installed life period from installation to retirement of an SSC

insulation the part that is relied upon to insulate the conductor from other conductors or conducting parts or from ground [A.7]

insulation level 100% cable for use on grounded systems or where the system is provided with relay protection such that ground faults will be cleared as rapidly as possible but in any case within one minute

insulation level 133% cable for use on ungrounded or grounded systems or where the faulted section will be deenergized in a time not exceeding one hour

interstices voids or valleys between individual strands in a conductor or between insulated conductors in a multiconductor cable

jacket a protective covering over the insulation, core, or sheath of a cable [A.6]. A thermoplastic or thermosetting covering, sometimes reinforced, applied over the insulation, core, metallic sheath, or armor of a cable [A.7]

lay the total amount of stranding required to form one completed twist of a cable

life period from fabrication to retirement of an SSC

life assessment synonym for ***aging assessment***

life cycle management synonym for ***life management***

life management integration of aging management and economic planning to: (1) optimize the operation, maintenance, and useful life of SSCs; (2) maintain an acceptable level of performance and safety; and (3) maximize return on investment over the useful life of the plant

lifetime synonym for ***life***

maintenance aggregate of direct and supporting actions that detect, preclude, or mitigate degradation of a functioning SSC or restore to an acceptable level the design functions of a failed SSC

malfunction synonym for ***failure***

margin the difference between the most severe specified service conditions of the plant and the conditions used in type testing to account for normal variations in commercial production of equipment and reasonable errors in defining satisfactory performance [A.8]

mean time between failures arithmetic average of operating times between failures of an item [IEEE Std 100] [A.7]

natural aging aging of an SSC that occurs under pre-service and service conditions, including error-induced conditions

normal aging natural aging from error-free pre-service or service conditions

normal aging degradation aging degradation produced by normal conditions

normal conditions operating conditions of a properly designed, fabricated, installed, operated, and maintained SSC excluding design basis event conditions

normal operating conditions synonym for *normal conditions*

normal stressor stressor that stems from normal conditions and can produce aging mechanisms and effects in an SSC

operating conditions service conditions, including normal and error-induced conditions, prior to the start of a design basis accident or earthquake

operating service conditions synonym for *operating conditions*

operational conditions synonym for functional conditions

overcurrent any current in excess of the rated current of equipment or the ampacity of a conductor. It may result from overload, short circuit, or ground fault [A.6]

overhaul (noun) extensive repair, refurbishment, or both

performance indicator synonym for *functional indicator*

periodic maintenance form of preventive maintenance consisting of servicing, parts replacement, surveillance, or testing at predetermined intervals of calendar time, operating time, or number of cycles

planned maintenance form of preventive maintenance consisting of refurbishment or replacement that is scheduled and performed prior to failure of an SSC

post-maintenance testing testing after maintenance to verify that maintenance was performed correctly and that the SSC can function within acceptance criteria

potting the sealing of a cable termination or other component with a liquid which thermosets into an elastomer

preconditioning synonym for *age conditioning*

predictive maintenance form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose, or trend an SSC's functional or condition indicators; results indicate current and future functional ability or the nature and schedule for planned maintenance

premature aging aging effects of an SSC that occur earlier than expected because of errors or pre-service and service conditions not considered explicitly in design

pre-service conditions actual physical states or influences on an SSC prior to initial operation (e.g., fabrication, storage, transportation, installation, and pre-operational testing)

preventive maintenance actions that detect, preclude, or mitigate degradation of a functional SSC to sustain or extend its useful life by controlling degradation and failures to an acceptable level; there are three types of preventive maintenance: periodic, predictive, and planned.

pulling tension the longitudinal force exerted on a cable during installation [A.7]

qualification verification of design limited to demonstrating that the electric equipment is capable of performing its safety functions under significant environmental stresses resulting from design basis accidents in order to avoid common-cause failures [A.11]

qualified life period for which an SSC has been demonstrated, through testing, analysis, or experience, to be capable of functioning within acceptance criteria during specified operating conditions while retaining the ability to perform its safety functions in a design basis accident or earthquake

raceway an enclosed channel designed expressly for holding wires, cables, or busbars, with additional functions as permitted in this Code [A.6]

radiation damage threshold the lowest dose which induces permanent change in a measured property(s) of a material; also, the first detectable change in a property of a material due to the effect of radiation

random failure any failure whose cause or mechanism, or both, makes its time of occurrence unpredictable [IEEE Std 100]

reconditioning synonym for *overhaul*

refurbishment planned actions to improve the condition of an unfailed SSC

remaining design life period from a stated time to planned retirement of an SSC

remaining life actual period from a stated time to retirement of an SSC

remaining service life synonym for *remaining life*

remaining useful life synonym for *remaining life*

repair actions to return a failed SSC to an acceptable condition

replacement removal of an undegraded, degraded, or failed SSC or a part thereof and installation of another in its place that can function within the original acceptance criteria

residual life synonym for *remaining life*

retirement final withdrawal from service of an SSC

rework correction of an inadequately performed fabrication, installation, or maintenance

root cause fundamental reason(s) for an observed condition of an SSC that if corrected prevents recurrence of the condition

root cause analysis synonym for *failure analysis*

routing the path followed by a cable or conductor

safety function the required action, non-action, or non-failure of safety-related equipment

safety-related equipment that is relied upon to remain functional during and following design basis events to ensure (i) the integrity of the reactor coolant pressure boundary, (ii) the capability to shut down the reactor and maintain it in a safe shutdown condition, and (iii) the capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposures comparable to 10CFR Part 100 guidelines. Safety-related electric equipment is referred to as Class 1E in IEEE 323-1974 [A.12]

screen a semiconducting layer used under and over the insulation of power cables rated over 2 kV to reduce electrical stresses and corona

screened conductor cable a cable in which the insulated conductor or conductors are enclosed in a conducting envelope or envelopes

semiconducting layer an extruded layer or tape of such resistance that when applied between two elements of a cable the adjacent surfaces of the two elements will maintain substantially the same potential.

service conditions actual physical states or influences during the service life of an SSC, including operating conditions (normal and error-induced), design basis event conditions, and post design basis event conditions

service life actual period from initial operation to retirement of an SSC

servicing routine actions (including cleaning, adjustment, calibration, and replacement of consumables) that sustain or extend the useful life of an SSC

sheath the overall protective covering for the insulated cable [A.7]

shield as normally applied to instrumentation cables, refers to a metallic sheath (usually copper or aluminum) applied over the insulation of a conductor or conductors for the purpose of providing means for reducing electrostatic coupling between the conductors so shielded and others which may be susceptible to or which may be generating unwanted (noise) electrostatic fields [A.7]

sidewall bearing pressure the crushing force exerted on a cable during installation [A.7]

significant aging mechanism an aging mechanism which could potentially affect the functionality of the equipment if left unmitigated (see Section 4)

significant and observed aging mechanism the subset of significant aging mechanisms which are reflected in empirical and/or anecdotal failure data (see Section 4)

simultaneous effects combined effects from stressors acting simultaneously

solid conductor a single unit not divided into parts

stress synonym for *stressor*

stressor agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation of an SSC

surveillance observation or measurement of condition or functional indicators to verify that an SSC currently can function within acceptance criteria

surveillance requirements test, calibration, or inspection to assure that the necessary quality of systems and components is maintained, that facility operation will be within the safety limits, and that the limiting conditions of operation will be met [10 CFR 50.36][A.13] (use only when specific regulatory and legal connotations are called for)

surveillance testing synonym for *surveillance*, *surveillance requirements*, and *testing* (use only when specific regulatory and legal connotations are called for)

tape wrap a spirally or longitudinally applied tape over an insulated or uninsulated wire

synergistic effects portion of changes in characteristics of an SSC produced solely by the interaction of stressors acting simultaneously, as distinguished from changes produced by superposition from each stressor acting independently

temperature rating the maximum possible normal and accident operating temperatures for a cable; typically written on the outer covering of a cable

testing observation or measurement of condition indicators under controlled conditions to verify that an SSC currently conforms to acceptance criteria

thermal aging one method of accelerated aging, usually associated with the Arrhenius model

thermal life the period of time for which a piece of equipment has been evaluated, on the basis of Arrhenius plots of materials, to be able to endure thermal conditions and still perform its required safety function during or after the occurrence of harsh environment conditions

time in service time from initial operation of an SSC to a stated time

useful life synonym for *service life*

voltage drop the difference in voltage between the two different ends of a cable

wearout failure produced by an aging mechanism

wire a factory assembly of one or more insulated conductors without an overall covering [A.6]

A.1 References

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A.4 D. Fink and H. Beaty, Standard Handbook for Electrical Engineers, Twelfth Edition, McGraw-Hill, New York, 1987.

A.5 NRC IE Bulletin 79-01B, "Environmental Qualification of Class 1E Equipment," Nuclear Regulatory Commission, January 14, 1980, [ftp://ftp.fedworld.gov/pub/nrc-gc/bl79001b.txt]

A.6 National Electrical Code® - 1990 (NFPA 70), National Fire Protection Association, Batterymarch Park, Quincy, MA, ©1989.

A.7 IEEE Standard 100-1984, "Standard Dictionary of Electrical and Electronics Terms," Institute of Electrical and Electronics Engineers, 1984.

A.8 IEEE Standard 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," The Institute of Electrical and Electronics Engineers, Inc., corrected copy June 1976

A.9 EPRI NP-1558, "A Review of Equipment Aging Theory and Technology," prepared by Franklin Research Center for the Electric Power Research Institute, September 1980.

A.10 ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, 1995 Edition, The American Society of Mechanical Engineers.

APPENDIX B. DESCRIPTION OF COMPONENTS

B.1 Component Descriptions - Cable and Wire

Conductors

Conductor electrical and mechanical properties are largely the result of the material used in fabrication of the conductor. In addition to the electrical requirements, mechanical properties of the conductor (such as tensile strength, weight, diameter, and thermal coefficient of expansion) is considered when choosing a material. Cable conductors used in nuclear plant applications are normally manufactured from copper (coated or noncoated), aluminum, or copper-clad aluminum.[1] Coating of copper conductors helps prevent conductor corrosion and ease insulation stripping and termination soldering. Copper-clad aluminum is predominantly used to prevent corrosion of the conductor [B.1], [B.2], [B.3], [B.4].

Copper conductors are the most popular type of conductor because of the following advantages: copper volume conductivity is greater than that of aluminum, thereby requiring less insulation, jacketing, and other materials; copper cable is smaller at equal ampacity levels, thereby requiring smaller conduit; and, copper cable is more economical.[2] In addition, aluminum conductors are susceptible to cold flow (creep), which can result in high resistance connections and increased ohmic heating. Contact of aluminum conductors with dissimilar metals may result in electrolytic corrosion if interposing coatings are not applied. Furthermore, aluminum conductors oxidize to a compound (aluminum oxide) that is nonconducting; therefore, special preparation of the termination area is required to remove and inhibit the formation of aluminum oxide. One benefit of aluminum conductors is their comparatively low weight for the same ampacity; therefore, based on the cost differential between aluminum and copper, aluminum conductors are usually only considered for larger sizes of power cable.

In the United States, conductors are most often sized according to the American Wire Gauge (AWG) system,[3] which is based on a constant mathematical ratio between diameters of successive gauge numbers (thus, the smaller the AWG number, the larger the cable). Typical indices for measuring conductor size include AWG number or kcmil (1 kcmil = 1 MCM = 1000 circular mils). A mil is defined as one thousandth of an inch, whereas a circular mil is the area of a circle one mil in diameter (equal to 0.7854 square mils) [B.1].

Most cable conductors are stranded, which is the twisting together of wire strands to form a conductor. ASTM B33 [B.5] defines the construction of a stranded copper conductor;

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[1] Other conductor materials include copper-clad steel, copper-chromium alloy, zinc-coated steel, copper beryllium alloy, aluminum-clad steel, and bronze; however, no cables using these materials were identified as being in use in U.S. commercial nuclear plants in any appreciable quantity.

[2] For a few years during the 1970s, the price of copper increased dramatically from its historical norms. Aluminum wires and connections were used in much greater quantities until the price of copper decreased to its typical market level.

[3] Other wire gauge measurements, such as the Steel, Birmingham, Standard (British), Old English, Millimeter, and German wire gauges are in varying degrees of use outside the nuclear industry.

the stranding class denotes the number and size of wires used in forming a given conductor. The purpose of stranding conductor cable is to produce a greater amount of flexibility. However, stranding generally results in increased weight and electrical resistance (due to increased conductor length), and may slightly reduce the tensile strength of the conductor. Most of the cable installed in nuclear plants uses stranded conductors; exceptions may include some coaxial/triaxial cables, mineral insulated (MI) cable, and thermocouple extension wire. Figure B-1 shows the conductor configuration of a typical nuclear plant medium-voltage power cable. Figure B-2 shows a typical shielded low-voltage control cable.

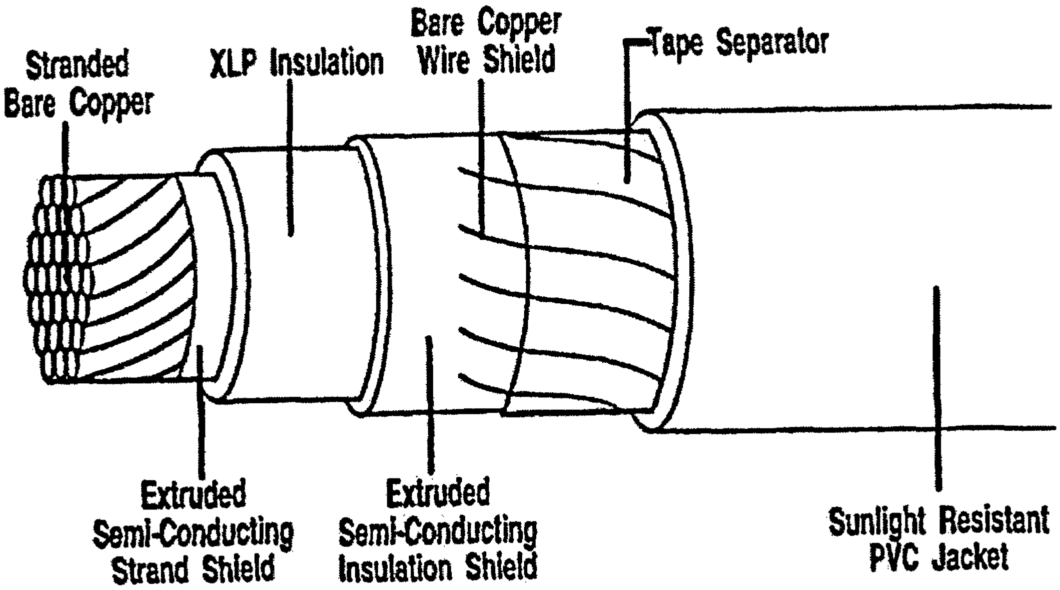

Figure B-1 Cross Section of Typical Medium-Voltage Electrical Power Cable

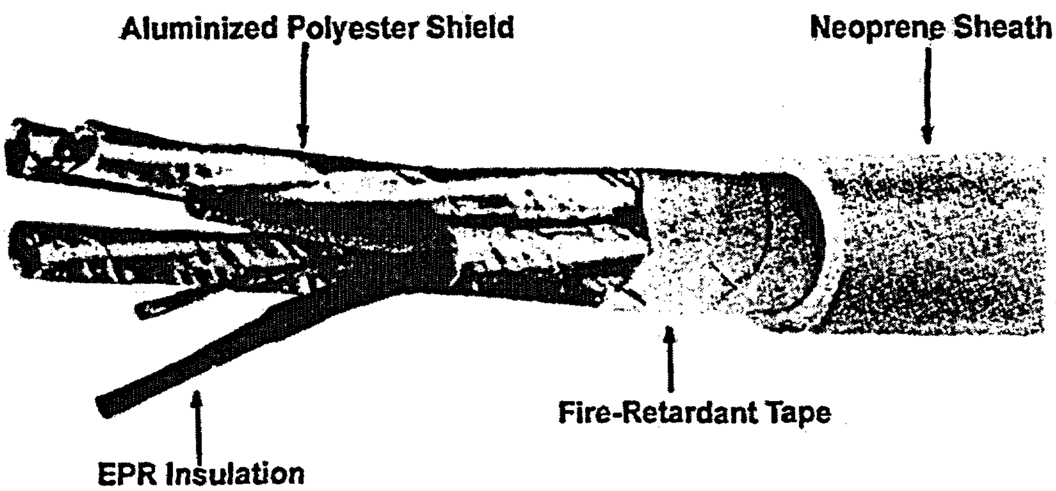

Figure B-2 Typical Low-Voltage Shielded Control Cable

Thermocouple extension wire generally uses solid metal alloy conductors; these alloys are chosen for their specific electrical characteristics (i.e., dissimilar metals produce an electromotive force (emf) or voltage that varies with the temperature of the junction). The inclusion of these alloys permits use of a known temperature-versus-voltage response curve. These cables are often composed of a twisted, shielded pair of conductors to minimize electromagnetic noise interference [B.2], [B.3]. A thermocouple extension is composed of the same materials as the junction to prevent formation of additional potentials at the interface between the junction and the extension cable.

Appendix C is a partial listing of standards related to electrical conductors.

Electrical Insulation and Semi-Conducting Shield

Essentially any material that has a high resistance to the flow of electric current can be used as insulation on an electrical cable. Material selection is based on the intended application and function, including the intended service voltage. Standard insulation ratings for nuclear plant cable include 300 and 600 Vac; 2, 5, 8 and 15 kVac; and 125 or 250 Vdc. Normal operating voltages are typically well below the ratings (i.e., 480 Vac for 600-V rated cable, 4160 Vac for 5-kV rated cable, etc.). Voltage applied to the dielectric may increase significantly during transient system operation, switching, surges, or faults.

The ability of an insulation to withstand such voltage stress without significant current flow through the insulation is measured by the material's dielectric strength. Dielectric strength is related not only to the electrical and physical properties of the insulation material, but also to the thickness of that material. Hence high dielectric strength material may be used in lesser thicknesses to achieve the same insulation capability as a lower dielectric strength material. Use of thinner insulation has substantial benefits with regard to cost, overall cable size and weight, and heat dissipation. Insulation thicknesses suitable for a given voltage rating are specified by ICEA and AEIC standards for each of the common cable insulating materials.

The following cable design characteristics are influential in the selection of a particular material: insulation temperature rating (with respect to normal and accident maximum operating conditions), dielectric strength, moisture resistance, flame resistance, flexibility, size, and weathering properties. Other mechanical and electrical properties that can influence the selection of a material include tensile strength, elongation, modulus of elasticity, hardness, partial discharge level, dissipation factor, insulation resistance (IR), and power factor [B.1], [B.2], [B.3].

Certain manufacturers' medium-voltage cable uses a "shield"[4] layer installed between the conductor and the insulation. The purpose of this layer is to reduce or control the dielectric stress between the conductor and the insulation and drain charges at the surface of the insulation such that large potential gradients do not occur at discontinuities between the insulation and the conductor. This layer is typically semi- or nonconducting, and provides several functions, including (1) reduction or elimination of voids between the conductor and insulation,

[4] This is not a shield in the sense of an electric or magnetic field shield. It is a mechanism to limit aging degradation of insulation due to voltage stress.

(2) reduction of electrical stress across the insulation, and (3) reduction of charge injection into the insulation [B.3], [B.6].

Voltage Withstand

Most power plant cable is not subject to lightning- or switching-induced surges; however, most cables are designed with sufficient basic impulse insulation level (BIL) capability so as to withstand the significant voltage stress resulting from these events. This capability is typically expressed in terms of voltage withstand capability (i.e., 110-kV BIL for a 15-kV power cable), and is somewhat higher for cable than that of other electrical distribution equipment. In general, however, the 60-Hz requirements of a cable dictate the insulation characteristics (rather than the BIL requirements) [B.1], [B.3].

Overload Characteristics

Insulation level, which is a measure of the material's ability to withstand fault conditions for given periods of time without experiencing dielectric breakdown, is another measurement of the capability of an insulating material. It is related to the thermal capability and physical properties of the material. Selection of a insulation level for a specific application is made based on the phase-to-phase voltage, and the type of system (i.e., grounded or ungrounded). Three distinct levels are specified [B.1], [B.2], [B.3], [B.6]:

100% Level: These cables may be applied on systems with sufficient protection such that ground faults will be rapidly cleared (within 1 min). 100% cables are primarily used on grounded systems.

