

Review of Suitability of EPR Medium Voltage Cables for Wet and Submerged Conditions

Revision 0, September 25, 2009

1 INTRODUCTION

This paper addresses medium voltage power cable (i.e., those rated 5-kV to 35 kV¹) used in underground/inaccessible applications where long-term wetting up to and including submergence may occur. The applications include cables in ducts, whether below grade or embedded under plant basement floors, cables in trenches, and direct buried cables. While some duct bank and trench systems can be maintained dry through natural drainage and/or pumping systems and activities, not all duct and trench systems can be completely drained and portions of direct buried cables are assumed to be wet/submerged. This paper discusses issues surrounding wetting/submergence of medium voltage cable including design and regulatory issues and long-term testing by manufacturers and researchers.

There are two distinct questions facing the nuclear power industry regarding medium voltage cables subjected to long-term wetted or submergence conditions:

1. Was the cable that was installed suitable and designed for wet or submerged conditions?
2. What is the current condition of the cable insulation?

This paper addresses the first question. The second question concerning current condition of medium voltage cable that has been wet or submerged for long duration is valid. However, its resolution is outside the scope of this paper and is being addressed separately. This paper does not provide a basis for continued use of cable nor does it provide a basis for the ultimate life of wet/submerged medium voltage cable.

With respect to the first question, NRC inspectors have requested proof that safety related cable that has been subjected to submergence was qualified for or designed for submergence. Violations have been issued to plants that have submerged cables. The NRC staff recognizes that the requirements of 10 CFR 50.49, Environmental Qualification of Electric Equipment Important to Safety for Nuclear Power Plants, do not apply because the environments of submerged cables do not change appreciably as result of design bases events (i.e., the cables are located in mild environments). This paper discusses the design of cables for wet/submerged conditions.

General operating experience with distribution cable, especially the earlier extruded insulation types, has indicated that wetted cable can suffer insulation deterioration before that of dry cable. Insulation systems that were used in earlier nuclear plants were an

¹ The operating voltages for these cables are typically 4 to 34 kV. Some cables may be operated at voltages as low as 2 kV, but this is rare in nuclear plants.

improvement over the types previously available, but did not necessarily live up to the expectations as being trouble free in wet/submerged conditions. While the acceleration of aging is not extreme, deterioration of some wetted cable has occurred after a few decades. More modern cable insulations appear to be much more resilient in wet conditions with two major types having no known failures to date related to wet conditions.

Paper Outline

The paper is meant to demonstrate that the medium voltage cable systems in use in nuclear plants were designed for wetted/submerged cable conditions and that wetting in and of itself does not constitute an immediate concern for cable operability. The paper starts with discussions of the concerns of staff members of the U. S. Nuclear Regulatory Commission and of the regulations cited in violations and presentations by the NRC staff. The paper then covers some of the basic definitions associated with underground/inaccessible cables that must be understood to determine whether utilities and cable manufacturers had a clear understanding that cables were being requested that could have service conditions including sections that were completely covered by water. Typical utility specifications concerning underground and direct buried conditions are provided as well as a discussion of manufacturing standards related to cables procured through the 1970s to 1990s. The fact that the main components of plant cables and submarine cables are identical and that moisture impervious layers are not required in submarine cables is presented because statements have been made by some regulatory staff that use of submarine cables would have been an acceptable design alternative. Comparisons of manufacturers' cable specification sheets are provided to further show that plant cables have the same insulation systems and design as submarine cable without the armor required by the rigors of subsea/submarine applications.

Figure 1 provides the basic structure of the document along with the intent of the sections of the paper. Additional information is provided concerning manufacturers' design qualification tests for wetted conditions and industry research on long-term water immersion at elevated voltages. Finally, conclusions are made based on the information provided in the paper.

Preparation Information

This paper was prepared by Gary Toman, Electric Power Research Institute, Plant Support Engineering. Specific manufacturers' information and review comments were provided by Robert Fleming of Kerite Company, Robert Konnik of Marmon Specialty Wire and Cable Group, and Edward Wolcott of General Cable Company.

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The paper was also subjected to a general review during the 2009 EPRI Cable Users Group Meeting in Concord, NC, on September 2, 2009.

Figure 1 Structure and Intent of Sections

Description of Submergence Issues	Introduces issues
Typical NRC Violation Related to Wetted Cable	Provides insights into NRC's concern
Review of Cited Regulations	Discusses the regulations that are the basis for violations and for the design of the cable systems
Definitions Related to Wetted Cables	Provides industry definitions of terms related to submerged and direct buried cable
Procurement Specifications for Cable	Shows that the industry specifications required cable suitable for submerged conditions
Evaluation of Manufacturing Standards Applicable to Nuclear Plant Cable with Respect to Plant Conditions and in Comparison to Submarine Cable	Shows that plant cable and submarine cable are essentially the same; supporting the position that plant cable was designed to be wet, up to and including submergence
Submarine and Plant Cable Manufacturing Comparisons	Compares manufacturers' cable specifications for plant and submarine cable

Additional Supporting Information	
Manufacturers' Information on Wet Testing of Cables	Provides manufacturers' discussions of design testing of cable under submerged conditions
Wet Testing of Black EPR	Provides a description of manufacture's testing of early black EPR
Long-term EPRI Research on Wet EPR Insulations	Describes long-term wet testing of modern EPRs

Overall Conclusions	

2 REGULATORY CONCERNS AND ISSUES

Content of a NRC Violation

Violations have been issued as a result of License Renewal Inspections and Component Design Basis Inspections. A typical violation from a License Renewal Inspection is as follows:

“The inspectors identified a Green NCV of 10 CFR Part 50, Appendix B, Criterion III, Control,” because [plant name] failed to adequately demonstrate that submerged 4160V safety related cables are qualified for such service, and that they will remain operable, although the cables are presently operable.”

