable for condition monitoring of non-shielded cable and may damage sound cable.
   d. Insulation resistance testing of low-voltage unshielded cable is a go/no go test for severe insulation degradation (i.e., shorts to ground). It is not useful for trending of cable condition. All other testing based on IR such as polarization index is also of little value.
   e. Test methods based on Time Domain Reflectometry (TDR) technology are effective for series impedance problems such as poor terminations. It has not as yet been demonstrated to be effective for determining general cable insulation conditions.
   f. Of all the physical properties that are available to determine acceptability of cable insulation, retained tensile elongation to break appears the most appropriate. On-going research into non-destructive test methods indicates that compressive modulus can be a

useful measure of the condition of insulations. The Indenter Polymer Aging Monitor under development by EPRI measures modulus.

6. The number of failures of medium-voltage cables within nuclear power plants does not warrant the application of condition monitoring of cables for all applications. Recent research results indicate that ac and dc high-potential testing will not detect significant deterioration in most cases. In the case of cross-linked polyethylene medium voltage insulation having water-trees, do high-potential testing will not identify the condition but appears to significantly reduce the remaining life of the cable (Note: The same research program determined that dc high-potential testing of unaged cross-linked polyethylene does not appear to affect service life.). Partial discharge testing appears to be the most promising method for evaluating deterioration of medium voltage cables, but the system is not fully perfected for in plant use.

RECOMMENDATIONS

1. Many within the nuclear industry do not have a sufficient understanding of the cable population, cable practice, cable installation, cable assessment efficacy, and related areas. It is recommended that industry organizations hold workshops on cable practice to promote a better understanding of cable applications and cable operability and to correct misconceptions. Other workshops could concentrate on cable installation practice to reflect the recently identified needs in the area of cable installation.

2. Many of the industry "standard good practices" for cable installation (e.g., sidewall pressure, pulling tension, pulling friction factors) are very conservative as demonstrated by EPRI research. The data from this research should be factored into the existing generation of national consensus guidelines (e.g., IEEE Std 690-1984 [17]). However, care must be taken not to remove all the conservatism that exists between good practice and the ultimate capabilities of cables.

3. Present industry standards (e.g., IEEE Std 690-1984) for cable installation are incomplete in regard to documenting good installation practice. Without such good practice guidelines, utilities are forced to establish their own programs to ensure adequate installations. Furthermore, the present standards provide little guidance on methods to assess or evaluate operability of low-voltage cables that are suspected of being damaged. The only

method included, mentioned, or implied is insulation resistance testing, which is of little value for unshielded low-voltage cable operability assessment.

The IEEE's Insulated Conductors Committee has proposed development of two new standards to address these issues. These are:

- To enhance coverage of IEEE Std 690-1984 to add, "Committee Report - Recommended Practice on Specific Aspects of Cable. Installation in Power Generating Stations," an ICC Task Force 14-1 Report.
- To develop a new standard P1186, "Recommended Practices for the Evaluation of Installed Cable Systems for Class BE Circuits in Nuclear Power Generating Stations"

Research activities sponsored by EPRI, DOE, NRC, and others are recommended to produce the input to the national consensus standards writing efforts needed by industry.

4. The use of high-level constant volts/mil test voltages to assess cable operability is discouraged since it may severely over-test heavy wall cable.

5. Suspect installations may be of less concern in the future due to the generation of new or enhanced installation guidelines. Conversely, currently available test techniques to assess suspect non-shielded cable do not appear effective. It appears prudent for industry to continue research into the development of tools for cable assessment.

6. As stated above under Conclusions, poor cable to connector terminations (solder joints) at coaxial and triaxial cable connections appear to be causing more problems than expected. The total quantity of such cable/ connector applications is rather limited as these cables/connectore typically service only ex-core or out-of core detectors and radiation monitoring instrumentation. Physical inspection of these connections may not be prudent (i.e., due to radiation exposure) or effective (i.e., poor termination may be hidden within a potted connector). Further research may be appropriate in this area. It is possible that Time Domain Reflectometry may be useful to evaluate defective coaxial connections.

7. To assure operability of cable systems, identification and control of hot spots is recommended; this should include, but not be limited to, in-panel local temperatures, instrumentation mounted on process pipes, such as primary loop RTDs, and cables installed near hot proeess piping.

8. Utilities should add a visual inspection requirement to maintenance procedures for cables and leads in the vicinity of equipment that is being maintained to identify unexpected cable deterioration. This effort should be done for components that are in high ambient temperatures, produce high temperatures, or are connected to hot process piping.

Section 12.0

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Section 12.0
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