133% Level: Cables in this category are used in primarily in ungrounded systems or where the clearing time requirements of the 100% level can not be met. A maximum clearing time requirement of 1 hr is imposed on cable of this type.

173% Level: Cables in this category are used in applications where the duration of the ground is indefinite.

Insulation Materials

Cable and wire insulation and dielectric materials include the following [B.1], [B.2], [B.3], [B.4], [B.6], [B.7], [B.8], [B.9], [B.10], [B.11], [B.12], [B.13], [B.14].

- Cross-linked polyethylene/polyolefin (XLPE/XLPO)
- Low molecular weight polyethylene (LMWPE)
- High molecular weight polyethylene (HMWPE)
- Chlorinated polyethylene (CPE)

- Hypalon® (Chlorosulfonated polyethylene (CSPE))
- Ethylene propylene rubber (EPR)
- Neoprene® rubber
- Nitrile rubber
- Butyl rubber
- Polyvinyl chloride (PVC)
- Silicone rubber (SR)
- Tefzel® (ethylene tetrafluoroethylene (ETFE))
- Kapton® (polyimide)
- Alkane imide
- Mineral insulation (MI)
- PEEK (polyethyl-ethyl ketone)

Each of these materials has unique thermal, irradiation, mechanical, chemical, and dielectric properties that make it suited for specific types of nuclear plant applications. Note that some materials (such as neoprene, PVC, and Hypalon®) may also be used as jacketing materials. Generally, these materials may be divided into two categories: organic and inorganic. Organic insulating materials (by far, the more prevalent of the two) can be further classified by their thermal characteristics as either thermosetting, thermoplastic, or elastomeric.

Thermosets are polymers that are cured or permanently set into shape. This curing is an irreversible reaction known as crosslinking, which results from exposure to heat or ionizing radiation. Once crosslinked, the material cannot be returned to its original state. Thermoset materials include polyesters, urethanes, epoxies, phenolics, and silicones [B.15].

Thermoplastics are not cured or permanently set with heat. These materials will melt under sufficient heat and may be subsequently reformed. Thermal degradation of the material limits the number of times a thermoplastic may be reheated and reformed. The molecular structure of thermoplastics is flexible compared with that of thermosets. Common thermoplastics include polyethylenes (crosslinked, and low/high density) and polypropylenes, polyimide,[5] vinyl (PVC), and fluorocarbon polymers (such as Teflon® and Tefzel®) [B.15].

[5] Polyimide (Kapton®) does not melt but rather decomposes at extremely high temperature.

Elastomers are rubber-like polymers whose service temperature is above their glass transition temperature.[6] Rubber is a natural material, whereas synthetic rubbers are materials synthesized to reproduce the best characteristics of natural rubber. Common cable elastomers include EPR, CSPE, styrene-butadiene rubber (SBR), butyl, nitrile, silicone, and neoprene rubbers [B.15].

Elastomers and thermoplastics (specifically EPR/EPDM and XLPE, respectively) are the most commonly used materials for nuclear plant cable insulation based on their low relative cost, good overall mechanical and electrical properties, and good availability. See discussion of EPRI NUS database contained in Section 3 of this guideline.

Polyethylene (a polyolefin) is a common cable insulation material. Three different grades or types are specified: low density, medium density, and high density polyethylene. High density polyethylene is used primarily in medium-voltage applications. Low-density is often used as a dielectric in coaxial or triaxial cables. Polyethylene may also be of the crosslinked variety, which refers to the chemical bonding or crosslinking between individual polyethylene molecules that occurs within the material. Low/medium/high density polyethylene has somewhat differing properties than crosslinked polyethylene. Various manufacturing processes control the size, disposition, and amount of crosslinking occurring in a specific type of polyethylene. Crosslinking in polyethylene used in electrical cable applications is usually achieved by one of two methods: chemical crosslinking or radiation crosslinking. The former method uses a chemical agent (such as a peroxide) to induce the crosslinking reaction, where as radiation (typically an electron beam) is used for the latter. Exposure to either of these processes results in a material with substantially increased properties over standard polyethylene [B.15], [B.16].

Other variants of the polyethylene family include chlorinated polyethylene (CPE) and chlorosulfonated polyethylene (CSPE, or Hypalon®). CPE is chemically cured and produced in varying grades based on chlorine content; higher chlorine content yields better fuel/oil resistance, gas impermeability, and tear resistance, whereas lower content gives better heat resistance and compression set. Hypalon® is an ethylene co-polymer that is added in varying quantities to elastomers to improve their properties such as ozone, chemical, or abrasion resistance. Hypalon® and CPE are used primarily as jacketing materials in nuclear plant cable, although some use of these materials as insulation has occurred [B.2], [B.15].

Polyvinyl chloride (PVC) is widely used as insulation due to its good mechanical and electrical properties, and low relative cost. It is also highly resistant to moisture and many chemicals. However, PVC is not very resistant to thermal or irradiation degradation, and hence is not frequently used in applications subjected to such environments.

Silicone rubber (SR) is often used as an insulation material in high ambient temperature environments because of its high resistance to thermal degradation. However, SR does have relatively poor resistance to cutting, tearing, and abrasion; therefore, silicone rubber-insulated

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[6] Per Reference [B.15], an elastomer is defined as (1) capable of being stretched 100%, and (2) after being stretched and held for 5 min, capable of retracting to within 10% of its original length within 5 min of release.

cables are often encased in a protective sheath or braid. Silicone rubber is also more expensive than typical EPR or XLPE-insulated cables, and is used to a lesser degree in nuclear plants [B.2].

Kapton® is a trade name for a polyimide film developed by E.I. duPont de Nemours Inc. Kapton® is typically applied by wrapping it around the conductor, rather than being extruded or injected. It is often used in conjunction with a fluoropolymer (such as Teflon®) in these applications. Kapton® has high thermal and radiation resistance in comparison to other common insulation materials, yet suffers other drawbacks with respect to properties under exposure to moisture and caustics, and resistance to incidental surface damage such as nicks and cuts. Kapton® is most often found in instrument or solenoid leads or electrical penetration assemblies, and is rarely[7] used in bulk cable runs in nuclear plants [B.17].

Tefzel® is a thermoplastic fluoropolymer with overall excellent electrical and mechanical properties. Tefzel® has a high resistance to thermal degradation and outstanding resistance to most chemicals. Radiation resistance is fair in comparison to other thermoplastics, and markedly better than Teflon® (another fluoropolymer) [B.18].

Specific formulations of the materials listed above vary significantly among different manufacturers, and other ingredients (such as fillers and plasticizers) are included with the base material to enhance material properties and/or reduce cost. The practical significance of different formulations is that each different cable type using ostensibly the same generic material (such as EPR) may have substantially different properties based on the differences in additives and formulation. Furthermore, differences or inconsistencies in the fabrication and extrusion processes (such as void formation or inclusions) may produce significantly different results in terms of the insulation's resistance to voltage stress over time; this is especially critical in medium-voltage cable, which experiences a proportionately higher voltage stress than low-voltage insulation.

Inorganic materials used in power plant cable insulation include various oxides such as magnesium, aluminum, and silicone (hence the term "mineral insulated"). These inorganic materials have extremely high resistance to thermal and radiation exposure; however, they are comparatively expensive, difficult to terminate, and have limited flexibility compared to thermoplastic or elastomeric insulation. In addition, they are typically hygroscopic (i.e., water absorbing) and require sealing from the effects of moisture via metal sheathing. Accordingly, they are used only in very limited applications requiring their unique properties, and only a small fraction of cable installed in the typical nuclear plant is mineral insulated [B.2].

Thermal Ratings

Organic cable insulation typically has three different thermal ratings: one for normal operation (continuous operation at normal current levels), one for emergency overload (short-term use at currents somewhat in excess of normal levels), and one for short circuit conditions (extremely short duration operation at currents substantially in excess of normal levels). These

[7] The most notable use of Kapton in nuclear plants is associated with leads in electrical penetration assemblies.

ratings take the form of maximum conductor temperatures at which the cable may operate, and are not necessarily indicative of the maximum ambient temperature in which the cable may be safely used. Ohmic heating of the conductor is a function of both the ambient temperature in which the cable is located and the relationship of the current to the rated ampacity of the cable; therefore, the effects of both ambient temperature and ohmic heating must be considered when evaluating the suitability of a given cable insulation's continuous thermal rating [B.1], [B.2], [B.3].

The longevity of the cable insulation is primarily related to the temperature at which it operates.[8] The term "continuous" in this context does not connote indefinite lifetime at the rated temperature; rather, it simply means that the cable may be operated for extended periods continuously at that conductor temperature with no significant insulation damage or loss of electrical properties.

Thermal ratings for continuous operation will vary from material to material; however, they generally fall in the range of 60°C to 125°C for most nuclear plant organic cables, with the majority being rated for 90°C [B.1], [B.2], [B.3], [B.4], [B.11], [B.19], [B.20]. Some of the high-temperature thermoplastics (such as Tefzel®) have thermal ratings of 150°C. Thermal ratings for a given insulation material may vary depending on the application and environment in which the cable is used; for example, some industry standards reduce the thermal rating of insulation if it is exposed to moisture (wet versus dry rating). Furthermore, some disparity exists within the industry as to the appropriate rating for a given material. EPR, for example, may be rated at 75°C in one standard and 90°C in another. Variations in thermal rating also occur based on the type or formulation of material used. For example, PVC insulation rated to 60°C, 75°C, and 90°C may be produced by the same manufacturer for different applications.

Thermal ratings for emergency overload are greater than those for continuous operation (typically 130° to 140°C for a cable rated at 90°C continuous temperature). Short-circuit ratings are generally much higher than the overload rating (generally 250°C), owing largely to the comparatively short fault clearing time as compared with operation under overload conditions. In determining the short circuit rating, consideration is given to the type of insulation material and its physical properties such as resistance to thermal aging and melting point [B.1], [B.3].

Flammability

In addition to resistance to thermal degradation, nuclear plant cable polymers are designed to resist combustion and the production of harmful atmospheric contaminants (including smoke and carbon monoxide). During combustion of a polymer, external heat dissociates (pyrolyzes) the material into various liquids and gases that fuel the combustion process. Flame-retardant additives affect this process through a number of different mechanisms, including interference with combustion reactions, reducing the rate of heat transfer from the flame to the polymer (thereby reducing the rate of pyrolyzation), interfering with the flammability of the pyrolysis by-

[8] With the exception of those cables exposed to other environmental or mechanical influences (such as substantial radiation dose) which may be the limiting factor in terms of insulation service life.

products, and reducing the diffusion rate for these by-products to the flame location. Various chemical agents are used (depending on the type of polymer and its predominant combustion processes) to control the flammability of cable materials. These include (but are not limited to) phosphorous, nitrogen, iodine, fluorine, chlorine, antimony, bismuth, and boron. Some consideration should be given to the effect of these agents on the physical, chemical, and electrical properties of the base material; even small amounts of fire-retardant may produce significant changes in these properties [B.10].

Filler Material

Filler material is used in electrical cable to fill the interstitial regions between individual conductors, thereby providing a more rigid and mechanically stable substrate upon which the outer shield and jacketing layers are applied. Filler also helps prevent migration of moisture longitudinally through the inner regions of the cable; accordingly, it is typically composed of nonhygroscopic (non-water absorbing) organic material so as to preclude swelling and potentially damaging stresses on binding tapes, shields, and cable outer jacketing. The filler material may be either extruded around the conductors during the fabrication process or composed of several discrete segments that are included with the conductors prior to application of the binder tape, shielding, and outer jacket. Filler material in this context should be differentiated from that used in the chemical formulation of insulation or jacketing polymers described previously; chemical filler is generally an inert compound used to improve the chemical and physical properties of the insulation/jacket (such as resistance to thermal aging or oil resistance) and/or reduce its cost [B.3], [B.4], [B.10], [B.12], [B.13].

Tape Wraps

Tape wraps are an economical method of providing added electrical or mechanical protection, or providing other functions. These wraps may be used to bind those components enclosed within the wrap together (to add additional mechanical stability and strength, or hold components in place during the manufacturing process), to provide additional electrical insulation or semiconducting properties, to identify individual conductors or conductor groupings, or to provide shielding of the conductors for electric and magnetic fields (see the discussion of shielding below). Tape wraps may be composed of a variety of materials depending on their purpose, including polymers (such as Mylar), metals (generally copper or aluminum), semiconducting materials (including thermoplastics, woven fabrics, or paint), or combinations thereof. These materials are often nonhygroscopic and flame-retardant. Tape wraps are typically applied in a layer between the conductor insulation and the outer jacket or shield (if installed), depending on the design requirements of the cable. Tape wrap thickness will vary based on design requirements, but generally is on the order of 1 to 2 mils. Tape wraps may be applied either radially (wound around the core in a helical fashion) or longitudinally (parallel with the central axis of the cable). Drain wires (uninsulated small-gauge conductors) are frequently used as a ground connection for metallic tape wraps; these wires are laid in physical contact with the metallic wrap during fabrication so that ground potential is maintained on the wrap during cable operation [B.1], [B.2], [B.3], [B.12], [B.13].

Shielding

Shielding is commonly used in instrumentation, control, and thermocouple extension applications to control electromagnetic and electrostatic effects on the conductor from external magnetic and electric fields. Similarly, shielding is used on medium (and high) voltage power applications to reduce electric field intensity generated external to the cable by the energized conductor, and limit radio frequency interference. A third function of shielding is to reduce the magnitude of transient voltages in control cables. Shielding helps preclude an uneven voltage gradient resulting from the electric field distribution of an unshielded cable in contact with ground. In medium-voltage cable (5 kV and greater), a symmetrical radial distribution of voltage stress can be obtained if shielding is used; however, nonshielded power cables may be used up to 8 kV under certain conditions [B.2]. The shield on a coaxial/triaxial cable acts as a conductor (signal return path) as well as shielding electric fields [B.1], [B.2], [B.3], [B.4], [B.12], [B.13].

The electrostatic shield is typically composed of either (1) a metallic tape (usually copper, cupro-nickel, zinc, lead, or aluminum) wound helically over the top of the underlying surface, (2) metallic braid, or (3) concentric wires. Power cable shielding components may also include a semiconducting shield screen, which is applied between the conductor insulation (or filler) and shield. This screen acts to fill the void space between the shield and the insulation. Due to the relatively high potentials at which shielded power cables are operated, a substantial voltage gradient may otherwise exist across this void space (air gap); this could result in ionization of the air and potential electrostatic discharge (corona). This effect would eventually result in deterioration of the insulation and cable failure. The semiconducting screen eliminates these air gaps and any associated voltage stress by equalizing the potential of the shield (ground) to that of the outer surface of the insulation. A drain wire is also used to electrically terminate or ground the shield; significant electrostatic potentials may build up on the shield if not properly grounded. In power cable shields that are grounded at two points, significant ohmic heating may result from circulating currents generated in the shield and drains. Drain wires are normally made of tinned copper or aluminum, and run the length of the cable [B.1], [B.2], [B.3], [B.12], [B.13].

Shielding from the effects of external magnetic fields is accomplished in instrumentation and control cables by twisting pairs or triads of conductors. The use of magnetic materials for shielding is not presently considered cost effective; however, new materials that may reduce this cost are currently under development [B.1].

Jacketing

Jacketing refers to a broad range of coverings used in cable construction, which is designed to protect various cable components from environmental effects. External (outer) jacketing is used to protect the underlying insulation, shields, and tapes from mechanical damage (such as abrasion or cutting), fire, chemicals, sunlight, moisture, and the effects of direct burial. Typical external jacket materials include neoprene, PVC, Hypalon®, chlorinated polyethylene (CPE), Tefzel®, Teflon®, nylon, polyethylene (high molecular weight), polyurethane, and glass or asbestos braids. These materials provide sufficient protective capability without inordinately affecting cable flexibility. Jackets for specialty cables (such as those exposed to high

temperatures or radiation) may consist of asbestos, glass, or other such resistant materials. External jacketing may also insulate any shielding or armor from ground, thereby allowing for single point grounding of the cable. In unshielded power cable, potential gradients can exist at the surface of the outer jacket, thereby resulting in tangential voltage stress between various points. If the jacketing material is not properly formulated, current can flow along the surface of the jacketing (surface tracking). Accordingly, special discharge-resistant materials are used to prevent this phenomenon. Jacket thickness varies with cable size, number of conductors, and materials of construction.

Similarly, conductor jacketing serves to protect the individual conductors and insulation from damage or degradation, especially in those applications where the individual conductors are exposed such as near terminations or splices. Some of the materials used in external jacketing may be found on individual conductor jackets (such as Hypalon®, nylon, PVC, and glass/asbestos braid); however, these are generally much thinner layers than the outer jackets, and may be thermally or chemically bonded to the underlying insulation [B.1], [B.2], [B.3], [B.12], [B.13].

Armor and Sheathing

Armor/sheathing is used on some cables to provide additional resistance to mechanical damage, moisture, liquids, and gases. Armor is usually composed of either lead, aluminum, or galvanized steel tape helically wound around the outside of the cable, except in applications where the cable will be exposed to severe environments such as those resulting from direct burial, embedment in concrete, or exposure to corrosive substances, or where single point grounding of the armor is desired; in these latter instances, an outer nonmetallic jacket (such as PVC) is applied over the armor. The edges of the armor tape generally overlap (interlock) so that both uniform protection and adequate flexibility are maintained. Armor may also be braided to provide increased flexibility and smaller diameter than the helical interlocking armor. The thickness of the armor varies based on cable size and material; however, these coverings are usually of sufficient thickness to protect the underlying cable from all but the most severe stressors. In general, only a very small percentage of cable used in the typical nuclear power plant (linear footage) is armored [B.1], [B.2], [B.3], [B.12], [B.13].

B.2 Component Descriptions - Terminations

Compression Fittings (Pressure Connections)

Pressure connectors are terminations used to connect the conductor of a wire or cable to another conductor or termination. They use pressure to form and maintain contact between the connector fitting (lug) and the conductor(s) being terminated. Pressure fittings may be applied to both single and multi-stranded conductors, and generally fall into one of two major categories; crimped or mechanical. Crimped lugs are attached by the pressure applied by a crimping tool, and deformation of the metal of the lug and the cable conductor during the crimping process results in a tight connection between the two components. Once crimped and deformed, the metal lug cannot be reused and is discarded upon removal. Use of the properly sized crimping tool and proper pressure are essential to effective crimp formation; furthermore, the crimp lug

must be correctly sized to the conductor being terminated (or fill material used if the lug is oversized).

Mechanical pressure fittings are similar to compression lugs, with the exception that the lug contains a separate mechanism for establishing the pressure connection. For example, a threaded bolt or set screw is used to create the required pressure on the conductor; tightening the bolt/screw deforms the conductor and creates the electrical connection. Because the bolt does not deform significantly when tightened, it (and the rest of the fitting) may be removed and refitted. As with crimped fittings, mechanical fittings must be appropriately sized for the conductor being terminated, and an undeformed section of conductor should be exposed when terminating the cable to ensure proper connection and prevent subsequent loosening of the fitting.

Fusion Connections

Fusion connections are formed by the fusion of the conductor material with that of another conductor via welding, brazing, or soldering. These are permanent connections, which require significant effort to determinate and reattach. Advantages of this type of connection include generally high strength and resistance to loosening caused by vibration or other mechanical stresses (loosening results in high electrical resistance). These types of connections are typically used in applications requiring a permanent, stress-resistant connection (such as medium-voltage power cable), where the allowable space for (or access to) the fitting is limited (such as in a multi-pin connector), or where access may be restricted after the initial connection is made [B.1], [B.3], [B.21].

Terminal Blocks

Terminal blocks are components that are mounted in fixed positions inside an electrical device where a number of wire connections must be made. Terminal blocks simplify the connection of wires from different components. Due to their fixed position, controlled grouping and routing of wires inside electrical enclosures is possible. This orderly layout permits rapid, accurate wire installation and speeds maintenance and troubleshooting operations. Terminal blocks are typically installed inside junction boxes or equipment for protection from both physical and environmental damage. Common nuclear plant terminal block manufacturers include GE, Westinghouse, Marathon, States, Kulka, Weidmuller, and Buchanan.

The common one-piece terminal block usually comes in standard units of 2, 4, 6, 8, or 12 terminals on a single base. The terminals can be located on a rigid insulating member, or between barriers that are open (allowing easy access to the contacts) or closed (protecting the contacts from external effects). The terminals themselves are made of conducting material and generally use a post/nut type arrangement for fastening the wire termination to the terminal. The terminal block base is fabricated from a nonconducting material such as phenolic, nylon, or melamine resin. Terminal blocks may also include other optional attachments such as protective covers and fuse holders.