During the inspection, the inspectors had manhole covers removed to allow inspection of essential service water cable trays and found that the cables were submerged. The inspectors determined that the plant “had not adequately evaluated design basis information to identify the acceptable environmental conditions that ensure the safety-related cables are qualified for submerged service. Specifically, [plant name]’s analytical methods were insufficient to justify continued operation.”

Both quoted sections from the violation are based on “qualification.”

Review of Cited Regulations

Utilities have been asked to demonstrate “qualification” when cable has been found to be submerged in water in underground applications. 10 CFR 50 Appendix A, General Design Criteria 4, 17 and 18 and Appendix B Quality Assurance Criterion III, Design Control, have been cited as requirements. These are listed below.

10 CFR50 Appendix A, General Design Criteria

“Criterion 4 – Environmental and dynamic effects design bases. Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit. However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.”

“Criterion 17 – Electric power systems. An onsite electric power system and an offsite electric power system shall be provided to permit functioning of structures, systems, and components important to safety. The safety function for each system (assuming the other system is not functioning) shall be to provide sufficient capacity and capability to assure that (1) specified acceptable fuel design limits

and design conditions of the reactor coolant pressure boundary are not exceeded as a result of anticipated operational occurrences and (2) the core is cooled and containment integrity and other vital functions are maintained in the event of postulated accidents.

The onsite electric power supplies, including the batteries, and the onsite electric distribution system, shall have sufficient independence, redundancy, and testability to perform their safety functions assuming a single failure.

Electric power from the transmission network to the onsite electric distribution system shall be supplied by two physically independent circuits (not necessarily on separate rights of way) designed and located so as to minimize to the extent practical the likelihood of their simultaneous failure under operating and postulated accident and environmental conditions. A switchyard common to both circuits is acceptable. Each of these circuits shall be designed to be available in sufficient time following a loss of all onsite alternating current power supplies and the other offsite electric power circuit, to assure that specified acceptable fuel design limits and design conditions of the reactor coolant pressure boundary are not exceeded. One of these circuits shall be designed to be available within a few seconds following a loss-of-coolant accident to assure that core cooling, containment integrity, and other vital safety functions are maintained.

Provisions shall be included to minimize the probability of losing electric power from any of the remaining supplies as a result of, or coincident with, the loss of power generated by the nuclear power unit, the loss of power from the transmission network, or the loss of power from the onsite electric power supplies.”

“Criterion 18 – Inspection and testing of electric power systems. Electric power systems important to safety shall be designed to permit appropriate periodic inspection and testing of important areas and features, such as wiring, insulation, connections, and switchboards, to assess the continuity of the systems and the condition of their components. The systems shall be designed with a capability to test periodically (1) the operability and functional performance of the components of the systems, such as onsite power sources, relays, switches, and buses, and (2) the operability of the systems as a whole and, under conditions as close to design as practical, the full operation sequence that brings the systems into operation, including operation of applicable portions of the protection system, and the transfer of power among the nuclear power unit, the offsite power system, and the onsite power system.”

10 CFR Part 50, Appendix B, *Criterion III – Design Control*

“Measures shall be established to assure that applicable regulatory requirements and the design basis, as defined in § 50.2 and as specified in the license application, for those structures, systems, and components to which this appendix applies are correctly translated into specifications, drawings, procedures, and instructions. These measures shall include provisions to assure that appropriate quality standards are specified and included in design documents and that

deviations from such standards are controlled. Measures shall also be established for the selection and review for suitability of application of materials, parts, equipment, and processes that are essential to the safety-related functions of the structures, systems and components.

Measures shall be established for the identification and control of design interfaces and for coordination among participating design organizations. These measures shall include the establishment of procedures among participating design organizations for the review, approval, release, distribution, and revision of documents involving design interfaces.

The design control measures shall provide for verifying or checking the adequacy of design, such as by the performance of design reviews, by the use of alternate or simplified calculational methods, or by the performance of a suitable testing program. The verifying or checking process shall be performed by individuals or groups other than those who performed the original design, but who may be from the same organization. Where a test program is used to verify the adequacy of a specific design feature in lieu of other verifying or checking processes, it shall include suitable qualifications testing of a prototype unit under the most adverse design conditions. Design control measures shall be applied to items such as the following: reactor physics, stress, thermal, hydraulic, and accident analyses; compatibility of materials; accessibility for inservice inspection, maintenance, and repair; and delineation of acceptance criteria for inspections and tests.

Design changes, including field changes, shall be subject to design control measures commensurate with those applied to the original design and be approved by the organization that performed the original design unless the applicant designates another responsible organization.”

GDC 4 states that components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. Accordingly, when utilities designed the cabling system, they needed to consider that portions of the cabling system could be subject to wetting and submergence and needed to select cable suitable for such conditions. GDC 17 defines the redundancy requirements for safety related electrical systems. No explicit statements are made regarding wet or dry cables. However, the inference could be made that no common mode effects should be present that would cause simultaneous failures of redundant cables. GDC 18 describes that the system must be capable of being tested to show that it is functional. It does not specifically discuss cable requirements. Appendix B Criterion III discusses checking and verification of adequacy of design. It also states that where testing is performed instead of other independent quality checking or verification to prove a design, it shall be performed by testing a prototype under the most adverse design conditions. There is no explicit requirement that such qualification testing must be performed to prove a design.

The combination of GDC 4 and Appendix B Criterion III require that a cable meant for wet and submerge conditions is necessary for applications where water can accumulate

around the surface of the cable. However, there is no requirement in either of these for a “qualification” test to be performed.