Other types of terminal blocks may employ individual terminal sections ("blocks") that are connected together in the desired length. These blocks have individual terminals, usually of the

compression type (i.e., typically a barrel screw), and are used for various power, control, or instrumentation functions, depending on their size and ampacity. The conductor may either be wrapped around the terminal in a "U" shape, or simply inserted underneath a compression device, which firmly clamps the conductor.

Another common terminal block configuration uses a sliding metal link, which allows easy wire installation and electrical disconnection of the two posts during testing (thereby avoiding wire removal). A metallic clamp-and-bolt arrangement is used to form the sliding link between the two posts. Other features are similar to those of the one-piece or unitized terminal blocks [B.3], [B.21], [B.22], [B.23], [B.24].

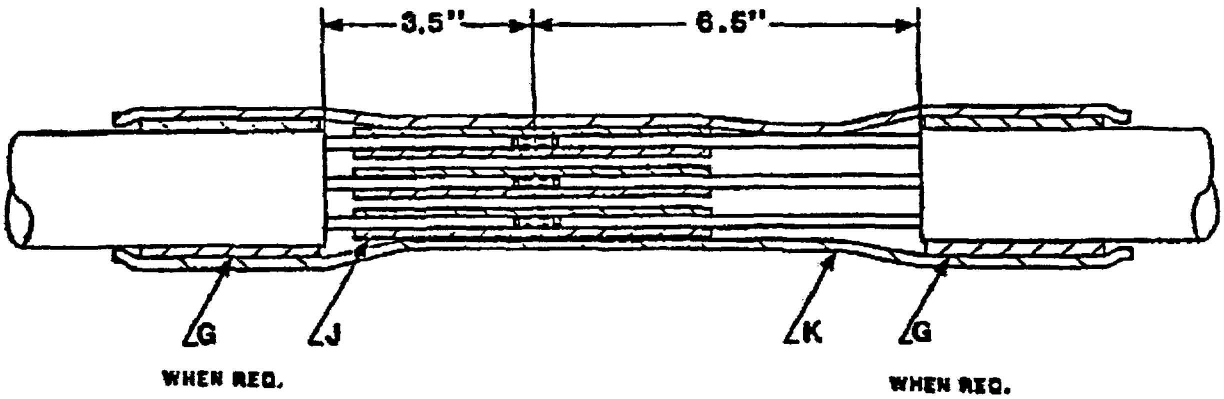
Splices and Splice Insulation

The term splice generally applies to connections made between sections of cable conductors and insulation within a given circuit, rather than those at the end of a circuit (more commonly referred to as terminations). Splices are frequently used to interface between device extension leads (pigtails) and field cable, or connect two or more segments of cable together. The connection of each individual conductor to another generally entails the use of one complete splice assembly, although multi-conductor splice designs have been used. Splices may be used to connect conductors of different types/sizes.

Splices are usually designated based on the voltage range in which they will be used (i.e., low-, medium-, or high-voltage); the greater part of nuclear plant splices are used in low-voltage (i.e., 600 V or less) cable systems. Splices used in higher voltage systems must be carefully constructed due to the comparatively high voltage stress.

Splice junctions are generally designated as being either in-line or V-type. In-line splices are formed by mating the conductors of the respective cables being spliced to one another via a fusion or compression connection (butt splice). V-type splices are formed by mating the terminations of the two conductors in parallel to one another using a nut/bolt arrangement or other mechanical connection. In either case, the splice is designed to provide a low-resistance connection between conductors with minimal voltage drop while maintaining adequate insulation resistance to ground in the expected voltage/current operating range. For some power and control circuits, splice ampacity at rated voltage is critical. For instrumentation and certain control circuits, insulation resistance and leakage current criteria may be of greater importance. In addition, splices used in environmentally qualified applications may have more stringent criteria related to the performance of the splice under accident conditions.

Insulation systems for nuclear plant splices are of one of two types: taped or heat shrink. In addition, splices may be further categorized based on their ability to isolate the spliced connection from the effects of the outside environment. Sealed splices are those that exclude external moisture or contaminants (such as may be encountered in harsh environmental areas). Alternatively, splices used in mild, dry environments may be unsealed. Nearly all splices that are installed in harsh environmental areas and require environmental qualification are of the sealed variety. Figure B-3 shows a typical in-line splice for a control cable.



KEY:
G - Cable Jacket Shim
J - Splice Sealing Sleeve
K - Outer Sealing Sleeve

Figure B-3 Raychem Type NPKC-3-31A Control Cable Splice Kit

Taped Splices

Taped splices are characterized by multiple layers of polymeric insulating tape wrapped over the conductor junction. These tape layers are applied in such a manner (i.e., generally stretched and wrapped at a specified angle and overlap) so as to provide insulation and sealing of the underlying junction. In addition, some of the older varieties of tape splice will use an insulating putty (similar to a potting compound) between the junction and the tape wraps; this putty acts as a further seal against moisture/contaminant intrusion.[9] In general, V-type splices are more susceptible than in-line splices to moisture intrusion because of an interstitial area between the insulation of the two parallel conductors. However, this is only of concern for EQ applications, which require sealing of the junction to ensure continued post-accident operability.

The predominant nuclear plant tape splice manufacturers include Okonite, Kerite, 3M, and Bishop. Okonite and Kerite constitute the bulk of EQ tape splices in use in the industry, whereas 3M and Bishop constitute the bulk of nonenvironmentally qualified splices. Each of these manufacturers use a proprietary tape formulation in their splices, which may be composed of a variety of different materials such as EPR, EPDM, silicone, or PVC.

Okonite T-95 tape is a high-voltage insulating tape that is also heat, corona and moisture resistant. The tape is an ethylene propylene (EP)-based thermosetting compound. Okonite T-95 tape is rated for 90°C continuous operations and 130°C for emergency operations. Okonite #35

[9] These putty compounds are rarely seen in most nuclear plants, especially those of more modern vintage.

jacketing tape is designed for protecting splices only in neoprene, plastic, and other synthetic rubberlike jacketed cables at all voltages. The maximum conductor operating temperature of the tape is 90°C [B.25].

"Kerite tape" is a name given to many types of tape defined in Kerite cable specification drawings. On various drawings, Kerite tapes are listed as Kerite friction tape, Kerite conducting fabric tape, Bishop Biseal 3 tape, vinyl electrical tape, silicone rubber tape, glass electrical tape, insulating tape Type 1, "A" tape, metal tape, and silicone rubber tape Type 1. Hence various types (and manufacturers) of tape appear to have been used in fabricating splices as specified by Kerite [B.14].

Biseal 3 is a Bishop Electric Corporation high-voltage tape. Biseal 3 is used in insulating, terminating, splicing and sealing up to 69 kV. Biseal 3 is a polyethylene-based tape that can be used with the following cable insulations: oil-based rubber, butyl rubber, EPR, thermoplastic and thermoset polyethylene, and PVC [B.26].

Heat-Shrinkable Splices

Heat-shrinkable splices use material that forms a tight, moisture-resistant seal of the conductor junction when exposed to heat. The material, typically in the form of a segment of tubing, is positioned over a preexisting junction (such as one crimped using a compression connector) and then heat-shrunk into place so that the contracting tubing seals against the cable insulation on either side of the junction. Heat-shrinkable splices are most often used inside primary containment because of their moisture sealing ability and relative ease of application.

Raychem is the largest manufacturer of heat shrink splices for the nuclear industry. WCSF-N is the primary Raychem product used in nuclear plant applications. WCSF-N is composed primarily of crosslinked polyethylene (XLPE). Another version of the product, WSCF (U), is similar yet has no adhesive coating. RNF, another Raychem product, was a predecessor to WCSF and may be found in limited nuclear plant applications [B.8], [B.27].

Included in the category of heat shrinkable splices are those manufactured by Sigma-Form, which use a heat-sensitive compound on the inner portions of the insulating sleeve. This compound extrudes throughout the interstices between the junction and outer sleeve (and ultimately out the ends of this sleeve) thereby forming an insulating barrier against external moisture and contaminants.

Plug-in Connectors

Various types of plug-in connectors are used by the nuclear industry, including single- and multi-pin (including Grayboot and Amphenol types), coaxial and triaxial (BNC) type, and a variety of other designs using a plug-and-socket arrangement. The exact configuration of each connector will vary based on its function and required service environment; however, there is some degree of commonality of design. Most plug-in connectors use the following generic components: (1) electrical contacts or pins and their receptacles (used to provide circuit continuity when the connector is assembled); (2) a dielectric material (used to provide electrical

insulation between individual contacts/receptacles and other conductive components inside the connector); (3) fastening or retaining hardware (to keep the electrical contacts properly mated, and maintain the physical and leak-tight integrity of the connector); (4) a cable clamp (keeps the cable jacket or insulation properly fastened to the connector to prevent stress on the electrical contacts or solder joints, and seal the interface); (5) a backshell or housing (comprises the outer housing of the connector and protects the other components; and (6) O-rings or seals (used on leak-tight connectors to prevent moisture or foreign material intrusion). Some connectors will use contact surfaces or pins coated with special conductive materials (such as gold) to limit the effects of oxidation on connector operation [B.3], [B.23], [B.28], [B.29], [B.30], [B.31], [B.32], [B.33].

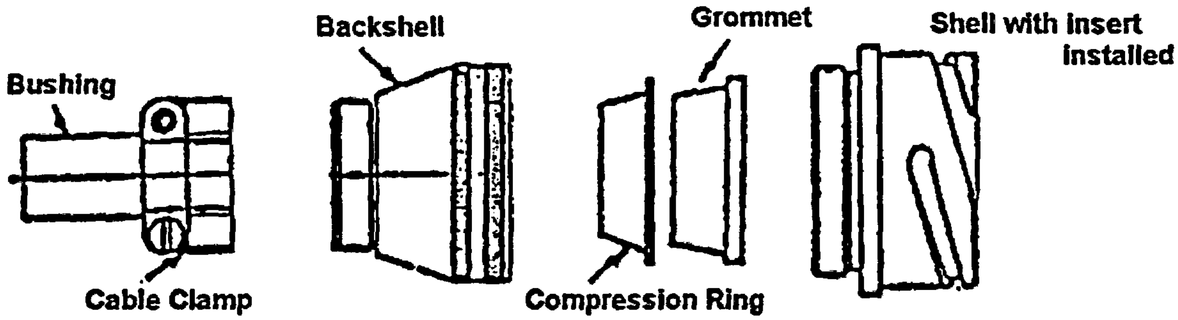


Figure B-4 Typical Connector and Components

B.3 Information Sources

A large volume of proprietary documentation was reviewed to ensure that the general discussions included in this section are representative of nuclear power plant applications. Each plant will need to perform a plant-specific review to ensure that the following documents are representative of its cable system installations:

Construction and Installation Specifications:

- Cable and conduit configurations
- Installation of safety- and nonsafety-related electrical cable in cable trays
- Safety-related and nonsafety-related electrical construction specification for installation of electrical cables in cable trays

Purchase Specifications:

- Safety-related 600 V control cable
- 600 V multi-conductor control cable (EPR or XLPE insulation)

- 600 V multi-conductor control cable (SR insulation)
- 600 V multi-conductor, control, and small power cable (PVC) for all areas outside the Reactor Containment Building for Westinghouse Electric Corporation
- 600 V single conductor, power cable (PVC) for general use for all areas outside the Reactor Containment Building for Westinghouse Electric Corporation
- 600 V power cable (XLPE insulation)
- Safety-related 600 V power cable
- 1000 V power cable (SR insulation)
- 600 V, 5 kV, and 15 kV silicone-rubber insulated lead-covered cable
- Kerite insulated 5-kV power cable
- Insulated 5-kV power cable
- Safety-related 5-kV power cable
- Kerite insulated 15-kV power cable
- Insulated 15-kV power cable
- Cable assemblies - In-core instruments
- Coaxial and triaxial cable (EPR or XLPE insulation)
- Computer, instrument, and specialty cable - multi-conductor shielded cable (EPR or XLPE insulation)
- GE Vulkene non-metallic sheathed insulated copper cable
- Heated junction thermocouple (HJTC) cable and connector assemblies
- Nonsafety-related cable
- Nonsafety-related grounding cable, connectors, and materials
- Nonshielded - twisted pair cable
- RG 11/U triaxial cable (inside and outside Containment)
- Safety-related instrument cable

- Shielded twisted pair & quad instrument cable for areas outside the Reactor Containment Building
- Single twisted pair and multi-pair thermocouple cable for Westinghouse Electric Corporation
- Single twisted pair thermocouple cable for Westinghouse Electric Corporation

Test Manual

- Power, control, & instrumentation cables, XLP or EPR insulated, 600 V

B.4 References

B.1 D. Fink and H. Beaty, Standard Handbook for Electrical Engineers, Twelfth Edition, McGraw-Hill, New York, 1987.

B.2 EPRI NP-7485, Power Plant Practices to Ensure Cable Operability, Nuclear Maintenance Applications Center, Electric Power Research Institute, July 1992.

B.3 EPRI EL-5036, Power Plant Electrical Reference Series, Vol. 4, "Wire and Cable," Electric Power Research Institute, 1987.

B.4 EPRI TR-103841, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report, Revision 1," prepared by Sandia National Laboratories and Strategic Resources and Technologies, Inc., July 1994.

B.5 ASTM Standard B33-94, "Tinned Soft or Annealed Copper Wire for Electrical Purposes," American Society for Testing and Materials

B.6 BIW Cable Systems Inc. product catalog, December 1984.

B.7 Brand Rex Industrial Cable products catalog (various dates).

B.8 Raychem Nuclear Products Guide IIA, August 1986.

B.9 Okonite Power, Control, and Instrumentation Cables and Splicing Materials product catalog, September 1984.

B.10 Modern Plastics Encyclopedia 1985-1986, Vol. 62, No. 10A, McGraw-Hill, New York, October 1985.

B.11 AEIC CS6-87, Specifications for Ethylene-Propylene Rubber Insulated Shielded Power Cables Rated 5 Through 69 kV, Association of Edison Illuminating Companies, Birmingham, AL.

B.12 Eaton Dekoron Wire and Cable product catalog (no date).

B.13 Cablec Continental product catalog, September 1991.

B.14 Kerite Cable Data Catalog, "Power Cable," 1993.

B.15 Harper, C. A., Handbook of Plastics and Elastomers, McGraw-Hill, New York, 1975.

B.16 Brady, G. S. and H. Clauser, Materials Handbook, 12th Edition, McGraw-Hill, New York, 1986.

B.17 EPRI NP-7189, "Review of Polyimide Insulated Wire in Nuclear Power Plants," Electric Power Research Institute, February 1991.

B.18 "Properties Handbook - Tefzel," E. I. duPont de Nemours, Inc., 1994.

B.19 ICEA Publication No. S-68-516 (NEMA WC8-1991), ICEA/NEMA Standards Publication, Ethylene-Propylene Rubber Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy.

B.20 ICEA Publication No. S-66-524 (NEMA WC7-1991), ICEA/NEMA Standards Publication, Cross-linked, Thermosetting, Polyethylene Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy.

B.21 AMP Electrical/Electronic Products Catalog EPC-2, 1984.

B.22 Equipment Qualification Reference Manual, Electric Power Research Institute, 1992.

B.23 NUREG/CR-5461, "Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants," July 1990.

B.24 NRC IE Information Notice 80-08, "The States Company Sliding Link Electrical Terminal Block," U.S. Nuclear Regulatory Commission, March 7, 1980.

B.25 Okonite Report No. NQRN-3, "Nuclear Environmental Qualification Report for Okoguard Insulated Cables and T95 and No. 35 Splicing Tapes," Rev. 3, March 1987.

B.26 Bishop Electric Corp. product literature, "No. 3 Bi-Seal High Voltage Tape" (undated).

B.27 Proprietary Nuclear Environmental Qualification Test Report on Raychem cable splices, Okonite tape splices, Kerite tape splices, scotch tape splices and AMP butt splices, prepared by Wyle Laboratories, March 1987.

B.28 Namco Controls Product Data Sheet, EC-210 Connectors (undated).

B.29 Litton Precision Products International Assembly Procedure, Litton/Veam CIR Series Connectors (undated).

B.30 Proprietary plant information sheet, Figure 7, "Cross Sectional View of ERD Connectors" (undated).

B.31 Proprietary Class 1E qualification test of ERD electrical connectors and mineral insulated cable, November 1984.

B.32 Proprietary environmental qualification report of Bendix electric cable connectors Model MS 3100 Series, January 1985.

B.33 Bow, K. E., J. H. Snow, D. A. Voltz, and W. D. Wilkens, "Specifying, Selecting, and Testing Quality Cable," IEEE Transactions Industry Applications, Vol. 29, No. 3, pp. 631-638, May/June 1993.

The following documents are not referenced in the text; however, the reader will find additional, related information in these documents:

B.34 American Insulated Wire Specification 6383 F for cross-linked polyethylene insulated switchboard wire, UL approved SIS 90°C, 600 Volts, 20 through 4 AWG.

B.35 Anaconda-Ericsson Specification AP-63231-00, Continental Flame-Guard NSGK Instrumentation Cable 600 Volts, September 10, 1982.

B.36 Cablec, Cable Installation Manual, Section V, Testing, Sixth Edition, CABLEC, Marion, Indiana.

B.37 EPRI EL-4201, "Long-Life Cable Development Cable-Processing Survey," Electric Power Research Institute, September 1985.

B.38 EPRI EL-4398, "Long-Life Cable Development: Cable Materials Survey," prepared by University of Connecticut, March 1986.

B.39 EPRI EL/NP/CS-5914-SR, "Application, Construction, and Testing of Generating Station Cables," prepared for Workshop on Power Plant Cable Condition Monitoring, July 1988.

B.40 General Electric Design Specification No. 22A1112, Special Wire and Cable.

B.41 Kerite 9401-H, "Hi Tension News," Kerite and Ohio Brass Companies, 1994 Special Edition.

B.42 The Okonite Company Engineering Data for Copper and Aluminum Conductor Electrical Cables, Bulletin EHB-90.

B.43 Raychem Specification 60, Raychem-Flamtrol Insulated Power, Control, Switchboard, and Instrumentation Wire and Cable, June 1, 1976.

APPENDIX C. DESIGN REQUIREMENTS INCLUDING CODES, STANDARDS, AND REGULATIONS

C.1 Design Requirements: Codes, Standards, and Regulations

The basic requirements for development of electrical cable systems for nuclear power plants are contained in General Design Criteria 17 and 18 of Appendix A to 10CFR50 [C.1], [C.2]. These criteria provide general guidance with respect to redundance, independence, and testability of the distribution system. Although these criteria provide guidance concerning attributes of the electrical system, they provide no direct guidance with respect to design or the application of cable or terminations.

Final safety analysis reports (FSARs) from various plants were reviewed to identify any additional criteria pertinent to cable or termination design. These FSARs provide varying levels of detail about licensing commitments regarding cable systems. In general, however, these documents list only ratings and other data specific to the installed equipment, and provide no further references to applicable standards or design commitments other than the applicable 10CFR50 Design Criteria discussed above.

Various industry standards related to on-site low- and medium-voltage electrical cable and terminations of the type covered in this AMG are listed at the end of this appendix. It should also be noted that cable separation and fire protection requirements may also be applicable, as well as seismic design and qualification of circuit support systems (which are not within the scope of this guideline).

C.1.1 Environmental Qualification

The eight primary codes, standards and regulations listed below define and control all of the activities that must be performed to establish environmental qualification (EQ) for an electrical cable or connection. Note, however, that other Regulatory Guides and IEEE Standards can be used in the process of establishing qualification for specific pieces of equipment.

- DOR Guidelines [C.3]
- NUREG-0588 Rev. 1 [C.4]
- 10CFR50.49 [C.5]
- Regulatory Guide 1.89, Rev.1 [C.6]
- Regulatory Guide 1.97, Rev. 2 [C.7]
- IEEE Standard 323-1971 [C.8]
- IEEE Standard 323-1974 [C.9]
- IEEE Standard 383-1974 [C.10]

Division of Operating Reactor (DOR) Guidelines

The DOR Guidelines were developed in November 1979 as a tool for the NRC staff to use in evaluating EQ submittals from a limited number of older nuclear plants. They were published in January 1980 for the industry's information and guidance. Section 7.0 of Reference [C.3]

stated that a plant did not have to demonstrate a qualified life[1] if the plant was already constructed and operating, unless the plant used material(s) that had been identified already as being susceptible to significant degradation due to thermal and radiation aging. Maintenance or replacement schedules were to include consideration of the specific aging characteristics of the material(s), and ongoing programs were to be established to review surveillance and maintenance records to assure that equipment that was exhibiting age-related degradation was identified and replaced as necessary.

NUREG-0588

NUREG-0588 [C.4] applied to all plants in existence at the time it was published except for those covered by the DOR Guidelines [C.3]. NUREG-0588 was initially published for industry comment in December 1979; it was subsequently revised and issued in July 1981. NUREG-0588 divided the population of safety-related electrical equipment into two categories, namely, Category I for equipment qualified in compliance with IEEE Std. 323-1974 and Category II for equipment qualified in compliance with IEEE Std. 323-1971. Section 4 of the Interim Staff Position in NUREG-0588 required that aging effects on all equipment, regardless of its location in the plant, should be considered and included in the qualification program for Category I equipment. Category II equipment had to comply in the same manner for qualification of valve operators and motors; however, for all other equipment the program had to address aging only to the extent that equipment that is composed, in part, of material susceptible to aging effects should be identified and a schedule for periodically replacing the equipment and/or materials should be established.

NUREG-0588 contained two aging-related elements for an EQ program (Category I) that may not be evaluated the same way in a general Aging Management Program developed for 10CFR54:

- Periodic surveillance testing under normal service conditions is not considered an acceptable method for on-going qualification, unless the plant design includes provisions for subjecting the equipment to the limiting service environmental conditions (specified in Section 3, item (7) of IEEE Standard 279-1971 [C.11]) during periodic surveillance testing

- Effects of relative humidity need not be considered in the aging of electrical cable insulation

[1] "The period of time for which satisfactory performance can be demonstrated for a specific set of conditions." [C.9] The definition was changed in the 1983 revision of IEEE Standard 323 to be "the period of time, prior to the start of a design basis event, for which equipment was demonstrated to meet the design requirement for the specified service conditions." The 1983 revision has never been endorsed by the NRC, and the change in definition occurred many years after most qualifications were established for operating plants. Therefore, this more specific/restrictive definition is not applicable to most of the operating plants in the United States.

10CFR50.49

10CFR50.49 [C.5] applies to electric equipment important to safety located in harsh environment areas. However, if the equipment had been previously qualified to the requirements of the DOR Guidelines [C.3] or NUREG-0588 [C.4], then it did not have to be requalified to the requirements of 10CFR50.49. Section (e) (5) of Reference [C.5] requires that equipment qualified by test must be preconditioned by natural or artificial (accelerated) aging to its end-of-installed life condition. If this is not practical, then the equipment can be preconditioned to a shorter designated life and must be refurbished at the end of this designated life unless ongoing qualification demonstrates that the item has additional life.

Regulatory Guide 1.89

Regulatory Guide 1.89, Revision 1 [C.6] describes a method acceptable to the NRC staff for complying with the requirements of 10CFR50.49 [C.5]. In its discussion on aging, Reference [C.6] states that there are considerable uncertainties regarding the processes and environmental factors that could result in such degradation. Because of these uncertainties, state-of-the-art preconditioning techniques are not capable of simulating all significant types of degradation, and natural pre-aging is difficult and costly.

Section C.5 of Reference [C.6] emphasizes the following:

- Periodic surveillance and testing programs are acceptable to account for uncertainties regarding age-related degradation that could affect the functional capability of equipment

- Results of such programs will be acceptable as ongoing qualification to modify qualified life of equipment and should be incorporated into the maintenance and refurbishment/replacement schedules.

Regulatory Guide 1.97

Regulatory Guide 1.97, Revision 3 [C.7] is an application-specific document, which describes a method acceptable to the NRC staff for complying with the Commission's regulations to provide instrumentation to monitor plant variables and systems during and following an accident in a light-water-cooled nuclear power plant.[2] Table 1 of Reference [C.7] presents Design and Qualification Criteria for Instrumentation and states that the instrumentation should be qualified in accordance with References [C.4] and [C.6].

No additional or special guidance is given concerning aging. Consequently, any cables or connectors used with post-accident monitoring equipment and subject to the provisions of Regulatory Guide 1.97 will not have any different aging requirements from those previously stated for References [C.4] and [C.6].

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[2] Revision 2 was issued as an active guide in December 1980, and is the revision number specifically cited in 10CFR50.49 [C.5]. None of the changes in Revision 3 had any effect on the aging of cables and connectors that might be used with post-accident monitoring equipment.

IEEE Standard 323-1971

IEEE Standard 323-1971 [C.8] was the first industry standard developed to provide guidance for demonstrating and documenting the adequacy of electric equipment used for the prevention of accidents and the mitigation of the consequences of accidents. It described the basic requirements for the qualification of Class I electrical equipment (equipment that is essential to the safe shutdown and isolation of the reactor or whose failure or damage could result in significant release of radioactive material).

Neither the word nor concept of aging is mentioned; consequently, cables and connectors qualified to the requirements of this standard should not be expected to have much information related to aging. However, this Standard is the one referenced in NUREG-0588 [C.4] for Category II plants. Thus, the concepts of aging management and ongoing aging review discussed previously for Category II plants qualified to Reference [C.4] apply.

IEEE Standard 323-1974

IEEE Standard 323-1974 [C.9] is the definitive industry standard for establishing qualification. It is specifically cited in NUREG-0588 [C.4], 10CFR50.49 [C.5], and Regulatory Guide 1.89, Rev. 1 [C.6]; it is also endorsed by Reference [C.6]. The concept of aging was addressed explicitly for the first time in IEEE Standard 323-1974, and this standard contained the first published definitions for the phrases "equipment qualification" and "qualified life."

Sections 6.3 and 6.6 of IEEE Standard 323-1974 [C.9] discuss aging and on-going qualification, respectively. Neither section considers the concept of aging management as envisioned by 10CFR54. Rather, the focus of Reference [C.9] is qualification by testing, such that even on-going qualification is based on additional periodic type testing instead of condition monitoring.

Because IEEE Standard 323-1974 [C.9] describes the methods to be used for cables and connectors qualified in accordance with the requirements of Category I NUREG-0588 [C.4], 10CFR50.49 [C.5], and Regulatory Guide 1.89 Rev. 1 [C.6], the comments stated previously for References [C.4], [C.5], and [C.6] concerning an aging management program and Aging Management Review apply to Reference [C.9].

IEEE Standard 383-1974

The Forward to IEEE Standard 323-1974 [C.9] states that guidance for demonstrating the capability of specific electric equipment (e.g., cables) may be found in IEEE Standard 383-1974 [C.10]. IEEE Standard 383-1974 provides direction for establishing type tests which may be used in qualifying Class 1E electric cables, field splices, and other connections for service in nuclear power generating stations. Type tests are used primarily to indicate that the cables, field splices, and connections can perform under the conditions of a design basis event. Because the design basis events may occur at any time in the station life, the thermal and radiation aging required in type tests to simulate these conditions may at the same time indicate the ability of cable types to operate under the normal service conditions within the station. IEEE Standard

383-1974 was endorsed, with some exceptions, by the NRC in Regulatory Guide 1.131 [C.12].

C.1.2 Compliance with Applicable Elements of Standard Review Plan, NUREG-0800

Section 8.1 of NUREG-0800 [C.13] provides a Standard Review Plan (SRP) for the review of electric power systems. Although the SRP did not form the licensing basis for the older plants, the SRP was reviewed to identify the issues and concepts related to aging management for electrical cable and terminations.

Table 8-1 of the SRP lists the "Acceptance Criteria and AMGs for Electric Power Systems." Review of this table indicated that eleven documents apply to on site ac power systems. Each document was reviewed for specific criteria related to the control of aging of cable system components important to license renewal. Overall, the review of the NUREG-0800 and the listed documents did not produce any criteria related to cable system aging beyond requirements for testability. Thus, NUREG-0800 provides no direct guidance about the control of aging of electrical cable or terminations.

Standard	Description
AEIC	
AEIC CS5-82	Specification for Thermoplastic and Crosslinked Polyethylene Insulated Shielded Power Cables rated 5 through 46 kV
AEIC CS5-87	Specifications for Thermoplastic and Crosslinked Polyethylene Insulated Shielded Power Cables Rated 5 Through 35 kV
AEIC CS6-82	Specification for Ethylene Propylene Rubber Insulated Shielded Power Cables rated 5 through 69 kV
ANSI (Note: ANSI/IEEE Standards are listed with IEEE)	
ANSI/ANS 59.4-1979	Generic Requirements For Light Water Nuclear Power Plant Fire Protection
ANSI/ASME NQA 1-1979	Quality Assurance Program Requirements for Nuclear Power Plants
ANSI/NFPA 70-1984	National Electric Code (NEC)
CAN	
CAN/CSA-C22.2	No. 241-M91, Standard for Cable Joints with Extruded Dielectric Cable Rated 5,000 V through 46,000 V and Cable Joints for Use with Laminated Dielectric Cable Rated 2,500 V through 500,000 V
ICEA	
ICEA P-32-382	Short Circuit Characteristics of Insulated Cable
ICEA P-54-440/NEMA WC51	Ampacities in Open Top Cable Trays
ICEA S-19-81/NEMA WC3	Rubber Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy
ICEA S-61-402/NEMA WC5	Thermoplastic Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy
ICEA S-66-524/NEMA WC7	Crosslinked Thermosetting-Polyethylene Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy

Standard	Description
ICEA S-68-516/NEMA WC8	Ethylene Propylene Rubber Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy
IEEE	
IEEE 48-1990	IEEE Standard Test Procedures and Requirements for High-Voltage Alternating-Current Cable Terminations
IEEE 55-1953	IEEE Guide for Temperature Correlation in the in the Connection of Insulated Wire and Cables to Electronic Equipment
ANSI/IEEE 100-1984	IEEE Standard Dictionary of Electrical And Electronics Terms
IEEE 141-1986	IEEE Recommended Practice for Electrical Power Distribution for Industrial Plants (Chapter 11, Cable Systems).
IEEE 279-1971	IEEE Standard for Criteria for Protection Systems for Nuclear Power Generating Stations
IEEE 323-1971	IEEE Trial Use Standard: General Guide for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
IEEE 323-1974	IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
IEEE 323-1983	IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
ANSI/IEEE 336-1980	IEEE Standard Installation, Inspection, and Testing Requirements for Class 1E Instrumentation and Electric Equipment at Nuclear Power Generating Stations
IEEE 367-1987	IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault
IEEE 383-1974	IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations
ANSI/IEEE 384-1981	IEEE Standard Criteria for Independence of Class 1E Equipment and Circuits

Standard	Description
ANSI/IEEE 400-1980	IEEE Guide for Making High-Direct-Voltage Tests on Power Cable Systems in the Field
IEEE 404-1986	IEEE Standard for Cable Joints for Use with Extruded Dielectric Cable Rated 5,000 V through 46,000 V, and Cable Joints for Use with Laminated Dielectric Cable Rated 2,500 V through 500,000 V
ANSI/IEEE 422-1986	IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations
IEEE 575-1988	IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths
IEEE 590-1977	IEEE Cable Plowing Guide
ANSI/IEEE 690-1984	IEEE Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations
IEEE 776-1974	IEEE Guide for Inductive Coordination of Electric Supply and Communication Lines
IEEE 789-1988	IEEE Standard Performance Requirements for Communications and Control Cables for Application in High Voltage Environments
IEEE 816-1987	IEEE Guide for Determining the Smoke Generation of Solid Materials Used for Insulations and Coverings of Electric Wire and Cable
IEEE 930-1987	IEEE Guide for the Statistical Analysis of Voltage Endurance Data for Electrical Insulation
IEEE 987-1985	IEEE Guide for Application of Composite Insulators
IEEE 1017-1991	IEEE Recommended Practice for Field Testing Electric Submersible Pump Cable
IEEE 1018-1991	IEEE Recommended Practice for Specifying Electric Submersible Pump Cable - Ethylene Propylene Rubber Insulation

Standard	Description
IEEE 1019-1991	IEEE Recommended Practice for Specifying Electric Submersible Pump Cable - Polypropylene Insulation
IEEE 1064-1991	IEEE Guide for Multifactor Stress Functional Testing of Electrical Insulation Systems
IEEE 1120-1990	IEEE Guide to the Factors to be Considered in the Planning, Design, and Installation of Submarine Power and Communications Cables
IEEE 1202-1991	IEEE Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies
IEEE S-135/ICEA P-46-426	Power Cable Ampacities for Copper and Aluminum Conductors
NEMA	
HP 3-1987 (R1992)	Electrical and Electronic PTFE Insulated High Temperature Hook-Up Wire; Types EE and ET
HP 4-1988	Electrical and Electronic FEP Insulated High Temperature Hook-Up Wire, Types K, KK, and KT
HP 100-1991	High Temperature Instrumentation and Control Cables
HP 100.1-1991	High Temperature Instrumentation and Control Cables Insulated and Jacketed with FEP Fluorocarbons
HP 100.2-1991	High Temperature Instrumentation and Control Cables Insulated and Jacketed with ETFE Fluoropolymers
HP 100.3-1991	High Temperature Instrumentation and Control Cables Insulated and Jacketed with Cross-Linked (Thermoset) Polyolefin (XLPO)
HP 100.4-1991	High Temperature Instrumentation and Control Cables Insulated and Jacketed with ECTFE Fluoropolymers
ICS 4-1983 (R1988)	Terminal Blocks
WC 3-1986	Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy

Standard	Description
WC 5-1992	Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy
WC 7-1993	Cross-Linked-Thermosetting-Polyethylene-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy
WC 8-1993	Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy
WC 50-1976 (R1993)	Ampacities, Including Effect of Shield Losses for Single-Conductor Solid-Dielectric Power Cable 15 kV through 69 kV
WC 51-1986 (R1991)	Ampacities of Cables in Open-Top Cable Trays
WC 53-1990	Standard Test Methods for Extruded Dielectric Power, Control, Instrumentation, and Portable Cables
WC 54-1990	Guide for Frequency of Sampling Extruded Dielectric Power, Control, Instrumentation, and Portable Cables for Test
WC 55-1992	Instrumentation Cables and Thermocouple Wire
WC 57-1990	Standard for Control Cables
WC 58-1991	Standard for Portable and Power Feeder Cables for Use in Mines and Similar Applications

C.2 References

C.1 Title 10, U.S. Code of Federal Regulations, Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," Part II, Criterion 17, "Electric Power Systems," published in the Federal Register, Vol. 52, October 27, 1987 (page 41294).

C.2 Title 10, U.S. Code of Federal Regulations, Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," Part II, Criterion 18, "Inspection and Testing of Electric Power Systems," published in the Federal Register, Vol. 52, October 27, 1987 (page 41294).

C.3 NRC IE Bulletin 79-01B, "Environmental Qualification of Class 1E Equipment," Enclosure 4 to "Environmental Qualification of Class 1E Equipment," Nuclear Regulatory Commission, January 14, 1980.

C.4 NUREG-0588 Rev. 1, "Interim Staff Position on Environmental Qualification of Safety-Related Equipment Including Staff Responses of Public Comments, Resolution of Generic Technical Activity A-24," Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, July 1981

C.5 Title 10, U.S. Code of Federal Regulations, Part 50.49, "Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants," published in the Federal Register, Vol. 53, May 27, 1988 (page 19250).

C.6 Regulatory Guide 1.89 Revision 1, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, June 1984

C.7 Regulatory Guide 1.97 Revision 3, "Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident, U.S. Nuclear Regulatory Commission, May 1983

C.8 IEEE Standard 323-1971, IEEE Trial Use Standard: General Guide for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, The Institute of Electrical and Electronics Engineers, Inc., April 1971

C.9 IEEE Standard 323-1974, IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, The Institute of Electrical and Electronics Engineers, Inc., corrected copy June 1976

C.10 IEEE Standard 383-1974, IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations, The Institute of Electrical and Electronics Engineers, Inc., 1974

C.11 IEEE Standard 279-1971, IEEE Standard for Criteria for Protection Systems for Nuclear Power Generating Stations, The Institute of Electrical and Electronics Engineers, Inc., June 1971 [American National Standards Institute, N42.7-1972]

C.12 Regulatory Guide 1.131, "Qualification Tests of Electric Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants," U.S. Nuclear Regulatory Commission, August, 1977.

C.13 NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Chapter 8: Electric Power, U.S. Nuclear Regulatory Commission, July 1981.

APPENDIX D. ACRONYMS

This list of acronyms is divided into two parts;

- Part 1 contains acronyms that are used in this Aging Management Guideline, and
- Part 2 contains common electrical cable and terminations, and nuclear industry acronyms.

Part 1: Acronyms Used in this Aging Management Guideline

ac	Alternating current
AEIC	Association of Edison Illuminating Companies
AMG	Aging management guideline
AMR	Aging management review
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
AWG	American wire gauge
BIL	Basic impulse insulation level
BR	Butyl rubber
BWR	Boiling water reactor
CAN	Canadian National Standards
CCNPP	Calvert Cliffs Nuclear Power Plant
CFR	Code of Federal Regulations
CLB	Current licensing basis
CLWR	Commercial light water reactors (DOE)
CM	Condition monitoring
CPE	Chlorinated polyethylene
CSPE	Chlorosulfonated polyethylene (Hypalon®)
CT	Computed tomography
DBE	Design basis event
dc	Direct current
DLO	Diffusion-limited oxidation
DOE	United States Department of Energy
DOR	Division of Operating Reactors (NRC)
EDG	Emergency diesel generator
emf	Electromotive force
EPDM	Ethylene propylene diene monomer (or Terpolymer)
EPR	Ethylene propylene rubber
EPRI	Electric Power Research Institute
EQ	Environmentally qualified
ESR	Electron spin resonance
ETFE	Ethylene tetrafluoroethylene (Tefzel®)

FIRL	Franklin Institute Research Laboratory
FR	Flame retardant
FRC	Franklin Research Laboratory
FSAR	Final safety analysis report
FTIR	Fourier transform infrared
HDPE	High-density polyethylene
hi-pot	High potential (voltage) testing
HMWPE	High molecular weight polyethylene
HTK	High-temperature Kerite (Kerite proprietary)
HVAC	Heating, ventilation and air conditioning
I&C	Instrumentation and control
ICEA	Insulated Cable Engineers Association (formerly IPCEA)
IE	Inspection and Enforcement (NRC)
IEB	Inspection and Enforcement Bulletin (NRC)
IEC	Inspection and Enforcement Circular (NRC)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IN	Information Notice (NRC Inspection and Enforcement)
INPO	Institute of Nuclear Power Operations
IPA	Integrated plant assessment
IPCEA	Insulated Power Cable Engineers Association (now ICEA)
IR	Infrared
IR	License renewal industry reports
IR	Insulation resistance
kcmil	One thousand circular mils (same as MCM)
LCM	Life cycle management program (EPRI)
LER	Licensee event report
LOCA	Loss-of-coolant accident
LRR	License renewal rule (10CFR54)
LWR	Light water reactor
MCC	Motor control center
MCM	One thousand circular mils (same as kcmil)
MIR	Multiple internal reflectance
MOV	Motor-operated valve
MR	Maintenance rule (10CFR50.65)
NEC	National Electric Code
NEI	Nuclear Energy Institute (formerly NUMARC)
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Prevention Association
NIR	Near-infrared reflectance
NMAC	Nuclear Maintenance Application Center (EPRI)

NMR	Nuclear magnetic resonance
NPAR	Nuclear plant aging research (NRC)
NPRDS	Nuclear Plant Reliability Data System (INPO)
NRC	United States Nuclear Regulatory Commission
NSIC	Nuclear Safety Information Center
NTS	National Technical Systems
NUMARC	Nuclear Management and Resource Council (now part of NEI)
NUREG	Nuclear regulatory (document series published by the NRC)
OIT	Oxidation induction time
PD	Partial discharge
PE	Polyethylene
PF	Power factor
PI	Polarization index
PLIM	Plant lifetime improvement program (DOE, now the CLWR Program)
PVC	Polyvinyl chloride
PWR	Pressurized water reactor
RCPB	Reactor coolant pressure boundary
RG	Regulatory Guide (NRC)
RH	Relative humidity
RTD	Resistance temperature detector
SR	Silicone rubber
SBR	Styrene-butadiene rubber
SER	Safety evaluation report
SIC	Specific inductive capacitance
SIR	Specific insulation resistance
SIS	Synthetic thermosetting insulation for switchboard wire
SOV	Solenoid-operated valve
SSC	System, structure or component
SSCs	Systems, structures and components
TDR	Time-domain reflectometry
TDS	Time-domain spectroscopy
TED	Time to equivalent damage
TID	Total integrated dose
TLAA	Time-limited aging analyses
TR-XLPE	Tree-retardant XLPE
UV	Ultraviolet
V	Volts
Vac	Volts, alternating current
Vdc	Volts, direct current