3 DEFINITIONS RELATED TO UNDERGROUND AND INACCESSIBLE CABLE

Definition of Wet, Damp, and Dry Locations

Understanding of the terms associated with design and procurement of cable for nuclear plant site cables is critical to understanding whether utilities and their architect engineers were requesting cables that could be submerged or sitting in water and that the cable manufacturers understood that they were supplying cable for such conditions.

Both Underwriters Laboratory and the National Electric Code define the terms dry, damp, and wet locations. These definitions are contained in Table 1. The definitions indicate that the term “wet” means up to and including submerged and not just damp, which has its own definition. The NEC definition indicates “saturation with water or other liquid.” The UL definition indicates “flow on or against electrical equipment.” Both definitions indicate a severe “wetting” condition and use of the term “wet” would have and still does indicate that manufacturers have to include long-term covering of cable with water in their design and testing considerations. Stating “wet” locations in cable specifications indicates that utilities wanted cable suitable for long-term submergence. Manufacturers understood this was a requirement.

Impervious Coverings

Some utilities have and continue to request and install cables with impervious coverings. The impervious coverings are designed to prevent penetration of water into the insulation system. Earlier cables employed either continuous lead or aluminum coverings tightly formed over the core of the insulation including cable shields. For a 1 inch (25.4 mm) diameter core the required lead layer was 2.03 mm (80 mils) and the required aluminum layer was 1.4 mm (55 mils). These continuous layers preclude water ingress and the result is a dry insulation that is not subjected to wetting even if the cable is completely submerged. A more modern design of water impervious cable uses a continuous linearly corrugated copper tape system that is wrapped around the cable core with the overlap glued shut (See Reference [1], Section 4).

Impervious coverings are optional and not required for submerged applications. They are most often chosen when particularly aggressive soil or water conditions exist.

Table 1 NEC and UL Definitions of Dry, Damp, and Wet Locations

Term	NEC Definition [2]	UL Definition [3]
Dry Location	A location not normally subject to dampness or wetness. A location classified as dry may be temporarily subject to dampness or wetness, as in the case of a building under construction.	A location not normally subject to dampness, but may include a location subject to temporary dampness, as in the case of a building under construction, provided ventilation is adequate to prevent an accumulation of moisture.
Damp Location	Locations protected from weather and not subject to saturation with water or other liquids but subject to moderate degrees of moisture. Examples of such locations include partially protected locations under canopies, marquees, roofed open porches, and like locations, and interior locations subject to moderated degrees of moisture, such as basements, some barns, and some cold storage buildings.	An exterior or interior location that is normally or periodically subject to condensation of moisture in, on, or adjacent to, electrical equipment, and includes partially protected locations.
Wet Location	Installations underground or in concrete slabs or masonry in direct contact with the earth; in locations subject to saturation with water or other liquids, such as vehicle washing areas; and in unprotected locations exposed to weather.	A location in which water or other liquid can drip, splash, or flow on or against electrical equipment.

Inaccessible Cable

Inaccessible cables are those cables that have sections located below grade or are imbedded in the plant base mat that are located in duct banks, buried conduits, cable trenches, cable troughs, or underground vaults, or that are direct buried. Cable tunnels that are accessible during plant operations are not considered inaccessible.

Sources:

NUREG-1801 GALL Report [4], Section XI.E3 Inaccessible Medium-Voltage Cables Not Subject to 10 CFR 50.49 Environmental Qualification Requirements:

... inaccessible (e.g., in conduit or direct buried) medium-voltage cables...

NRC Generic Letter 2007-01 [5]:

... in inaccessible locations such as buried conduits, cable trenches, cable troughs, above ground and underground duct banks, underground vaults, and direct-buried installations.

4 TYPICAL SPECIFICATION STATEMENTS FOR PROCUREMENT OF MEDIUM VOLTAGE CABLE

A number of cable purchase specifications from the period between 1968 and the mid 1980s were reviewed to determine the statements concerning the expected service and the manufacturing standards that were referenced.

Nearly all of the specifications stated that the cable could be in wet locations. One [5] was explicit regarding the type of water:

“The cable shall be suitable for installation indoors and outdoors in metal trays, conduits, underground duct banks, submergence in **brackish** water, and direct burial in earth in wet and dry locations.”

Most stated that the cable was for use in wet and dry locations. Examples of the statements are as follows:

“5,000 volt power cable for use in dry and wet locations in cable tray, exposed and concealed conduit, and underground duct systems for connecting between 4,160 volt metal-clad switchgear assemblies and nuclear power plant auxiliary drive motors and low voltage distribution transformers.” [7]

“The cable shall be suitable for installation in underground conduit, outdoor wet locations, and in exposed conduit or on expanded metal trays in indoor, basically dry locations.” [8]

“Underground and above ground applications in wet or dry locations on high resistance grounded systems with indefinite clearing time – 5 KV cable for 2400 and 4160 volt circuits and NESCRC condition(s) B.” [9]

“For Ungrounded 4160 volt circuits in underground ducts, conduits, terms (sic) or direct burial.” [10]

“The cable shall be suitable for installation indoors and outdoors in metal trays, conduit, underground duct banks in wet and dry locations.” [11]

All of the specifications stated that the cable could be used in underground applications. Nearly all stated that the cable could be used in wet locations. One directly stated that the cable would be submerged in brackish water. The one specification that did not state that the cable could be used in wet locations did state that it could be direct buried. All of these specifications indicate that the utility and its architect engineer and cable suppliers new that the cable could be used in wet locations and that suitable cable for such conditions was being specified and procured.