XLN	Cross-linked neoprene (ITT Surprenant proprietary)
XLPE	Cross-linked polyethylene
XLPO	Cross-linked polyolefin

Part 2: Common Electrical Cable and Terminations, and Nuclear Industry Acronyms

A	Amperes
ASME	American Society of Mechanical Engineers
BNL	Brookhaven National Laboratory
DBA	Design basis accident
DF	Dissipation factor
DSC	Differential scanning calorimeter
EP	Ethylene propylene
FEP	Fluorinated ethylene propylene
FRMR	Flame retardant, moisture retardant
HELB	High energy line break
LMWPE	Low molecular weight polyethylene
MC	Metal-clad cable (NEC type designation)
MI	Mineral insulated
MSLB	Main steam line break
MV	Medium-voltage (NEC type designation)
NBR	Nitrile butadiene rubber
ORNL	Oak Ridge National Laboratory
PIXE	Proton-induced x-ray emission
PTFE	Polytetrafluoroethylene (Teflon®)
RF	Radio frequency
RG	Designation prefix for coaxial cables (e.g., RG-57)
RHH	NEC conductor type designation for heat resistant conductors
RHW	NEC conductor type designation for heat and moisture resistant conductors
RMS	Root means square
SA	NEC designation for conductors with silicone insulation and glass braid
SF	Service factor
SNL	Sandia National Laboratories

TGA	Thermogravimetric analysis
UL	Underwriters Laboratory
XHHW	NEC conductor designation for XLPE or EP insulation with heat and moisture resistance
Z	NEC conductor designation for ETFE-insulated conductors in dry locations
ZW	NEC conductor designation for ETFE-insulated conductors in wet locations

APPENDIX E. TRADE NAMES FOR CABLE AND TERMINATIONS

Trade Name	Manufacturer	Primary Constituent Material
Alkane	Raychem	Polyalkene
Bostrad 7E	BIW	EPR/EPDM
Dekorad	Eaton/Samuel Moore	EPR/EPDM
Durasheet EP	Anaconda	EPR/EPDM
Firewall EP	Rockbestos	EPR/EPDM
Firewall III	Rockbestos	XLPE
Flamenol	GE	PVC
Flametrol	Raychem	XLPE
FR	Kerite	*
FR-EP	Continental	EPR/EPDM
FR-EP	Eaton/Samuel Moore	EPR/EPDM
HTK	Kerite	*
Hypalon	DuPont	CSPE
Kapton	DuPont	Polyimide
Neoprene	DuPont	Chloroprene
Okoguard	Okonite	EPR/EPDM
Okolon	Okonite	CSPE
Okonite	Okonite	EPR/EPDM
Okonite-FMR	Okonite	EPR/EPDM
Okoprene	Okonite	Chloroprene
Okoseal	Okonite	PVC
Okozel	Okonite	ETFE
Pyrotrol III	Cerro	XLPE
Tefzel	DuPont	ETFE
Ultrol	Brand-Rex	XLPE
Viton	DuPont	Fluoroelastomer
Vulkene	GE	XLPE
WSCF	Raychem	XLPE
X-Olene	Okonite	XLPE

* Kerite polymer formulations are proprietary and their primary constituents not readily ascertainable.

APPENDIX F. DISCUSSION OF NPRDS DATA

This appendix discusses specific attributes and limitations regarding the use of the Nuclear Plant Reliability Data System (NPRDS) database during preparation of this guideline.

F.1 Categorization of Reports

Due to the virtual interchangeability of the terms "cable" and "wire," drawing a clear dividing line between the two categories was difficult. What may be described as a cable in one report is often described as a wire in another. In addition, the distinction between field cable, panel (SIS) or local wire, and wiring internal to various electrical components or subcomponents is often unclear. Some applications have a wire terminated directly on or within a component; some have the wire terminated on a terminal block within a panel or control board. Others have wiring harnesses that emanate from the component. In addition, individual conductors within a cable may be termed "wires." Hence, some effort was made to distinguish field cable from panel or local wiring. Internal component/subcomponent wiring (such as that found in electrical switchgear or instrument drawers) was not considered within scope, except where it could be ascertained that the wire originated from outside the component. Although these criteria are somewhat imprecise and subjective, they do provide some boundary for evaluation of the NPRDS data.

In many NPRDS reports, oxidized or corroded conductor surfaces were identified as being "dirty" or requiring cleaning. This is somewhat confusing in that failures caused by actual dirt or foreign material contamination were also often referred to as "dirty." Accordingly, dirty, oxidized, or corroded components were grouped together with respect to cause of failure because they could not be accurately differentiated in many cases.

Another difficulty encountered while analyzing the NPRDS reports relates to the primary type of failure noted; that is, loose or broken "terminations." It is very difficult to determine from the NPRDS reports exactly what the failed component/subcomponent is. For example, a "loose" termination may include a lug or compression fitting that is loose on the conductor, or a termination that is loose at its point of connection to the device (i.e., loose terminal nut or screw). Similarly, a "broken" termination may mean a lug or fitting that has itself broken, or a wire conductor that has broken in the immediate vicinity of the termination (i.e., termination is broken off). Although apparently trivial, these distinctions are important in characterizing the failure rate of specific components such as wire conductors and compression lugs. Reports in which the connected device terminal hardware was the root cause were considered out of scope.[1]

Failure reports deemed to be applicable were then grouped by major component (i.e., cable, panel (SIS) wiring, splice, compression fitting, connector, or terminal block); each component was then sorted by failed subcomponent, failure mode, failure cause, and method of failure detection. Due to the absence of any substantial information regarding the component

[1] This is true with the exception of loose or broken terminal block hardware, which was considered within scope.

manufacturer, the relative reliability of cable/terminations from various manufacturers cannot be estimated from the available data. Although infrequently stated in explicit terms, the voltage class of the failed component described could almost always be deduced based on the application described in the narrative. No effort was made to classify reports in terms of application type (i.e., power, control, or instrumentation), as these categories are not commonly defined from plant to plant, and substantial overlap often occurs. In several cases, the failure mode and/or failure cause were not identified; these reports were tagged as "unidentified."

"Normal aging" was cited in numerous reports as the cause for the component/subcomponent failure. In most cases, this term is not descriptive of the actual failure cause; however, these reports were assigned their own failure cause category so as to differentiate them from other causes, and provide some indication of the fraction of total failures that these reports constituted.

F.2 Method of Detection

The method of failure detection refers to the circumstances under which the component failure was noted. Different categories of detection method were considered, including detection during maintenance, during surveillance testing, during operations, and during in-service inspection. Those failures detected during operation of the equipment were further categorized as to the effect of the detection on the functionality of the cable, termination, or circuit in general. For example, a cable or wire failure noted during operation that prevented or limited the circuit or connected load from fulfilling its required function was categorized separately from a failure detected during circuit operation that had no appreciable effect on functionality. For conservatism, circuit grounds were considered to affect functionality unless clearly indicated otherwise in the applicable report.

F.3 Cable Insulation Materials

Little specific information regarding cable insulation material was recorded in the NPRDS reports pertaining to cable failure. Some of the reports describing failures of components or subcomponents other than cable insulation (such as the cable conductor, connectors, splices, and terminal blocks) had information regarding the type of insulation material; however, this was not considered relevant to the failure of the insulation. Accordingly, only those reports with insulation data and which related to the failure of the insulation were included in the statistics for insulation failures. The number of such reports was a very small fraction of the total (only a few percent of the total reports related to insulation failure). Therefore, little meaningful inference can be made regarding the failure or degradation propensity of certain types of insulation materials.

APPENDIX G. EVALUATING THERMAL LIFE

G.1 Introduction

In a typical power plant, cables are installed in a variety of configurations. The physical characteristics of each installation are a significant consideration in any assessment to determine a cable's operating temperature. Given identical external environmental conditions and electrical loading, the operating temperature of identical cables installed in conduit, open cable tray, closed cable tray, behind a fire barrier, etc. will all be different. The heat transfer characteristics of each installation must be considered in an evaluation to determine a cable's operating temperature. Finally, local heat sources (e.g., an adjacent power cable) must be considered in the evaluation.

In addition, insulation and jacket materials are subject to a broad range of service conditions. Service conditions are rarely constant with respect to a given stressor. Although a passive device (i.e., one which generates no self-heating) may be maintained at a constant temperature throughout its life, this is the exception rather than the rule. In general, a device will be exposed to a range of temperatures over its lifetime. This variation may be regular (cyclic) or irregular.

The effect of cable loading and ambient temperature on thermal life can be examined for:

- constant cable temperature (see Figure 4-1)
- combinations of constant ambient temperature and constant electrical loading that yield a 40-year or 60-year service life (see Figure 4-5, Table 4-2)
- variable service conditions (see Figures G-1 through G-6)

G.2 Temperature Rating

Any given cable has an associated conductor *temperature rating*, which is "the maximum temperature, along its length, that the conductor can withstand over a prolonged time period without serious degradation" (NEC [G.1] article 310-10). As one will see, the concept of a prolonged time period in the NEC differs substantially from the 40 to 60-year time periods of interest to nuclear power plant operators. Note that the conductor temperature is used as the temperature rating because this is the hottest part of the cable and thus conservatively estimates the temperature to which the cable's insulation and jacket will be exposed. From NEC Tables 310-13 and 310-61, each cable type has an associated conductor temperature rating; typical values are 60, 75, 85, 90, 125, 150, 200, and 250°C (90°C is the most common rating for general purpose cables in a nuclear power plant).

G.3 Ampacity

When a metallic conductor is energized with a current (I), the conductor temperature (T_c) increases above its deenergized temperature due to ohmic heating. Because the conductor

temperature rise is roughly proportional to the power (P) dissipated by the conductor ($P = I^2R$), this is often referred to as "I^2R heating."

Ampacity[1] is "the current that a conductor can carry continuously under the conditions of use without exceeding its temperature rating" (NEC article 100); thus, when a conductor is energized continuously with a current equal to its ampacity, the metallic conductor will stabilize at a temperature equal to the cable's temperature rating.

Ampacities are tabulated in standard industry tables for a limited range of simple configurations. For example, assume that a single copper conductor, 8 AWG cable[2] with a 90°C temperature rating is in free air at an ambient temperature of 30°C. From a standard industry ampacity table (NEC Table 310-17, "Ampacities of Single Insulated Conductors, Rated 0 through 2000 Volts, In Free Air Based on Ambient Air Temperature of 30°C (86°F)", for conductors ranging in size from 18 AWG to 2000 kcmil), this conductor has an ampacity of 80 A. This means that if the conductor were energized continuously with 80 A, the conductor temperature would be increased by 60°C, resulting in a final conductor temperature of 90°C.

As the ambient temperature increases, a cable's ampacity decreases. Ampacity correction factors (temperature derating factors) are provided in standard ampacity tables to account for changes in ambient temperature from that used in the table. For example, NEC Table 310-17 requires that the previously cited ampacity of 80 A at 30°C must be multiplied by a factor of 0.91 for ambient temperatures in the range between 36 and 40°C. Thus, if the same single conductor cable described above is at an ambient temperature of 40°C, it will reach its 90°C temperature rating when energized continuously with 72.8 A (=0.91*80) instead of the 80 A required at 30°C. Ampacity correction factors also exist for other parameters such as the number of conductors in the cable; cable diameter; grouping of cables in a single raceway, conduit, or cable tray; installation of a fire barrier; and grouping of multiple conduits in close proximity.

Ampacity correction factors can also be calculated analytically in lieu of using tabulated values. For instance, an equation to correct a tabulated ampacity value for any combination of conductor temperature rating, ambient temperature, and dielectric temperature rise is given by Equation (5) from page III of AIEE S-135 [G.2], namely:

$$I' = I\sqrt{\frac{T_c' - T_a' - \Delta T_d'}{T_c - T_a - \Delta T_d} \times \frac{\tau_c + T_c}{\tau_c + T_c'}}$$

where: I = Current based on conditions associated with T_c and T_a
I' = Current based on conditions associated with T_c' and T_a'

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[1] The word "ampacity" is a contraction of the phrase "amperage capacity" to signify the current-carrying capacity of a conductor.

[2] An 8 AWG conductor is used for the example because NEC Table 310-17 requires overcurrent protection for 10 AWG and smaller cables, in addition to the ampacity limits.

T_a	=	Ambient air temperature (°C) (e.g., 30, 40) for the conductor temperature rating
T_a'	=	Ambient air temperature (°C) for the changed condition
T_c	=	Conductor temperature rating (°C) (60, 75, 90, 105, etc.)
T_c'	=	Actual conductor temperature (°C) for the changed condition
ΔT_d	=	The temperature rise due to dielectric loss associated with T_c and T_a. An ac voltage impressed across a dielectric will produce a heat loss which leads to a cable temperature increase. The temperature rise is negligible for low voltage cables and may be relatively small for cables operating at higher voltages, although it increases as the square of voltage [G.3]. Relations for the dielectric loss are given by Equations (36) and (37) of a paper [G.4] that was used to develop IEEE S-135; the temperature rise is proportional to the power factor and specific inductive capacitance (SIC) of the insulation.
$\Delta T_d'$	=	The temperature rise due to dielectric loss associated with T_c' and T_a'
τ_c	=	The inferred temperature of zero electrical resistance • 234.5 for copper • 228.1 for aluminum

The variables ΔT_d and $\Delta T_d'$ are negligible relative to $(T_c - T_a)$ and $(T_c' - T_a')$, respectively, for most cables of interest and the equation reduces to:

$$I' = I\sqrt{\frac{T_c' - T_a'}{T_c - T_a} \times \frac{\tau_c + T_c}{\tau_c + T_c'}}$$

If a cable ampacity is known for a given conductor temperature rating and ambient temperature, this equation gives the resulting ampacity for a different ambient temperature and conductor temperature rating. This equation yields the same results as the ampacity derating factors from NEC Table 310-17.

In addition to performing ampacity derating calculations, the equations can be rewritten to calculate the conductor temperature (T_c') that results from a current loading (I') at a given ambient temperature (T_a'), as

$$T_c' = \frac{T_a'(\tau_c + T_c) + \tau_c(T_c - T_a)(I'/I)^2}{(\tau_c + T_c) - (T_c - T_a)(I'/I)^2}$$

The conductor temperature for any current load can be determined using this equation and ampacity data for the configuration of interest (e.g., a single cable in open air). If the cable used in the previous example has a current load of 32 A (= I') at an ambient temperature of 30°C (= T_a'), then the resulting conductor temperature is 38.1°C.

G.4 Thermal Life of Constantly Energized Cables

For the purpose of this example, it is conservatively assumed that there is no temperature drop across the insulation and jacket (i.e., the conductor, insulation, and jacket all operate at the conductor temperature). The temperature for which a 60-year cable life is projected (using 50% retention of absolute elongation-at-break as the end-of-life criterion) can be calculated from the Arrhenius data in Table G-1 and the Arrhenius equation in Section 4.1.1.1.2. This temperature (T_c) can be used to calculate the continuous current loading (I) that results in a projected 60-year cable life. This has been performed for the materials listed in Table G-1, and the results are shown in Figure 4-5. Finally, please note that irradiation aging and other environmental factors, as applicable, must be considered when establishing the service life of a material.

Table G-1 Activation Energy and Thermal Life

Generic Material Type	Activation Energy[1] (eV)	Basis Temperature (°C)	Basis Temperature (°F)	Life[2] @ Basis Temperature (years)
CSPE	1.14	80°C	176°F	13.5
EPDM[3]	1.35	91°C	196°F	40.0
EPR	1.20	135°C	275°F	0.2
ETFE	0.95	148°C	298°F	11.4
Neoprene®	0.94	80°C	176°F	2.5
PVC[4]	0.99	120°C	248°F	0.2
Silicone[5]	1.8	136°C	277°F	40.0
Viton A	1.17	200°C	392°F	1.7
XLPE/XLPO[3]	1.24	150°C	302°F	0.1

Notes:

1. In most cases, the minimum temperature of tests performed to measure activation energy is much higher than temperatures in power plants. This time-temperature extrapolation can lead to significant differences between predictions based on accelerated aging tests and aging under power plant conditions. Recent measurements of activation energy at room temperature (25°C [77°F]) can be used to eliminate the time-temperature extrapolation.
2. End-of-Life is defined as $e_{absolute}$ = 50% for most materials (see notes 3 to 5). Limited sources of non-proprietary data are available. The data in this AMG are adequate to exhibit general relationships only.
3. The end-of-life condition for EPDM and XLPE is 60% relative elongation (e/e_0 = 60%). This endpoint is much more conservative than $e_{absolute}$ = 50%; the service life would increase significantly.

4. The end-of-life condition for PVC is electrical failure, which would leave no margin for design basis event degradation. The actual material specification is MIL-W-5086/2 (a PVC-Nylon). Data were not available for $e_{absolute} = 50\%$.
5. The end-of-life condition for Silicone is 50% relative elongation ($e/e_0 = 50\%$). This endpoint is much more conservative than $e_{absolute} = 50\%$; the service life would increase significantly.

G.5 Variable Service Conditions

Most cables are not energized continuously at a fixed current. Therefore, it is more useful to investigate the thermal life of a cable that is energized for only a fraction of the time, which is known as *duty cycle*. The calculation of thermal life is performed using the following procedure:

1. Calculate the energized cable temperature (Section G.2).

2. For the given duty cycle and design life, calculate how many years the cable will be energized and how many years the cable will be deenergized.

3. Using the Arrhenius relationship, calculate the time at ambient temperature that is equivalent to the energized time and energized cable temperature. Then add this equivalent time to the actual deenergized time to get the total equivalent thermal life at ambient temperature. (The technique to calculate equivalent overall exposure time is similar to that found in Section 4.6, "Consideration of Variable Service Conditions," of EPRI NP-1558 [G.5])

Figures G-1 through G-6 give the results of this calculation for Neoprene® and XLPE. From these figures, it is obvious that the operating time of a power cable that is heavily loaded has significant impact on the total life (or qualified life) of the insulation. The Neoprene® data in Figure G-2 will be used to explain the nomenclature and demonstrate how Figures G-1 through G-6 can be used.

- *X-axis:* The electrical loading of the cable (when it is energized) is plotted on the x-axis. The x-axis is normalized by dividing the energized cable current by the 30°C ambient ampacity.

- *Y-axis:* The remaining life of the cable at the end of its design life (lower left corner of the figure) is plotted on the y-axis. The y-axis is normalized by dividing the remaining life by the material thermal life. Note that:

  - material thermal life is the time required at ambient temperature (lower left corner of the figure) for the elongation-at-break of new material to degrade to 50% absolute.

  - remaining life is the time required at ambient temperature for the elongation-at-break of the material at the end of its design life to degrade to 50% absolute.

- *NEC Ampacity Derating:* The vertical ampacity derating line at 91% is the calculated ampacity for a 40°C ambient temperature. The calculated ampacity (or derated ampacity) is less than the ampacity at 30°C which is used to normalize the x-axis. When the cable is energized with a current equivalent to the ampacity derating line, the conductor temperature will equal the cable temperature rating (90°C, top margin of the figure). When the cable is energized, operating conditions to the left of the ampacity derating line result in cable conductor temperatures less than the temperature rating, and operating conditions to the right of the ampacity derating line result in cable conductor temperatures above the temperature rating. If the ambient air temperature is increased, the ampacity derating line will move to the left on the plot.

- *Y-axis intercept:* An unenergized Neoprene® cable (0% of rated ampacity) has a remaining life of 54% after 60 years of service at an ambient temperature of 40°C. At 0% of rated ampacity (e.g., an I&C cable), the cable carries no current and it operates at the ambient air temperature. The life of Neoprene® at 40°C is 130 years (top margin of the figure, calculated from the Arrhenius equation using Table G-1 data). Therefore, it has 70 years (= 130-60) of remaining life, or 54% (= 70/130) of its thermal life remaining, after a 60 year design life.

- *X-axis intercept(s):* A continuously energized Neoprene® cable (100% duty cycle) in a location where the ambient air temperature is 40°C can be operated at currents up to 37% of its 30°C ampacity for 60 years. If this cable's duty cycle is reduced from 100% to 33%, then a current loading of 52% of the 30°C ampacity results in a remaining thermal life of 0% at the end of 60 years. Such a cable is energized 33% of the time at 52% of the 30°C ampacity and is not energized the other 67% of the time. The cable has no remaining life after operating under these variable service conditions for 60 years, which means that the Neoprene® has degraded to an absolute elongation-at-break of 50%.