With regard to cable manufacturing standards that applied, some of the specifications [6, 7, 8 and 11] explicitly called for “IPCEA No. S-68-516: Cables Rated 0-35,000 Volts and Having Ozone - Resistant Ethylene-Propylene Rubber Insulation”. The rest [9, 10] stated that the latest IPCEA standards were to be followed. The next section of this paper

evaluates IPCEA No. S-68-516 with respect to the manufacture of cables suitable for wet and submarine applications.

It should also be noted that a number of the specifications indicated to the manufacturers that the cable could be direct buried as well.

5 REVIEW OF ICEA S-68-516 [12]

ICEA /NEMA Standards Publication S-68, *Ethylene-propylene-rubber-insulated Wire and Cable for the Transmission and Distribution of Electrical Energy*, is the standard under which the cables were designed and manufactured for the bulk of nuclear plants having ethylene-propylene-rubber (EPR) insulated cables. This standard covers the manufacture of and the differences between submarine cables and cables intended for in duct and direct burial applications. The intent of the following analysis of the standard is to show that cables for use in submergence (submarine, subsea, etc.) have the same manufacturing requirements for the core (i.e., conductor, insulation, and its semi-conducting screens) as the cable types selected for use in ducts and direct burial at nuclear plants and that no additional layers are included in submarine designs that would preclude water ingress to the core of the cable. The discussion shows that the cable was designed and manufactured for wet conditions, including submergence, and that the only difference between “submarine” and cables intended for “indoor and outdoor, above and below grade and direct buried” use is that the submarine cable has armor to protect it from boat anchors and other abuse that could occur on river and sea bottoms, and that the required armor is not impervious to water ingress to the core of the cable.

ICEA S-68-516 was the EPR cable manufacturing standard in place during the bulk of the construction of the current nuclear fleet and covers the cables that have been installed at nuclear plants inside and outside of the plant. The following shows that the cables have the same core design whether they are manufactured for indoors, outdoors, above or below grade, wet or dry, or submarine use and that there is no protection of the core from water for submarine use. The core comprises the conductor, conductor shield, and insulation system. The text follows the sections of the standard in order. Those items in the standard related to the differences between plant (i.e., indoor and outdoor, above and below grade and direct buried) and submarine applications are shown. The quotes from Part 1 show applicability of the standard to wet and dry applications.

Part 1. GENERAL

“Section 1.1 Scope. These standards apply to materials, constructions and testing of ethylene-propylene-rubber-insulated wires and cables which are used for the transmission and distribution of electrical energy for normal conditions of

installation and service, such as **indoor and outdoor installations, above and below grade and submarine.**²

Section 1.1.1 Characteristics of System on which Cable is to Be Used.

(g) Description of installation.

- (1) In buildings.
- (2) *In underground ducts.*
- (3) Aerial.
- (4) *Direct burial in ground.*
- (5) *Submarine.*

(h) Conditions of installation.

....

- (5) *Wet or dry location.”*

Review of Part 1, GENERAL, shows that the standard applies to the type of cable used in underground ducts, direct burial, and submerged applications, and in wet or dry locations.

Part 2. CONDUCTORS

This section covers the conductor and the conductor shield. There are no statements requiring differences in construction of the conductor and its shield related to whether or not the cable is used in wet conditions.

Part 3. INSULATION

“3.1 Material. The insulation shall be an ethylene-propylene rubber meeting the dimensional, electrical and physical requirements specified in Part 3.

This insulation is suitable for use on cables in *wet or dry locations* at not more than 35,000 volts between phases at 100 percent insulation level and at not more than 25,000 volts at the 133 percent level....

3.2 Insulation Thicknesses. The insulation thicknesses given in Table 3-1 are based on the rated circuit voltage, phase to phase, and on the cable insulation level....

3.2.1. The thickness of insulation for various systems shall be determined as follows:

² Emphasis added to highlight the point. Note: These are expected normal conditions for the cables manufactured under this standard.

3.2.1.1 For Three-phase Systems With 100 or 133 Percent Insulation Level. Use the thickness values given in the respective columns of Table 3-1.”

Table 3.1 defines the insulation thickness and associated manufacturing test voltages for 100 and 133 percent insulated cable. This table applies to cables for both wet and dry conditions.

“3.3 Insulation Thickness of Submarine Power Cable

The insulation thickness shall be as given in Table 3-1, except that for voltage classifications up through 5 kV:

- (a) When Type I insulation (see 3.6) is used, the thickness of insulation in cables without a metallic sheath shall be increased by 30 mils (0.76 mm);
- (b) When Type II insulation (see 3.7) is used, the thickness of insulation shall be as given in Table 3-1 except that for cables without a jacket or a sheath, it shall be not less than 60 mils (1.52 mm).”

Type I insulation per Section 3.6 must have a covering (jacket or sheath) and has lesser physical strength requirements but higher electrical requirements. Type II insulation per Section 3.7 has higher physical strength requirements and lesser electrical requirements. Section 3.6 (Type I) pertains to the cable used in nuclear plants for 5 kV and greater and also applies to submarine cable.

Section 3.6.2 Electrical Requirements describes the basic electrical requirements for the cables including the manufacturing tests to be performed, which are insulation resistance tests, voltage tests, and partial-discharge extinction level. These apply to both plant and submarine cable.

“3.6.3 Additional Requirements

3.6.3.2 Accelerated Water Absorption (See 6.21).

The insulation shall meet the following requirements:

Electrical Method

Dielectric constant after 24 hours maximum.....	4.0
Increase in capacitance, maximum percent	
1 to 14 days	3.5
7 to 14 days	1.5
Stability factor after 14 days, maximum	1.0
Alternate to stability factor (stability factor difference 1 to 14 days, maximum)	0.5

Gravimetric Method

Water Absorption, maximum milligrams per square inch	10.0”
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The accelerated water absorption test is for all cable types and not just for wetted or submerged applications.