  To generalize for a given duty cycle, service conditions to the left of the duty cycle line's x-axis intercept are acceptable for the design life; to the right of the duty cycle line's y-axis would require replacement.

  Operating cables at large current loadings significantly decreases their thermal life, even when energized for a very small percentage of the time. The Neoprene® cable in a 40°C environment that is energized at ~91% of its 30°C ampacity and a 1% duty cycle (i.e., energized for only 0.6 of 60 years) will reach its end-of-life condition after 60 years, but there is little margin to spare.

- *Equivalent thermal aging:* Cable materials subjected to equivalent thermal aging will have identical remaining thermal life. For instance, the thermal degradation for a Neoprene® cable energized continuously at either 31% of its 30°C ampacity, or energized 1% of the time at 87% of its 30°C ampacity, for 60 years is identical as they both use 80% of the material's thermal life (i.e., 20% remaining thermal life).

- *Practical application:* As an example of how a user would implement the figure, consider a Neoprene®-jacketed power cable located in a 40°C ambient environment

(where the jacket is required to be intact throughout the cable lifetime) that is energized 10% of the time. Per Table 4.2, 40°C would exceed the maximum recommended ambient temperature for a 60-year lifetime (14°C at 80% of its 30°C ampacity), thereby making this cable a candidate for further evaluation. From Figure G-2, the cable could be operated with a 10% duty cycle at up to ~67% of its 30°C ampacity over a 60-year period and the Neoprene® jacket would still exceed the 50% retained absolute elongation-at-break criteria. Therefore, if the 10% duty cycle circuit is determined to operate below ~67% of its 30°C ampacity, the cable may be eliminated from further consideration.

The thermal life of an energized cable, as shown in Figures G-1 to G-6, depends on a large number of parameters, namely:

1. material activation energy

2. material life at ambient temperature (life at any other temperature will also suffice, as the activation energy can be used to calculate the equivalent lifetime at ambient temperature). Note that cable life depends on the criterion used to define cable life (for this Appendix, the end of cable life is at 50% absolute elongation).

3. ambient air temperature

4. cable current when energized

5. load factor (fraction of time the cable is energized)

6. conductor temperature rating

7. ampacity for the cable configuration at the ambient air temperature (this may require correcting the ampacity from a standard industry table that is based on a different ambient temperature and/or cable configuration)

Because of the large number of parameters, it is not practical to plot the cable life as a function of all the parameters in a single figure. Instead, a set of figures can be created, each showing a set of cable thermal lifetimes versus cable current load for several load factors, while all other parameters are held fixed.

The following comments and observations refer to the data shown in Figures G-1 to G-6:

1. These Figures use the thermal aging data from Table G-1 which provide a generic indication of a given material's thermal aging behavior. It is important to use thermal aging data specific to the material of interest when estimating the allowable temperature for a projected 60-year life.

2. Ampacity is based on continuous operation; however, there are conditions where a cable will be operated for short periods of time at currents above the ampacity (e.g., motor in-rush current). While such overload or transient conditions are not addressed

in the NEC, they are addressed in several other standards. For instance, AIEE S-135 (Appendix III, Section 4) [G.2] and ANSI/IEEE Standard 242-1986 (Section 8.5.2) [G.6] include information on cable overload capacity. Even short-term overload conditions can have a significant effect on thermal life and should be evaluated.

3. A conductor temperature rating is not directly correlated to cable life; a temperature rating of 90°C does NOT mean that the cable can survive for 40- or 60-years at 90°C.

4. The thermal life of a cable becomes less sensitive to changes in temperature as the activation energy is increased. The thermal life of cables with high activation energies does not decrease as quickly with increasing current load or load factor as those with low activation energies.

5. These figures are for cables that are energized. It is important to recognize that even a deenergized cable can be subjected to elevated temperatures if it is in close proximity to an energized cable.

6. These figures are based on rated ampacity values. It is standard practice to size cables so the maximum current load is some fraction of their rated conductor ampacity. This provides a safety factor, or margin, to account for design and load uncertainty, reduced voltage (increased current) conditions, and overload conditions.

7. Ampacity values are based on conductor temperature, which is the hottest point on the cable. The implied assumption is that the temperature of the cable's insulation and jacket is conservatively estimated as being equal to the conductor temperature. In reality, there will be a temperature gradient across the cable insulation and jacket, and the majority of the energized cable's polymer material will be at a temperature somewhat lower than the conductor temperature.

8. Care must be taken to ensure that the proper ampacity is used. Fire barriers, penetration seals, etc. can have a significant ampacity derating.

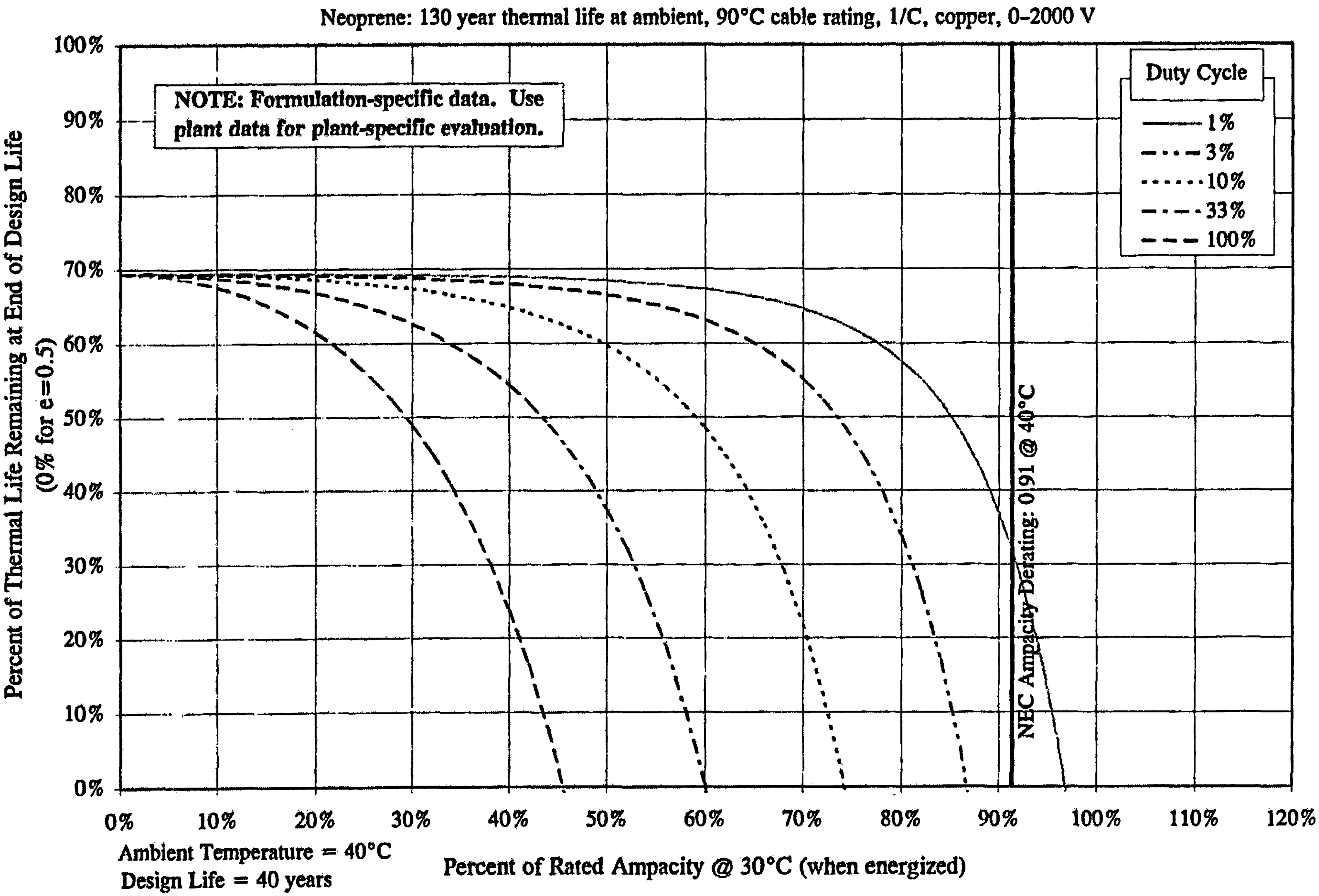

Figure G-1 Ampacity versus Thermal Life With Duty Cycles: Neoprene®, 40°C Ambient, 40 Years

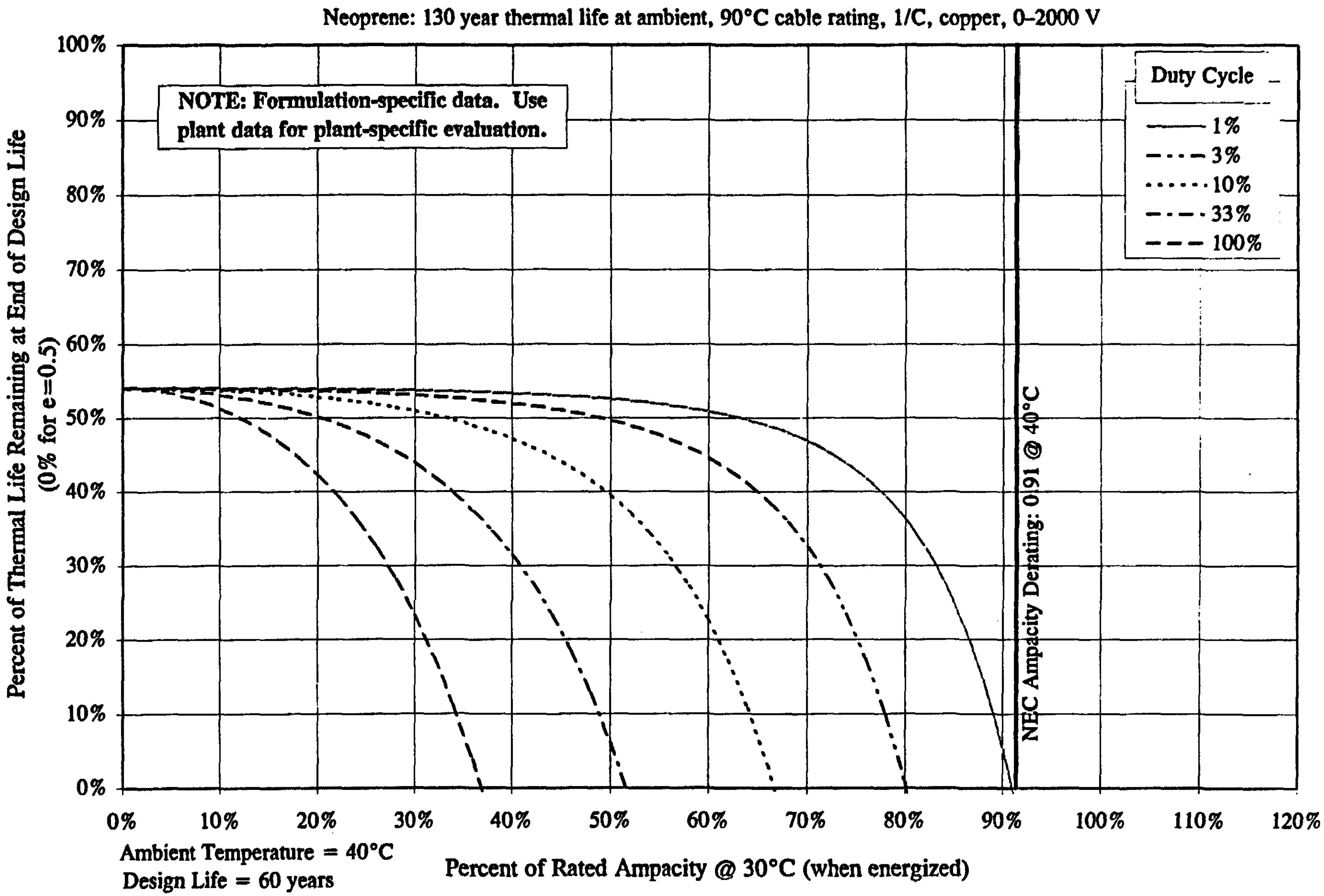

Figure G-2 Ampacity versus Thermal Life With Duty Cycles: Neoprene®, 40°C Ambient, 60 Years

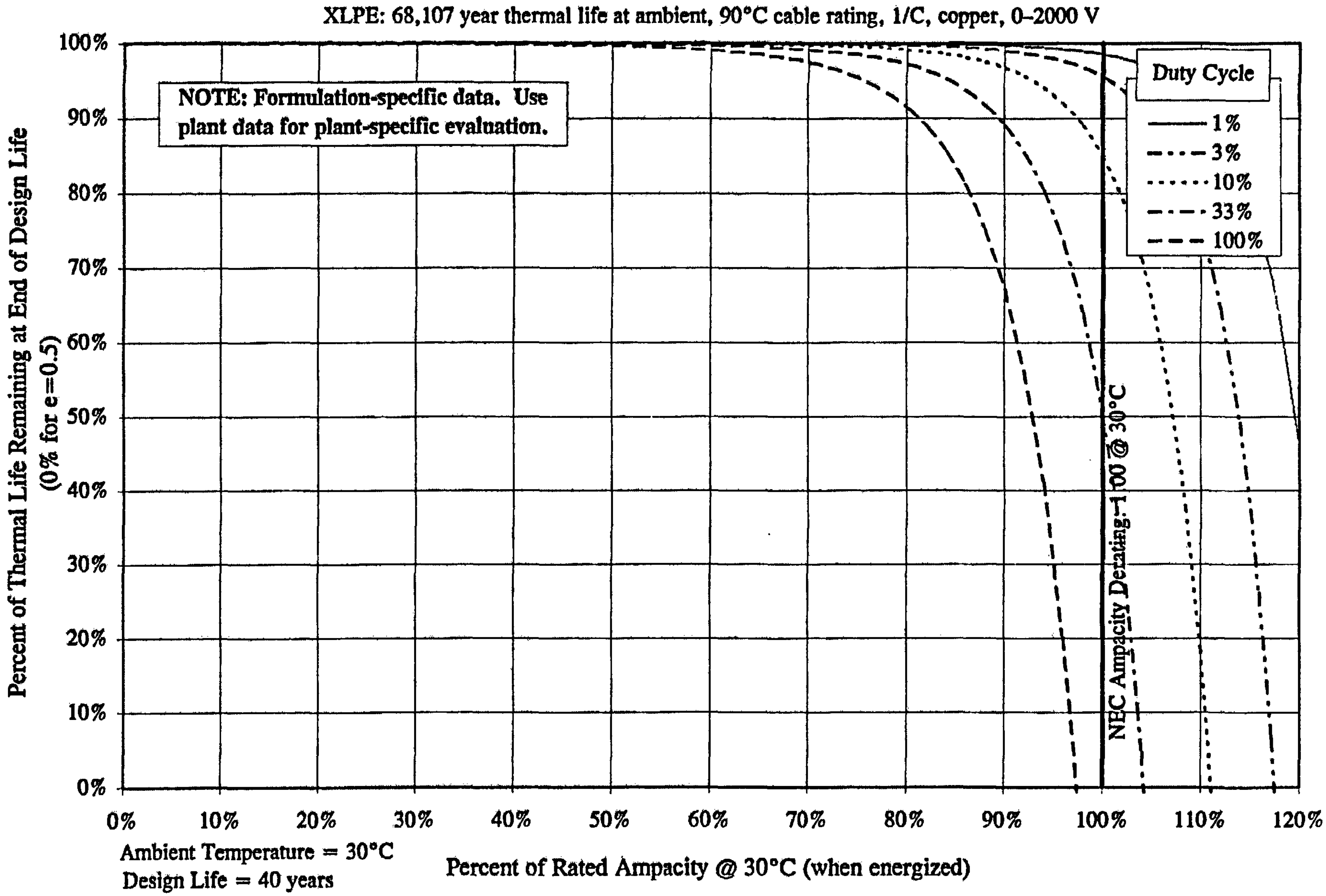

Figure G-3 Ampacity versus Thermal Life With Duty Cycles: XLPE, 30°C Ambient, 40 Years

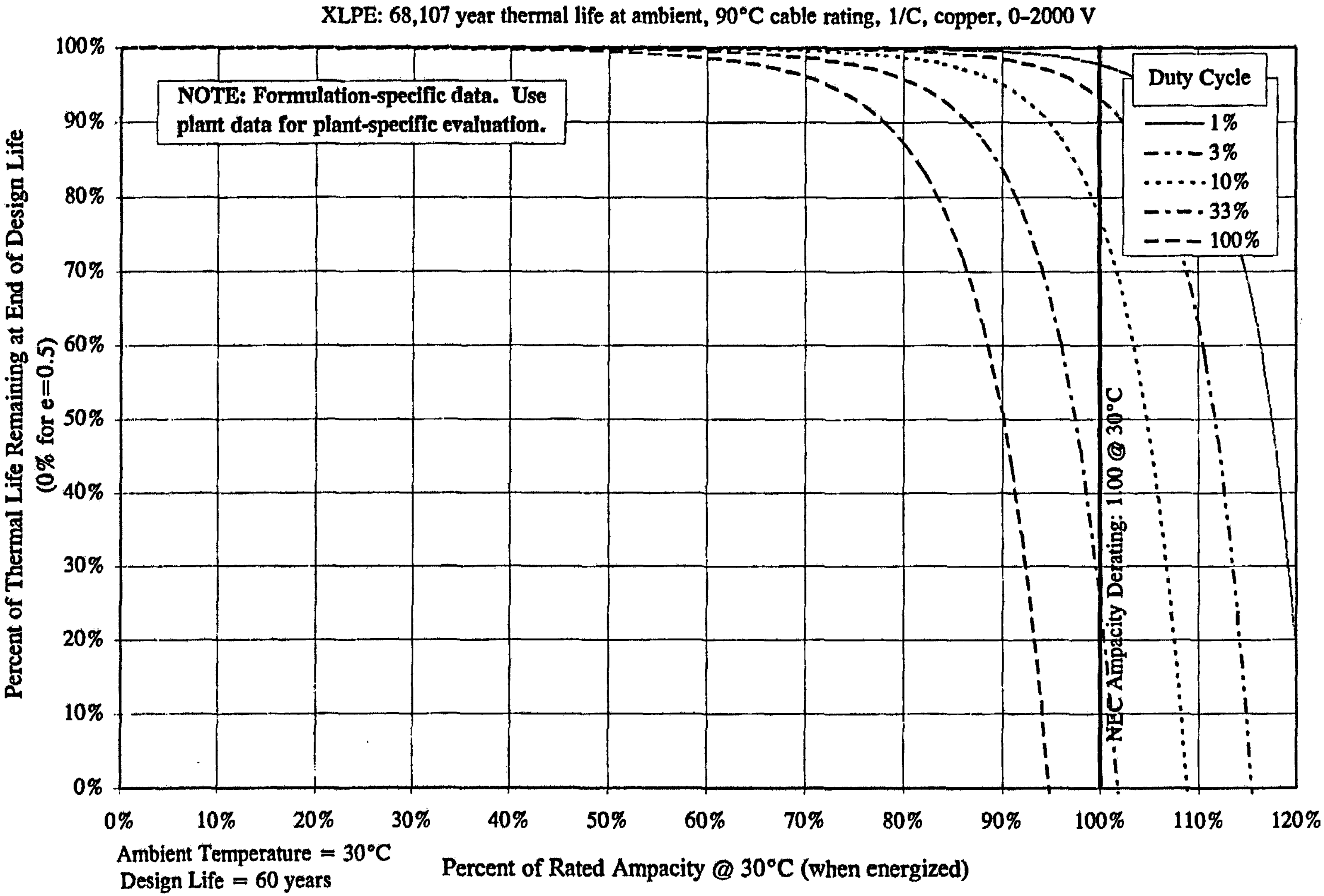

Figure G-4 Ampacity versus Thermal Life With Duty Cycles: XLPE, 30°C Ambient, 60 Years