Part 4 Shielding and Coverings.

Part 4, Sections 4.1 and 4.2, describe the shields that may be used over the insulation. For 5 kV rated cable, the shield was optional. The shields when used consisted (in 1976 through 1980) of thermoplastic or thermoset layer of polymer with a non-magnetic metal over or in the polymer. There are no differences in the requirements for the shield for submarine, wet, or dry application cables. The metal layer over the insulation that is described is not a sealed sheath. It employs a helical tape, wires, or straps.

Sections 4.3 and 4.4 cover non-metallic jackets. The second covers the plastic and rubber jackets that could be used. No separate requirements are given for submarine, wet, or dry applications.

4.5 Metallic and Associated Coverings.

This is the section where the most significant difference in design exists for submarine cable.

“4.5.1 Scope. This section covers the following:

Division I (See 4.5.3 through 4.5.16) Materials, constructions and requirements for metallic and associated coverings recommended for use under normal conditions of installation, operation and maintenance of power and lighting circuit wires and cables. It also covers submarine cables.

Section 4.5.2.2 Types of Metallic Coverings and Conditions of Installation.

(d) Galvanized steel wire armor.

(1) Submarine Cable.

Jute covering ... is required on submarine, borehole and shaft cable where severe installation and service conditions exist.”

Section 4.5.1 says that galvanized steel wire armor with a jute covering is required for submarine cable. Section 4.5.8 covers the details of the sizes and coating of the galvanized steel wires to be used and how they are to be applied to submarine and cables “for normal use.” Per Section 4.5.9, a jute layer is applied with tar or asphalt prior to application of the steel wires. An overall jute layer is applied in the same way over the last layer of armor. Sections 4.5.14 and 4.5.16 cover thermoset and thermoplastic jackets that may be applied over the armor. While asphalt or tar layers are used, they slow ingress of water but do not form an impervious layer.

It should be noted that currently manufactured cables no longer use jute layers, but rather polypropylene.

Section 4.5.4, Metallic Sheath, covers placing a continuous layer of lead or aluminum over the insulated cable to make it impervious to water. At most, this is an option and not a requirement of IPCEA S-68-516 for submarine cables.

The key specified differences in the IPCEA Standard between the submarine cable and the cable suitable for ducts, direct bury and indoors are the layers of jute and galvanized steel wires in the submarine cable that do not exist in the cables used in nuclear plants. While the jute lies in a bed of tar or asphalt, this layer and the galvanized steel wires do not impede slow ingress of water to the core of the insulation. Slow migration of water into the core of the cable is expected. The jute/tar layer provides padding between the steel wires and cable core and between the steel wires and exterior environment.

Part 5 of the standard addresses Assembly, Fillers, and Conductor Identification and presents no requirements that would distinguish submarine cable from the types used in nuclear plants.

Part 6 describes Testing and Test Methods that are used to show compliance to the standard. Section 6.21, Accelerated Water Absorption, describes two tests that are used to show acceptable insulation behavior under wet conditions. Following manufacture, samples of the insulated conductor (no jackets or non-conductive conductor shield) are either subjected to the Electrical Method (EM-60) or the Gravimetric Method. The EM-60 test uses a sample that is 15 feet in length. The middle 10 feet is immersed in 75°C water. The capacitance is measured with 80 V/mil (e.g., 90 mil insulation would have 7200 V applied) 60 Hz applied at 1, 7, and 14 day's immersion. The power factor is measured at 80 and 40 V/mil at 1 and 14 day's immersion. The stability factor is the difference between the percentage power factor at 80 and 40 V/mil at the specified time. The alternate to stability factor is the 14-day stability factor minus the 1-day stability factor.

In the Gravimetric Method, a short sample is cleaned and dried in a vacuum for 48 hours, and then weighed to the nearest milligram. The total area in square inches is determined, the sample is bent in a U and submerged in distilled water, at 70°C for 168 hours and then weighed after blotting lightly with a lint-less cloth. The sample is dried for 48 hours at 70 °C under a vacuum and then weighed again. The milligrams of absorption are then determined from the data.

The criteria for acceptance are shown in Section 3.6.3.2 as described above.

To assure that their insulations will be acceptable for these manufacturing tests, cable manufacturers perform extended EM-60 or gravimetric tests to prove their insulations' stability in water, often for a year in duration.

Many other manufacturing tests unrelated to water immersion are described in Part 6 of the standard. Completed product tests for non-shielded individual and triplexed cables include elevated voltage electrical testing in water to prove the insulation's integrity (Section 6.27). The water is used as the testing shield. This test is not used to project long-term water stability.

The tests described in Part 6 apply to submarine, wet, or dry application cables.

Part 7 describes the Constructions of Specific Types of Cables. No requirements in this part distinguish between indoor, direct buried, and submarine cables. The minimum nominal insulation thickness for unshielded cable insulation is given in Section 7.9.3 as 90 mils.

Part 8, Appendices, contains no information that distinguishes between indoor, direct buried, and submarine cable.

Conclusion from Review of S-68-516

This manufacturing standard for EPR insulated cable covers cables suitable for indoor, outdoor above and below grade, direct buried and in ducts, wet and dry, and for submarine applications. The only significant difference between cables suitable for wet use below grade versus for use in submarine applications is that the submarine cables have galvanized steel wire layers for physical protection of the cable. In the 1976 through 1980 version of the standard that was reviewed, the galvanized steel wire layers are padded with jute between the insulation system and the wires and between the wires and the outer jacket. This armor in no way stops the ingress of water.

The only other difference is in Section 3.3 that indicates that a 5-kV submarine cable should have 30 mils of additional insulation when lesser physical strength insulations are used (Type I).

Accordingly, there is no engineering difference between submarine cables and cable for wet use below grade with regard to long-term water ingress. The underground cables manufactured for nuclear plants per ICEA S-68-516 were designed to function in wet (i.e., submerged) applications and were selected appropriately.

6 EVALUATION OF MANUFACTURER CONSTRUCTIONS

Comparison of Kerite Submarine and Underground/Non-Submarine Cables

Table 2 compares the construction of a 15 kV rated copper tape shielded Kerite cable for installations above and below grade, indoors or outdoors and in wet or dry locations to a 15 kV rated Kerite cable for subsea applications. The insulation thicknesses in the two cable types are the same (at 100% thickness 165 mils for below 1000 kcmil and 210 mils above).

Table 2 shows that the Kerite subsea cable is different from underground/non-submarine cable only in that there is a layer of polypropylene and high density polyethylene covered galvanized steel wire, which would not preclude water from entering the core. Accordingly, by design and similarity to the subsea cable, the Kerite cable used in underground applications at nuclear plants are acceptable for submergence.

Table 2. Comparison of Kerite 15 kV Submarine Cable Construction to Underground/Non-Submarine Power Cable [13, 14]

Component	Underground/ Non-Submarine Cable	Subsea Cable	Comment
Conductor	Stranded copper or aluminum	Stranded Copper	Optionally, may be filled in either version.
Conductor Shield	Extruded black, non-conducting thermoset material	Extruded black, non-conducting thermoset material	Same thicknesses used in both types of cables
Insulation	Discharge resistant EPR	Discharge resistant EPR	Same discharge resistant characteristics and ICEA Standard requirement
Insulation Shielding	Extruded nonmetallic semiconducting material with 5 mil copper tape helically applied	Extruded nonmetallic semiconducting material with 5 mil copper tape helically applied	Insulation and tape to the same ICEA standards requirement
Jacket on individuals	PVC	PVC	Jacket type the same regardless of application
Cabling	As specified by purchaser	3 individual with filler for rounding out the core. Helically wrapped overall binder tape	
Biological Protection (optional)	Not required	10 mil bronze tape	For torpedo worms
Armoring	Only if required by purchaser (If so, interlocked steel is generally used)	Double reverse layer of polypropylene and a layer of galvanized steel armor wire individually jacketed with high density polyethylene	Required for physical strength for laying operation and protection from anchors and other subsea protrusions

Comparison of Okonite Submarine and Underground/Non-Submarine Cable

Table 3 compares the construction of a 15 kV rated copper tape shielded Okonite cable for installations above and below grade, indoors or outdoors, and in wet or dry locations to a 15 kV rated Okonite cable for submarine applications. The insulation thickness in the submarine cable is based on 133% insulation level and is the same thickness as the normal cable (220 mils).

Table 3. Comparison of Okonite Submarine Cables to Underground/ Non-Submarine Cables [15, 16]

Component	Underground/ Non-Submarine Cable	Submarine Cable	Comment
Conductor	Stranded copper	Stranded Copper	
Conductor Shield	Extruded semiconducting EPR	Extruded semiconducting EPR	Triple extruded with insulation and insulation shield
Insulation	Okoguard thermoset EPR	Okoguard thermoset EPR	
Insulation Screen	Extruded semiconducting EPR	Extruded semiconducting EPR	
Shield	5 mil helical copper tape	5 mil helical copper tape	
Jacket on Individual Conductor	None	Black Okolene polyethylene	Jacket on individual unnecessary on non-subsea cable. Overall jacket performs function.
Fillers	Non-specified filler	Polypropylene	
Binder tape	Non-specified binder tape	Non-specified binder tape	
Jacket	Okoseal (PVC)	None	Overall jacket not needed in subsea cable.
Bedding for Armor		Polypropylene yarn	Part of subsea armoring system
Armor		Galvanized Steel Wire	Part of subsea armoring system
Covering		Nylon Serving Slushed with Tar	Part of subsea armoring system

The cores of the normal and submarine cable are the same. The pertinent difference between the two cables in terms of moisture protection is that in the submarine cables, the individual conductors have a polyethylene jacket. Rather than having individual insulated conductor jackets like in the normal cable, there is an overall PVC jacket. (Note: In most nuclear applications, chlorinated polyethylene, Hypalon or neoprene jackets have been used rather than PVC.)

Accordingly, by design and similarity to the subsea cable, the Okonite cable used in underground applications at nuclear plants are acceptable for submergence.

7 DISCUSSIONS PROVIDED BY CABLE MANUFACTURERS

Kerite Long-Term Water Submergence Position [17]

Cables are frequently installed underground (direct buried, in duct backs, conduits, trenches, etc.). These cables have a long service history that we can draw on. ICEA T-22-294 [18] provides an accelerated test to evaluate performance in a long term water environment. This test along with ICEA S-97-682 [19] and AEIC CS8 [20] accelerated water treeing tests (AWTT) (See Figure 1) plus internal supplier tests provide the basis for reviewing long term water performance. The primary objective of the AWTT test is to provide a standardized manufacturer's design qualification³ test method that will give reasonable assurance that an extruded, medium voltage cable design made by a given manufacturer will meet minimum performance requirements for operation in a wet environment. The AWTT is a one year test in tap water in PVC tubes with three times rated voltage to ground, 45°C on the insulation shield and 60°C on conductor for 8 out of 24 hours, with ac breakdown as the performance indicator with samples taken at 120, 180 and 360 days as shown below. The load cycling is intended to simulate expansion and contraction within the cable under cyclic loading that occurs in many applications. The overvoltage is applied to provide some acceleration during the test and thereby prove a lack of susceptibility to energized wet aging of cables. An ac withstand of 300 V/mil minimum is required for the samples aged for 120 days. The high voltage time test is done at 180 days and 360 days for engineering information. For EPR, 500 V/mil is the acceptance criterion after cyclic aging. Tree count is also performed for engineering information.