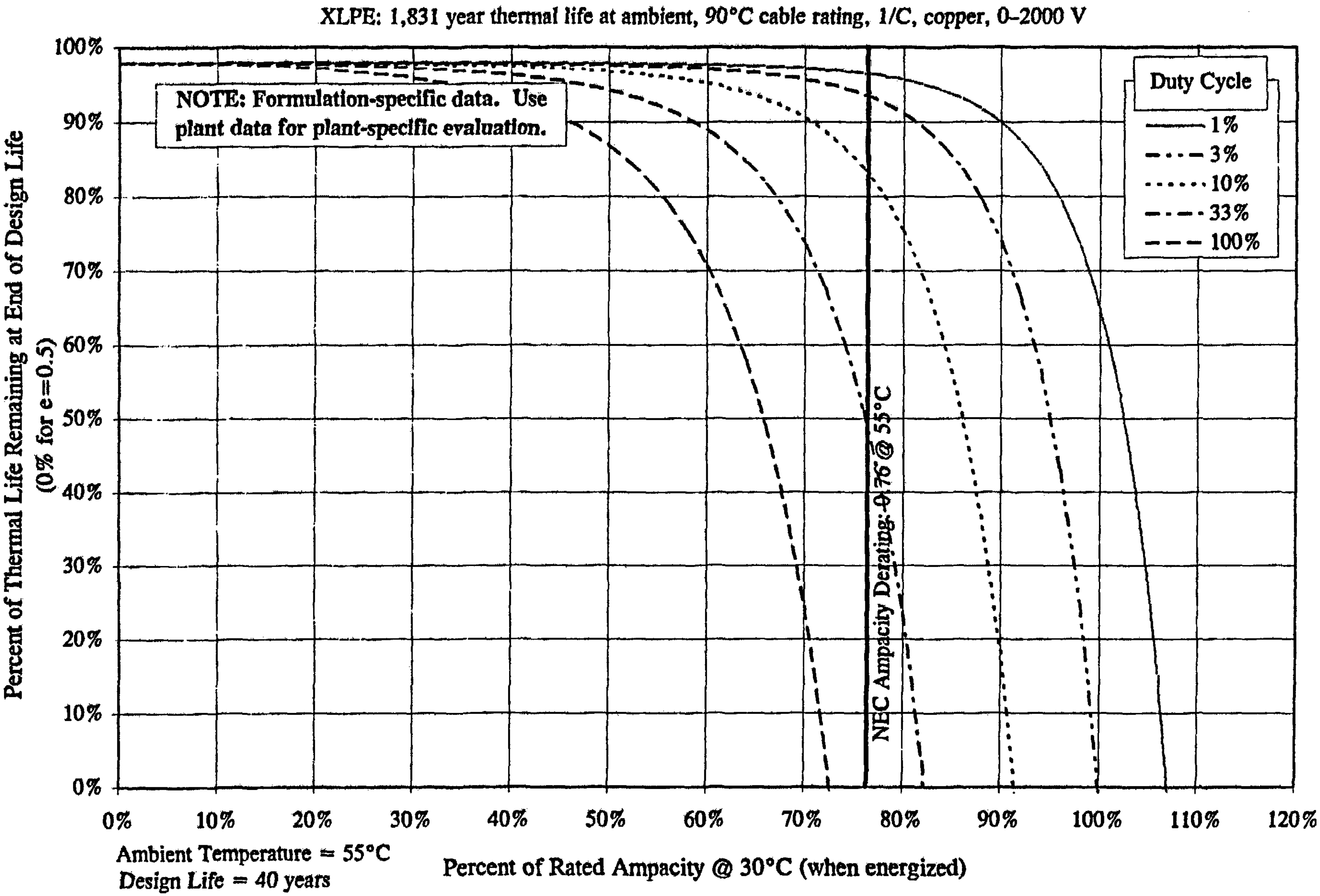

Figure G-5 Ampacity versus Thermal Life With Duty Cycles: XLPE, 55°C Ambient, 40 Years

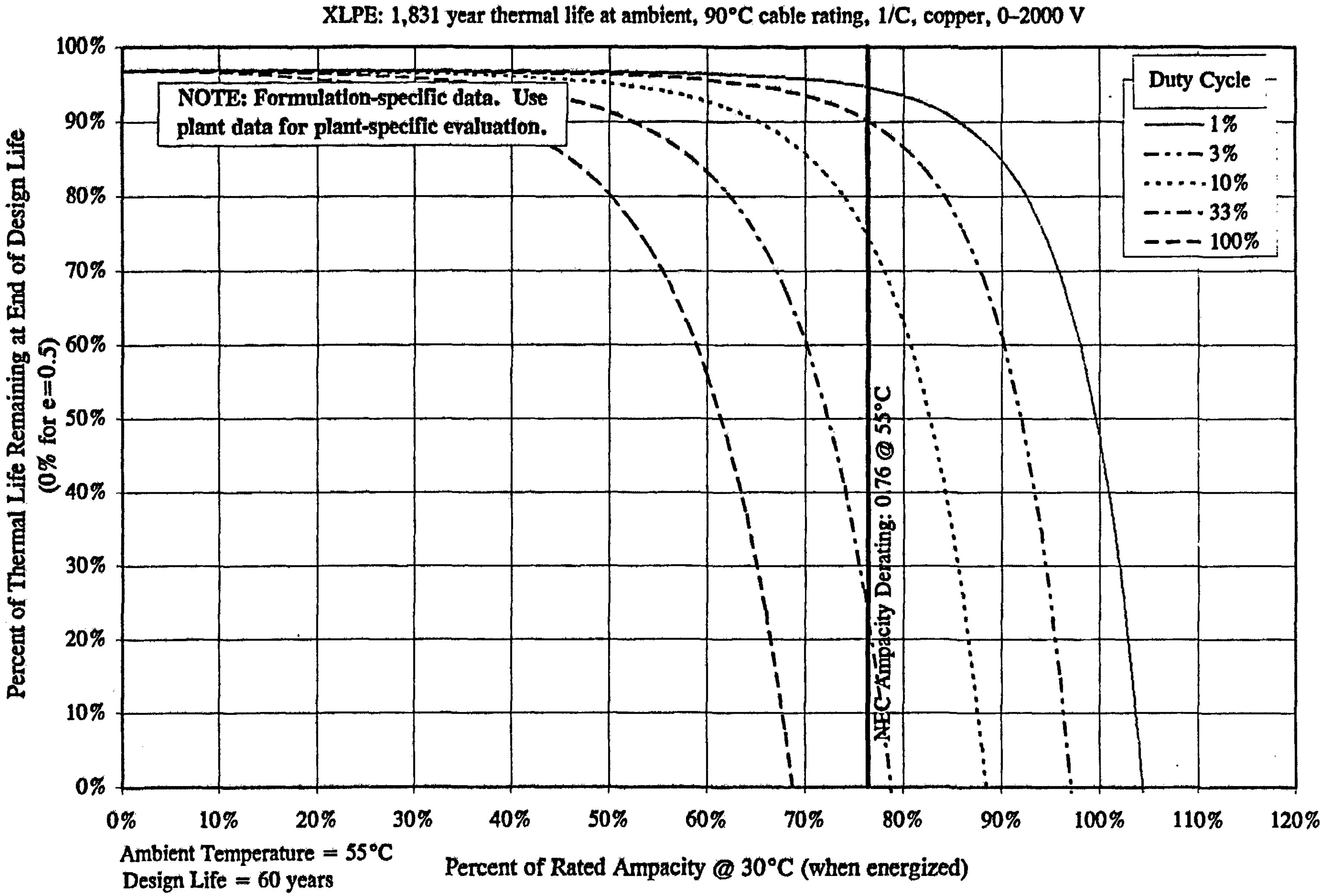

Figure G-6 Ampacity versus Thermal Life With Duty Cycles: XLPE, 55°C Ambient, 60 Years

G.6 References

G.1 ANSI/NFPA 70-1990, "National Electrical Code (NEC-1990)," National Fire Protection Association, Quincy, MA, 1989.

G.2 AIEE Pub. No. S-135, "Power Cable Ampacities: Volume 1 - Copper Conductors," AIEE is now The Institute of Electrical and Electronics Engineers, 1966 (IPCEA Pub. No. P-46-426).

G.3 Kommers, T. A., "Ampacity Ratings for Insulated Conductors," IEEE Conference Record of 1982 Annual Pulp and Paper Industry Technical Conference, The Institute of Electrical and Electronics Engineers, June, 1982.

G.4 Neher, J. H. and M. H. McGrath, "The Calculation of Temperature Rise and Load Capability of Cable Systems," AIEE Transactions, Part III, Vol. 76, p. 752, American Institute of Electrical Engineers (now IEEE), October, 1957.

G.5 EPRI NP-1558, "A Review of Equipment Aging Theory and Practice," prepared by the Franklin Research Center, Electric Power Research Institute, September, 1980.

G.6 ANSI/IEEE 242-1986, "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems," The Institute of Electrical and Electronics Engineers," 1986.

APPENDIX H. REGULATORY REQUIREMENTS RELATED TO SYNERGISMS

H.1 Regulatory Requirements

The first mention of synergistic effects in NRC documents related to EQ appeared in NUREG-0588 [H.1], issued in December 1979. NUREG-0588 did not define the term "synergistic effects," and the response comments received by the NRC from the industry were not in favor of including such a requirement. Nonetheless, the NRC retained the requirement when it issued Rev. 1 of NUREG-0588 [H.2] in July 1981. The complete text [Section 4.(3), page 15] is as follows:

> Synergistic effects should be considered in the accelerated aging programs. Investigation should be performed to assure that no known synergistic effects have been identified on materials that are included in the equipment being qualified. Where synergistic effects have been identified, they should be accounted for in the qualification programs. Refer to NUREG/CR-0276 (SAND78-0799) and NUREG/CR-0401 (SAND78-1452), "Qualification Testing Evaluation Quarterly Reports," for additional information.

The requirement was restated in the EQ Rule, 10CFR50.49 [H.3], when it was issued in February 1983. The wording related to synergism was modified significantly from that in NUREG-0588, Rev. 1; again no definition of synergism was provided. The complete text [paragraph (e) (7)] is as follows:

> Synergistic effects must be considered when these effects are believed to have a significant effect on equipment performance.

Regulatory Guide 1.89, Rev. 1 [H.4], issued in June 1984, described a method acceptable to the NRC staff for complying with 10CFR50.49. The complete text related to synergism [Section 5 a, page 1.89-5] is as follows:

> If synergistic effects have been identified prior to the initiation of qualification, they should be accounted for in the qualification program. Synergistic effects known at this time are dose rate effects and effects resulting from the different sequence of applying radiation and (elevated) temperature.

The wording in the Regulatory Guide can be interpreted in various ways. No definition of synergism is presented, but two examples of synergistic effects in aging programs are given. This is the most recent explicit guidance on synergism.

Appendix A includes a definition of "synergistic effects" from EPRI TR-100844 [H.5]; however, this definition is not endorsed by the NRC.

H.2 References

H.1 NUREG-0588 ("For Comment"), "Interim Staff Position on Environmental Qualification of Safety-Related Equipment, Resolution of Generic Technical Activity A-24," Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, December 1979.

H.2 NUREG-0588, Rev. 1, "Interim Staff Position on Environmental Qualification of Safety-Related Equipment Including Staff Responses of Public Comments, Resolution of Generic Technical Activity A-24," Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, July 1981.

H.3 Title 10, U.S. Code of Federal Regulations, Part 50.49, "Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants," published in the Federal Register, Vol. 53, May 27, 1988 (page 19250).

H.4 Regulatory Guide 1.89, Revision 1, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, June 1984.

H.5 EPRI TR-100844, "Nuclear Power Plant Common Aging Terminology," prepared by MPR Associates, Inc., Electric Power Research Institute, November 1992.

APPENDIX I. EPRI CABLE AGING RESEARCH PROJECTS

This section was reproduced from the draft EPRI Cable Aging Research Summary, August 1996. It is included in this AMG for the reader's convenience; current information can be obtained from the EPRI Plant Support Engineering group in Charlotte, NC.

Introduction

Electrical cable installed in fossil and nuclear power plants are expected to offer many years of trouble-free service. In the case of nuclear plants in particular, certain cable has been qualified for a 40-year life. In a limited number of cases, cables have been known to experience failure for a number of reasons, including mechanical damage, chemical attack, thermal degradation, electrical aging, radiation aging, and manufacturing defects. However, virtually all failures experienced have been premature in that their root cause was error-induced (e.g., damage due to handling or excessive high temperature conditions) and not due to long-term aging degradation.

Although rapid or widespread deterioration of cable systems is not expected to occur within the current design life of 40 years, localized problems such as hot spots may require reevaluation of cable life. Also, although it is expected that most cable, in the absence of hot spots, can provide 60 years or more of reliable service, such an extension of qualified life requires an evaluation. Without adequate data and evaluation techniques, utilities may find themselves needlessly replacing cable or entering into extensive evaluation programs. EPRI Cable Aging research will provide valuable data and methodology for use by utilities in making appropriate decisions concerning testing, continued use ,and replacement of cables. This work will also be useful in responding to increased regulatory interest related to generic issues such as synergisms and dose rate effects as the industry's cable systems grow older or cable-specific such as cracking of bonded cable jackets during research tests. The U.S. Nuclear Regulatory Commission is involved with cable performance issues and is presently sponsoring a cable condition monitoring research effort with Brookhaven National Laboratory (BNL). EPRI is cooperating in some of this research.

The EPRI Cable Aging Research Projects currently underway consist of the following:

1. University of Connecticut Artificial versus Natural Aging Program
2. Development of In-Plant Trials of Indenter Polymer Aging Monitor
3. Cable Diagnostics Matrix
4. Detection of Localized Cable Damage Using Preionized Gas, High Potential Testing
5. University of Virginia Oxidation Induction Time Methodology Development
6. Cable Life Database

7. Improved Conventional Testing of Power Plant Cables

8. American Electric Power Service Corporation - EPRI Life Cycle Management Program, Cable Aging Management Program

The purpose of this document is to summarize EPRI Cable Aging Research projects currently underway and to provide a brief status report on each project.

I.1 University of Connecticut Artificial Versus Natural Aging Program (RP-1707-13)

OBJECTIVE:

To demonstrate the validity and conservatism of the thermal and radiation accelerated aging models for organic materials used in electrical equipment that must be environmentally qualified.

DESCRIPTION AND PROGRAM HISTORY:

The Program seeks to understand the aging of polymeric materials used in cables and other components used in harsh environment areas of nuclear power plants by comparing the results of aging under natural in-plant conditions with those under accelerated laboratory aging used in environmental qualification programs. To achieve this goal, 15 bundles containing samples of four commonly used cables and materials used in electrical components or subcomponents of switches and solenoid valves were placed in each of 15 different locations in 8 power plants. The specimens include various types of small electrical devices and cables. The devices include solenoid valves, pressure switches, and electrical feedthroughs. Four types of power, control, and instrument cable from four major suppliers are in bundles at all fifteen of the original plant locations. Three of the types, manufactured by BIW, Kerite and Okonite, have ethylene-propylene copolymer insulation (EPR) covered with chlorosulfonated polyethylene (Hypalon) jackets. The fourth type, manufactured by Rockbestos, consists of a cross-linked polyethylene (XLPE)insulation covered with a Neoprene cover. In addition, each utility has placed one cable type of plant-specific interest in its bundles. Over 6000 specimens are involved. The locations have measured average temperatures ranging from 77°F to 132°F. Temperature monitoring and radiation monitoring devices have been installed with the bundles and are periodically withdrawn and replaced to provide a basic understanding of the environment at the bundles. In addition, utility temperature monitoring information from nearby areas is evaluated to allow adjustment for cyclic variations in temperature.

The initial specimens were placed in the plants in 1985. In 1989-1990, 60 additional bundles containing three cables selected from the NRC-sponsored program at Sandia Laboratories were placed at five of the existing locations (in four plants). The types added were Rockbestos coaxial cable with XLPE insulation, Rockbestos cable with silicone rubber insulation, and Champlain cable with polyimide (Kapton) insulation. Of the Sandia bundles, 13 have been removed. To obtain additional data at more severe aging conditions, five additional specimen bundles were placed at each of two "hotter" locations of Virginia Power's Surry containments during 1988. Of the Surry bundles, four have been removed for analysis. These bundles contain cable specimens of the same type as had been used by the research program at Sandia National Laboratories so that complementary data could be gathered by the two programs.

As part of a separate but similar program, Northeast Utilities (NU) placed, in 1982, three cables of different compositions in its Millstone 2 plant for aging studies. These cables are located in trays above the reactor vessel and experience quite severe conditions. In the case of these special NU specimens, a sample withdrawal consists of cutting off a piece of the cable. A total of six withdrawals of the NU special samples have been made.

Individual specimen bundles are periodically removed from the plants and evaluated. Initial specimen removal was approximately once per refueling cycle; however, due to the long-term nature of this segment of the program, removals are now less frequent so that adequate bundles exist through the end of the current license for the plants. When the bundles are received, elongation-at-break tests, density, and weight measurements are performed on the cable samples and some of the material specimens. All specimens that have been removed from the plants are stored under benign conditions to limit further aging and allow additional testing in the future.

Specimens of the same materials have also been aged under accelerated laboratory conditions and subjected to elongation, density, and weight measurement to allow comparison to the data from the in-plant specimens.

As the program has progressed, additional considerations and concerns have had to be addressed. One of the major problems with the in-plant specimens has been gathering and evaluating in-plant environmental data. A reduction of about 10°C in the average temperature may cause a doubling of time to reach a given level of degradation. Therefore, accuracy of the environmental data is crucial. To gather environmental data, three independent measures are made. One consists of a passive monitoring unit containing three types of dosimeters (two film and one LiF pellet) and a set of maximum-temperature pellets. The second measure is from the closest instruments used by the plant to monitor containment environment. Although not all of these instruments are close enough to be directly useful, they should provide confirming data that can fill in the history between withdrawals of the passive unit. The third and more recent measure involves placing a self-contained digital data logger capable of recording temperatures every hour for up to two years. On the data logger's removal, the temperatures can be downloaded into a computer file. When combined with plant-instrument data, the entire temperature history at each site should be able to be reconstructed accurately.

To date, data from the first 10 years of the long-term natural aging indicate that most of the cable materials have not begun to age appreciably. An exception is the neoprene jacket on the Rockbestos cable that has had a noticeable drop in elongation properties in warm (120° to 140°F) locations. This is not unexpected and the properties have not deteriorated to the point where a significant concern exists.

Because there is a desire to identify changes in advance of the aging of the installed cables in the plants, an additional task was added to the program in 1994. In this program, called the Pace Cable Program, cable specimen bundles have been placed in plant locations that are hotter than the locations where most cables are located such that an acceleration factor of 5 to 8 times that of normal natural aging occurs. In this way, the equivalent of 40 years of aging will occur in only 5 to 8 years so that an understanding of the effects of aging of the materials will be obtained earlier than for the specimens under near normal conditions. (Accelerated aging factors used in qualification programs are on the order of 1000 to 2000, which causes relatively large

uncertainties in the degree of aging achieved.) If the behavior of materials under Pace conditions is relatable to real conditions, then these sites could be used for testing and monitoring of new or existing materials. Pace sites were selected at PSE&G and NU.

As a further attempt to understand long-term slow aging of cable materials, oven aging at low accelerated aging temperatures has been implemented in parallel with the Pace Cable Program. Differences between natural and artificial aging may be due merely to the lower levels of temperature and dose rate in the former or to other factors that differ between the plant and the laboratory. Humidity is one example of such a factor. To test the possibility that the differences are only due to lower temperature, samples were placed in ovens with low temperatures, e.g. 140°F (60°C) and 195°F (90°C), to parallel the natural environmental temperatures anticipated at the Pace cable sites.

STATUS:

The program is being performed at the University of Connecticut under the direction of Dr. Montgomery Shaw. An Interim Report (the second) on the project was issued in January 1992 (EPRI TR-100245, Natural Versus Artificial Aging of Nuclear Power Plant Components). The third Interim Report will be published in 1996. Specimens and environmental monitoring modules continue to be retrieved from the plants. Activities for the year 1995 are described under the following topics:

- Environmental Monitoring

  Six dosimeter/temperature (D/T) units were received, and 14 were shipped to the various utilities. Eighteen recovered D/T units were refurbished for subsequent shipments.

  Ten sets of maximum temperature pellets were read from the D/T units received. A total of 45 LiF dosimeters were sent to Northeast Utilities for analysis during 1995, and the results were used to help update the environmental exposure database.

  Environmental data from the plants' monitoring instruments continue to be collected and analyzed.

  Dosimeter/temperature units continue to be received from the host utilities. Some decontamination effort is required. New D/T units continue to be delivered to the host utilities as needed.

- Withdrawals

  Two bundles were received from Washington Public Power Supply System (WPPSS). Additional decontamination work on all the bundles is necessary before testing can begin. At the end of 1995, 99 bundles out of the 225 originally placed will have been received.

  Bundles are being withdrawn from the sites as scheduled.

- Testing

A total of 92 specimens from 15 bundles were tensile-tested during 1995. Of this total, 9 control specimens were tested. A total of 956 density specimens from 15 bundles were analyzed in 1995.

- Analysis

Component Aging. The artificial and natural aging of components are compared using time shifts for temperature and dose rate in a manner described in previous reports. The shifts are determined by minimizing the scatter of the data points about an unknown property decay curve. This work will continue in 1996 as much as funding will allow.

Modeling Study. Procedures for testing the modeling algorithms continue to be developed. The physical property data on the naturally and artificially aged specimens are compared in a number of ways. One method involves constructing predicted property values for the set natural aging conditions using the Arrhenius equation, along with published activation energies, and the equal-dose-equal-damage premise. These predicted values are then compared with the actual values. Another method uses the natural data set, which involves temperatures ranging from 90° to 160°F, to derive an activation energy and dose-effect parameters. The results are then compared with published values. In a third method, two materials that are supposed to behave similarly in both accelerated and natural conditions are compared side-by-side; if they are, in fact, not behaving similarly, the notion that accelerated tests are a valid indicator of aging performance in the field can be rejected.

- Pace Cable Aging

Temperature data for the period July 21 through October 3, 1995, were received from PSE&G for the Pace bundles in containment. The maximum temperatures listed for this period are 159° and 140°F, respectively, for the thermocouples at the top and bottom of the bundles. The average dose rate for the period August 4 through October 3, 1995, was listed as 850 mR/hr.[1] Northeast Utilities is postponing precise site selection and Pace cable placement, pending completion of ongoing engineering work.

Pace cable specimens are installed at the Hope Creek site. Environmental data through October 1995 have been received. Hope Creek has recently been restarted.

- Other

The draft 10-year Interim Report for this project has been written and is at EPRI for draft review and publication.

Actions are in progress to cooperate with Brookhaven National Laboratory in their NRC-sponsored Cable Insulation Condition Monitoring Project by making aged cable insulation samples available for their test program.

I.2 Development and In-plant Trials of Indenter Polymer Aging Monitor

OBJECTIVE:

To develop a non-destructive technique that may be used in a plant to evaluate the aging of nuclear power plant cables that have been subjected to normal or abnormal service conditions.

DESCRIPTION:

Under earlier EPRI programs, a non-destructive test method was developed for evaluating the aging of jackets and insulation of electrical cable. The test evaluates changes in compressive modulus, a mechanical property of the insulation and jacket material. For low-voltage cables, significant mechanical property changes occur due to thermal and radiation induced aging prior to electrical property changes. Essentially, the mechanical properties must change to the point of embrittlement and cracking before significant electrical changes are observed. Commonly, changes in mechanical properties of jacket and insulation systems have been evaluated by means of elongation-at-break testing. However, elongation testing is by nature destructive and requires relatively large specimens, making it undesirable for analyzing installed cables. As an alternative to the destructive elongation-at-break tests, compressive tests were evaluated during the proof of principles research. In this research, compression, relaxation, creep, and recovery properties were evaluated. The research showed that the change in force divided by change in position of a probe pressing against the jacket or insulation of a cable at a constant velocity provided a systematic indication of aging of the material. For materials that harden with age (i.e. most cable insulations and jackets), the measured compressive modulus increases with duration and level of exposure to thermal and radiation stresses.

Therefore, the relative age of a cable insulation can be evaluated on the basis of the change in compressive modulus as measured by a small anvil pressing at the surface at a fixed velocity while measuring the imparted force.

The Indenter is a self-contained system and includes its own data logger. The system includes a laptop computer, a control box, cable, and a cable clamp assembly. The operation of the Indenter is digitally controlled, allowing different velocities and force limits to be used in testing, and contains self-nutting on the force reading to eliminate offset drift effects. The clamp assembly was improved to allow easy application on the cables and contains status indicating lamps. The tests are initiated from the clamp assembly. A long cable was added between the clamp assembly and the control box to allow use of the clamp in areas where the cable under test was remote from a satisfactory staging area.. The entire system is battery operated.

The in-plant trials of the Indenter proved that the system is practical and readily usable. Actual application of the Indenter in the plants proved that it could be readily used in junction boxes, back planes of motor control center, and even in condulets. The in-plant tests proved that reasonable consistency in results could be obtained in the field.

The Indenter concept works for any insulation or jacket that has a systematic change in properties with aging. Rubber and rubber-like materials, such as EPR, silicone rubber, neoprene, PVC and Hypalon, all are monitorable with the Indenter. The suitability of the

Indenter for direct monitoring of the aging of cross-linked polyethylene is currently under investigation. If neoprene or Hypalon jackets have been used on cables with cross-linked polyethylene insulation, the jackets may also be used as aging indicators for the entire cable.

STATUS:

The Indenter in-plant trial use program is complete. Life projection criteria have been developed for a number of cable types, including Okonite, BIW and Kerite. Given the current age and an Indenter measurement of a cable, a projected qualified life can be determined based on actual condition. The report for the in-plant trials and life projection criteria development was expected to be published in early 1996. In commercial, non-EPRI funded programs, the Indenter has been used to evaluate hot-spot conditions at River Bend, LaSalle, and Fermi. An aging evaluation of in-containment cables at Enrico Fermi has been completed. EdF (France) has completed an in-depth evaluation of the Indenter for use in its plants; the results of this evaluation have been satisfactory. The Indenter is available for commercial use via Ogden Environmental and Energy Services Company under license to EPRI.

There is no change in the Cofunding Agreement between EPRI and EdF for the Indenter project. EPRI has the action item.

There is no change on the revision of the licensing details on the sale of the Indenter to commercial customers. EPRI has the action item.

Potential Indenter sales in 1996:

- AEA Technology
- Detroit Edison
- EdF (France)
- Exxon Engineering (Refinery)

I.3 Cable Diagnostics Matrix

OBJECTIVE:

To provide a utility applications based assessment of cable diagnostic techniques currently available or in an advanced state of development.

DESCRIPTION:

During the past 10 or so years, a number of diagnostic techniques have been developed that enable varying degrees of assessment of the condition of power plant cables. Some of these techniques are useful for evaluation of installed cables, whereas others are destructive tests that must be conducted with samples of cable materials removed from installation. Some techniques are useful for trending the long-term performance of cables, whereas others are useful only troubleshooting. The remainder consist of laboratory tests for characterizing the properties and performance of specific cable materials.

This program compiled and consolidated published and technical report information on the principles, applications, cost, and other major test method considerations with particular attention to their applicability. This information was collected into an organized reference document and a computerized database for use by the utilities who operate fossil and/or nuclear power plants. The test method matrix will be accessible on the basis of many topics of concern, including cable construction, failure analysis application, trending analysis application, destructive versus non-destructive test method, etc.

This program primarily addresses power plant low-voltage control and instrumentation cables.

The program is described in the following outline.

1. Review of the available diagnostic tools, including:

    - technical description of the test equipment
    - specific properties measured
    - relative cost of instrumentation
    - portability of test equipment
    - defects/aging to which method is sensitive
    - commercial availability of equipment
    - relative complexity of test performance
    - relative complexity of data interpretation
    - relative availability of reference data
    - potential for damage to the specimen under test and to adjacent circuits
    - sensitivity of method to local and overall degradation
    - type of result provided (go/no-go vs. trending)
    - ability to locate degraded areas along cable application in-situ or laboratory
    - if destructive, relative amount of material required for testing
    - insulation/jacket/shielding materials to which the test is sensitive
    - reference to publications describing the theory involved

2. Development of Cable Diagnostic Matrix

    - compilation of data in a user-friendly format
    - preparation of reference document

3. Summary of the applicability and limitations with present diagnostics techniques

STATUS:

A draft report has been submitted and is under EPRI review for comments.

I.4 Detection of Localized Cable Damage Using Pre-ionized Gas, High Potential Testing (RP-3427-04)

OBJECTIVE:

To provide an electrical test technique for identifying local defects in unshielded low-voltage cable located inside conduits.

DESCRIPTION:

From time to time, concerns have arisen in the industry that require utilities to determine if damage has occurred to low-voltage cables either during or subsequent to installation. The lack of a shield on most low-voltage cables used in nuclear plants has made use of electrical testing to evaluate the condition difficult.

For cables located in conduits, one available technique for developing a ground plane at the surface of the insulation is to fill the conduits with water and perform a high potential test between the conductors and the conduit. However, filling conduits with water is difficult in that they are not tightly sealed and water can leak onto surrounding energized electrical equipment, causing the potential for flashover. Removal of the water at the end of the test is also difficult. Also, clear-cut definitions of acceptable test voltages are not available for such testing.

To provide an alternative to use of water as the ground plane and to determine acceptable test voltages, the use of ionizable gas for providing in conduit ground planes during high potential testing is being developed as are acceptance criteria based on as-low-as-possible test voltages. Although the cables are called low-voltage cables with 600- to 1000-Vac ratings, the thicknesses of the insulation are capable of withstanding very high voltages. Data from the program indicate that 30-mil thick insulation can withstand voltages on the order of 22 to 26 kVac, which is much higher than the manufacturing proof tests, and much higher than desirable for in-plant testing. High potential tests are go/no-go in nature. If the insulation successfully withstands the test voltage, a statement can be made that at least the amount of insulation thickness associated with the test voltage acceptance criteria remains in place (i.e., even though one cannot state that no damage has taken place, an indication of the minimum possible remaining wall can be made).

The research determined that high potential testing of cables in ionized helium yields high potential test results similar to those when the ground plane is provided by water. In the associated tests, specimens of cable with a 30-mil insulation wall with varying depths of insulation damage from 0 to 30 mils were tested to breakdown. The tests showed a significant reduction in test voltage between testing with the conduit filled with air and the conduit filled with water. The tests also showed that testing with the conduit filled with helium had nearly the same results as with the conduit filled with water. It should be noted that when testing in air, identification of completely through wall damage required nearly 14 kVac, whereas testing with water and helium required only 1 to 2 kVac. The slight difference in results with water and helium is predominantly related to the voltage at which the helium ionizes. Once the helium ionizes, the stress across the insulation under test increases significantly with most of the test voltage across the insulation under test. The research to date has shown the method to be viable and not to be destructive to cables surrounding the cable under test. It should also be noted that

dilution of the helium rapidly decreases its ability to ionize. Therefore, if helium escapes from the conduits under test, there is no possibility of causing flashovers in surrounding electrical equipment that uses air as an insulation medium (e.g., circuit breakers and switches).

The initial development of the process has been completed under Sandia National Laboratories, and the report of the testing was finalized in 1994 (TR-104025). During the course of the work, conflict of interest concerns on the part of the U.S. NRC dictated that follow-on work be performed elsewhere. The continuation of the program is being performed by Ontario-Hydro Research under the direction of Dr. Jean-Marie Braun[1]. Work started in early 1994. The efforts include:

- Optimization and selection of the ionizable gas to further reduce test voltages
- Evaluation of differences in results from longer lengths of cables ("length effect")
- Determination of the need to monitor current and voltage during the tests to provide more information concerning the degree of damage
- Development of a useful dc test method (dc withstand and transient measurements)

STATUS:

The selection of ionizable gas was investigated; the gas selection issue is now limited to two candidates. Dr. Braun reported that the initial investigations with an 8% conduit fill with one "faulted wire" resulted in successful location of the fault. Both pure helium and neon/0.1% argon will be used to further study which gas will provide a satisfactory voltage gap.

Dr. Braun needs about 3000 meters of #14 or #16 wire to continue the project into Task 2. Cable donations from participating utilities have not yet been made; therefore, the requisite cable will be purchased from a cable manufacturer. Single-conductor EPR-insulated cable will be selected. Although the lack of cable is now holding up progress, some investigation has been made using #17 PVC cable that was available on site.

I.5 University of Virginia Oxidation Induction Time Methodology Development

OBJECTIVE:

Oxidation induction time (OIT) testing is a means of evaluating the degree of aging of polymers subjected to thermal and radiation stresses. The purpose of this program is to develop consistent methodology in using OIT to evaluate the aging of nuclear power plant cables and to prepare life estimation criteria based on measurements of OIT of specimens artificially aged as in environmental qualification programs.

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[1] The results of related research at the University of Connecticut performed by Dr. Matthew Mashikian are contained in EPRI Report TR-101273, Using an Ionizable Gas to Troubleshoot Nonshielded Electric Cables.

DESCRIPTION:

Oxidation induction time (OIT) testing is an alternate and complementary test to that of the cable Indenter. It is a means of evaluating aging of cable materials by measuring the period of time before a small sample of insulation experiences rapid oxidation when subjected to a constant elevated temperature in an oxygen atmosphere. The test evaluates the amount of anti-oxidants remaining in an insulation material. The anti-oxidants are materials that react with oxygen from the atmosphere surrounding the cable before it can react with the polymers of the insulation. As long as the anti-oxidants are not depleted entirely in the material, the mechanical properties (and, therefore, the electrical properties) remain relatively stable. Even a few percent of the initial anti-oxidant is sufficient to prevent oxidation of the polymers. When the anti-oxidants are depleted, the material properties will begin to degrade, in some cases relatively.

OIT testing is performed using a differential scanning calorimeter. A small sample (8 milligrams) of insulation or jacket is removed from the cable, then heated to approximately 215°C in oxygen and held at this temperature. The energy required to sustain the temperature is monitored. When the energy required to main temperature begins to decrease, the material has begun an exothermic reaction, indicating that the anti-oxidants have been depleted and that rapid oxidation is occurring. The period from the start of the test until the point of rapid oxidation is the oxidation induction time. For cable materials, the OIT decreases from approximately one hour when new to a few minutes when near the end of its useful life. The test is essentially non-destructive; although samples have to be removed, they are small enough that cables do not have to be destroyed or removed. Samples are taken by removal or terminal lugs, stripping a small segment of insulation (0.5 cm or less), and relugging the conductor.

Although OIT testing has been in use for a long time, testing protocols for use with nuclear power plant cables have not been previously developed. The following tasks are complete:

- Determination of the Feasibility of Developing Life Projection Criteria
- Correlation of OIT with Elongation at Break
- Standardization of OIT Methodology
- Development of Acceptable Field Sampling Techniques

STATUS:

The project has been performed at the University of Tennessee under the direction of Dr. Albert Reynolds. The project is completed and the report is being published.

I.6 Cable Life Database

OBJECTIVE:

To provide the industry with a computerized database of aging behavior and plant experience data for low-voltage cable. The data will be obtained from manufacturers, qualification tests, research studies, and on-going plant cable evaluations.

DESCRIPTION:

A large quantity of information related to low-voltage cable exists, and useful information will be generated at an accelerating rate in the future. However, the data are not easily accessed or arranged for ease of use or understanding by front-line utility personnel involved in design engineering, qualification, assessing cable system longevity, or troubleshooting.

The Cable Life Database will provide the ready reference resource needed by utilities via a remotely accessible, computerized system. It will contain existing information organized by cable material type, test data from cable monitoring techniques as they are generated, material aging data, and qualification research results. The database will provide a strong reference tool for resolution of day-to-day problems as well as long-term issues. The sources of the initial data will be from utilities, past and on-going EPRI program, government research programs, and the general literature. The database will continue to be updated as new information applicable to low-voltage cable evolves.

The need for organizing available cable data and gathering new data as it is generated is driven by the following factors:

1. Many of the original manufacturers of nuclear plant cables no longer are in business or produce nuclear grade cables. As such, they cannot or will not provide data and information for decision-making and engineering efforts related to cable system longevity. Gathering and organizing existing data related to these manufacturers' cable is desirable before all of it is lost or forgotten.

2. Hot spots leading to more rapid localized deterioration of cable properties have been identified in some plants. Test results from cable removed from these locations may be useful to the industry as a whole in determining the actual effects of elevated normal temperatures. These data from previous hot spots may be instrumental in resolving new hot spot problems as they occur at other utilities.

3. Some plants have had elevated containment temperatures for long durations due to errors or unexpected conditions. These plants need information to determine the extent of cable to be removed and, at the same time, may be able to provide information to the remainder of the industry when the removed cables are tested.

4. Many plants are now or will be addressing cable system longevity. They will need to show that their existing qualifications cover the entire period for which their cables will be installed. The more data that are available related to cable insulation system behavior under

actual conditions (which include synergistic effects), the easier it will be to defend the decisions that are made with respect to retention or replacement of a plant's cables.

Each of these factors indicates that any data that are available (be it descriptions of cable insulation systems and their basic properties, physical or electrical property data, or information related to cable insulation system formulations) should be collected, catalogued, and retained in a format that allows the information to be easily accessed and used by utility and industry personnel.

The database will record information on older cable material formulations, qualification, and aging test results that are in the public domain, and research data important to understanding and controlling aging and synergisms. The database will also record results of condition monitoring and condition evaluation tests as they become available, including acceptance criteria and methodology descriptions.

STATUS:

An evaluation of the type of data to store, the format and structure, and the depth of detail is complete. The project was suspended in mid-1994. Further development of the database is under review.

I.7 Improved Conventional Testing of Power Plant Cables

OBJECTIVE:

To develop improved condition monitoring techniques for assessing the condition of power plant cables, particularly unshielded cables in older thermal plants.

DESCRIPTION:

Many diagnostic tests have been proposed to assess the condition of power plant cables. Electrical tests are inherently attractive, as they offer the potential of assessing an entire cable run rather than a predetermined, accessible area. However, most station cables are unshielded and lack a well-defined, stable ground plane, implying that all electrical tests will be insensitive to anything but gross changes in the insulation. This project -- cosponsored by EPRI, Consolidated Edison Co. of New York, Inc., and the Canadian Electrical Association -- was initiated to determine the potential for electrical testing to detect thermal aging.

Investigators selected cable insulations representative of older thermal plants. Insulation materials included polyvinyl chloride (PVC), styrene butadiene rubber (SBR), ethylene propylene rubber (EPR), polyethylene (PE), and cross-linked polyethylene (XLPE). The cables of interest -- single conductor, twisted pair, triplex and multiconductor, 600 V and 5 kV, shielded and unshielded -- were thermally aged to embrittlement and characterized by physical, chemical, and electrical tests. These tests determined oxidation induction time (OIT), oxidation induction temperature, gel content, solubility, swelling ratio, plasticizer content, density, melting temperature, and crystallinity. Dielectric characterizations included low-frequency dispersion, the appearance of dipolar features, and steady-state conductivity.

A broad range of destructive and nondestructive diagnostic techniques were applied successfully to aged insulation materials and cable configurations. Dielectric characterizations revealed the importance of performing tests other than dc insulation resistance and polarization index, which are insensitive to thermal aging. In all, different tests were particularly suited to different types of insulation. Particularly important were low-frequency insulation analyses to probe the bulk condition of cable insulation and partial discharge testing to detect cracks and defects. A high-voltage instrument was designed during this project to perform low-frequency measurements on long lengths of cables at up to 5 kV with 0.01 to 100 mA sensitivity from dc to 1-Hz bandwidth. The instrument was successfully tested, meeting all design specifications.

STATUS:

The final report was published (TR-105581). Licensing negotiations to commercialize a tester based on low frequencies dielectric spectroscopy are in progress. Efforts are currently underway to obtain funding for further development of the tester for commercialization and the compilation of a standard parameter database.

I.8 American Electric Power Service Corporation - EPRI Life Cycle Management Program, Cable Aging Management Program

STATUS:

The four phases of the project are described below.

Phase 1 - Background Data Collection

The background information on the cable design, type, layout, and ambient environment was determined for all cables (53,250) in the Donald C. Cook Nuclear Plant. The final report has been submitted.

Phase 2 - Life Cycle Management

Every cable in the plant was evaluated for its service life based on thermal and radiation effects. Cables were identified if it was determined that the cable could possibly fail due to thermal aging (radiation effects were found to be negligible) before the end of the 40-year design life of the plant. A subset of the identified cable has been evaluated as risk significant based on the failure mechanism associated with the specific cable. The final report has been submitted.

Phase 3 - License Renewal

This phase evaluates cable, as in Phase 2, for a 60-year service life. The final report has been submitted.

Phase 4 - EPRI Report

This phase combines the efforts of Phases 1, 2, and 3 into a combined EPRI report. The draft has been submitted to AEP and EPRI for review. The final report will be submitted for publication in August 1996.

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