It should be noted that testing is generally done with pure (tap or distilled) water. The purity of the water in actual use can be variable, but except for spills or other issues that have caused high concentrations of chemicals, good performance in the standardized test have translated into good performance in actual applications. There are cables that are designed to be submersed for life. These may be in fresh water, as in a river crossing (not always pure water though) or in salt water such as submarine cable. There are generally two design philosophies, a wet design or a dry design. A dry design uses barriers to limit the water exposure to the insulation. A wet design may be the same as used for a standard utility cable; it is just that served wire armor is frequently used as a strength member to support the cable during the installation process and provide mechanical protection. Current power cable designs are generally wet designs.

³ This qualification test is a manufacturer's design qualification test rather than a nuclear power plant environmental qualification test.

Figure 2. Accelerated Water Tree Testing Setup



There are many design considerations that can influence cable life in an underground environment. Some designs can limit water contact with the insulation. Even with this, sometimes these design barriers can be breached, or water can be introduced at a splice or termination point. Many times, decreasing peak and average stress can be beneficial. This can be done by increasing the conductor size and increasing the insulation thickness (generally 133% level and/or using the next higher voltage class – (For example, using 15-kV cable for 5-kV applications)).

The choice of conductor stress control layer can also limit the amount of stress, as with a high permittivity layer. A high permittivity conductor stress control layer can also limit ions into the insulation, which may be areas that water trees can form. Limiting stress at the conductor stress control layer and insulation boundary can also minimize treeing. A high permittivity layer may also dampen a transient, and limit additional degradation that can be caused by switching and lightning surges.

The insulation choice can also influence the long term water performance. Tree retardant additives may smooth out localized stress points and have been found to improve performance in water. Some formulas, especially amorphous EPR formulas, have shown resistance to water tree formation and very good long term water history.

Case Study

A Kerite cable was directly buried in Syracuse, NY in 1977. This cable would undoubtedly have been periodically wet. It had been in continuous operation for 28 years and was tested in July of 2005. The cable was a 2 AWG stranded aluminum conductor, Permashield, non-conducting, strand shield, 175 mils Kerite EPR insulation rated 15kV, (100% level) semiconducting insulation shield, with a concentric shield of ten 14 AWG

copper concentric wires and no jacket. Physical testing, AC breakdown, impulse testing, and discharge resistance (U-Bend) testing was performed.

The cable passed the U-Bend discharge plate test for 1,000 hours when energized at 44 kV (250 V/mil). There was no deterioration of performance characteristics. All parameters measured were still within the range expected for a new cable. Since there is no age related degradation an extrapolation to end-of-life cannot be made. Therefore, the cable should last for another 28 years, or even longer. Tables 4 and 5 provide the test results for the 28 year old cable.

Table 4. Physical Test Results for 28 Year Old Kerite Cable Used Underground

	28 Year Old Cable	Acceptance Criteria for New Cable	
	As Tested	Minimum	Range
Tensile (PSI)	1019	650	700-900
Elongation (%)	478	350	400-525
Voids	None	4 mil Max	
Contaminants	None	10 mil Max.	
Trees	None	N/A	

Table 5. AC Breakdown (1-3) and Impulse (4-7) Tests

	28 Year Old Cable	Acceptance Criteria for New Cable
Sample 1	63kV	54kV
Sample 2	60kV	
Sample 3	74kV	
Sample 4	194kV@RT	160kV
Sample 5	195kV@RT	
Sample 6	197kV@RT	
Sample 7	220kV@130C	

Millions of feet of Kerite insulated cables have been installed in all types of environments with no known failures due to insulation degradation or weakness. Kerite insulation features leading to long life include corona immunity; long-term, over-voltage endurance; long-term moisture resistance; and impulse withstand. Based on field experience, Kerite

cable has operated for over 45 years with no indication of the beginning of age related failure. Kerite’s cable warranty is for the life of the installation.

General Cable Information [21]

General Cable provided access to a report of their accelerated water treeing test of the pink EPR insulation and conductor shield system used in their UniShield™ and standard design cables [22]. UniShield is a compact design cable that incorporates concentric neutral wires in the insulation shield. The insulation shield also acts as the jacket for the cable resulting in a cable of smaller diameter that fits into smaller ducts. This design originated with Anaconda, and now is owned and manufactured by General Cable.

The testing program was a standard protocol in accordance with Insulated Cable Engineers Association (ICEA) and The Association of Edison Illuminating Companies (AEIC) standards. The test program was conducted on 15 kV cable samples having a 1/0 AWG aluminum conductor, a semi-conducting conductor shield, a pink EPR insulation layer, a semi-conducting insulation shield and six concentric neutral wires. There was no additional layer over the wires.

With respect to water degradation susceptibility, approximately 145 ft of the above cable was subjected to accelerated water tree testing (AWTT) after the cable had been subjected to cyclic thermal aging. The cable was immersed in ducts full of water and the conductor was filled with water and maintained that way throughout the year-long test. An accelerating voltage of 26 kV ac, 3 times rated phase to ground voltage, was applied between the conductor and the shield drain wires. Current was induced in the conductor such that the conductor attained a temperature of 45°C ± 3°C (113°F ± 5°F) on the cable in water for 8 hours every day and then current was off for 16 hours. Three specimens were aged for 120 days; three for 180 days; and three for 360 days and then each specimen subjected to a high voltage time test (HVTT). Table 6 summarizes the results. The approximate thickness of the insulation for the specimens was 178 mils (4.5 mm) (100% insulation level for a 15 kV rated cable). In service, the expected phase to ground voltage would be approximately 8 kV and the average stress would be 45 V/mil (1.77 kV/mm).

Table 6. General Cable Pink EPR Insulation Accelerated Water Aging Test Results (Arithmetic Averages)

Condition	Withstand Test (Average of three breakdowns) [Multiples of Rated Voltage]	Actual Breakdown for Wall Thickness at Breakdown Site (Average of three breakdowns)
Unaged	833 V/mil (32.8 kV/mm) [18.5]	862 V/mil (33.9 kV/mm)
120 days wet aging	607 V/mil (23.9 kV/mm) [13.5]	643 V/mil (25.3 kV/mm)
180 days wet aging	567 V/mil (22.3 kV/mm) [12.6]	592 V/mil (23.3 kV/mm)
360 days wet aging	445 V/mil (17.6 kV/mm) [10]	496 V/mil (19.5 kV/mm)

General Cable also provided data from accelerated cable life testing performed on 15 kV rated cable with the same insulation system. All of the cables were immersed in water and all were energized at 4 times rated voltage (34.6 kV). Three different protocols were used as shown in Table 7.

Table 7. Accelerated Cable Life Test Conditions (Note: 10 to 12 cables per set)

Test Set	Wetted Length	Preconditioning	Aging Condition
47	15.4 ft (4.7 m)	72 hrs @ 90°C	50°C tank temperature, 75°C conductor temperature 8 hrs / day
44	26.2 ft (8 m)	72 hrs @ 90°C	90°C conductor temperature (in air) 8 hrs / day
41	26.2 ft (8 m)	72 hrs @ 90°C	45°C conductor temperature (in air) 8 hrs/day

The accelerated cable life test is designed to induce end of life failures. The testing continued for 4 to 4.3 years without failures and was then terminated. The testing durations and breakdown strengths are shown in Table 8. The purpose of the preconditioning period is to drive off volatiles left from manufacturing that could result in longer test life if they were not driven off before the test was begun.

Table 8. General Cable EPR Insulation Accelerated Cable Life Test Results

Test Set	Days without Failure (Years)	Retained Breakdown Strength (Wiebul analysis of several HVTT breakdowns)
47	1579 (4.3)	461 V/mil (18.1 kV/mm)
44	1487 (4.1)	434 V/mil (17 kV/mm)
41	1599 (4.4)	523 V/mil (20.6 kV/mm)

The results from these tests indicate that the General Cable EPR insulated cable is suitable for wet conditions. While these results are for more recently manufactured cable and represent current design testing practices, they indicate that the cable industry has been aware of wetting of cable as a consideration and that accelerated wet testing has been incorporated into the design process for medium voltage cables.

It should be noted that the testing of a 15 kV, 1/0 AWG specimen is more severe than the normal operating voltage stress of 5- or 8 kV rated cables and for large size conductors. In addition even at normal operating voltage, the voltage stress concentration is higher in 15-kV cables. Likewise, the voltage stress at the conductor surface is higher for smaller diameter conductors than for larger sizes.

While these tests that are summarized here were performed recently, similar tests were performed on earlier versions of the cable.

8 WATER RESISTANCE OF BLACK EPRS

Relatively little independent research has been performed on early black EPRs. However, some IEEE papers on the capabilities of materials were published during the period when EPR insulations were first being applied as cable insulation. Reference [23] describes development research and properties for the black EPR used for insulation by Okonite. This is a very detailed paper describing numerous properties that were evaluated between butyl rubber, a filled crosslinked polyethylene, and the black EPR that was being used as the insulation of EPR cables produced by Okonite in 1968. This material and the associated data would apply to the black EPR cable insulations manufactured through the early 1970s.

The paper compares the capabilities of a filled crosslinked polyethylene, and a butyl rubber to the black EPR. The filled crosslinked polyethylene is not representative of the XLPE insulations used in nuclear plants in that nearly all of the XLPE designs used in nuclear plants were unfilled.

Reference [23] has a specific section labeled “Stability in Water,” which describes testing to determine if the insulation was stable in water. The tests were performed on No. 14 AWG solid conductors with 47 mils of insulation. Sets of specimens were immersed in water while energized at 600 volts, 60 Hz between the conductor and the water of the bath. Specimens were subjected to three different temperatures (23, 75, and 90 °C). Each month $\tan \delta$ measurements were performed to evaluate condition. Table 9 provides the results. In comparison with the previously used butyl rubber and filled crosslinked polyethylene, the black EPR had far superior water immersion characteristics. It should be noted that as the temperature of a polymer increases, the $\tan \delta$ value would be expected to increase due to the normal increase in leakage current with increase in temperature. The $\tan \delta$ measurements remained stable for the black EPR through three years of immersion.

These data indicate that the manufacturer considered water immersion and stability under wet conditions as an important factor in their choice and evaluation of insulation materials.

Table 9. 100 x Tan δ Measured at 40 V/mil ac

Time (Months)	Filled XLPE			Butyl			Black EPR		
	23	75	90	23	75	90	23	75	90
Temperature (°C)									
0	0.27	0.52	0.60	0.96	2.21	4.98	0.55	1.50	2.70
6	0.27	0.40	1.62	0.80	2.98	12.68	0.70	1.60	2.40
12	0.20	1.70	3.00	0.80	3.27	>30	0.70	1.70	2.50
18	0.30	2.00	3.70				0.80	1.30	2.00
24							0.90	1.50	2.00
30							0.77	1.14	1.84
36							0.65	1.74	2.01

9 EPRI LONG TERM AGING TESTS OF EPR CABLES

EPRI 1003085 [24] reports the results of testing of five EPR insulations and TR-XLPE (tree retardant crosslinked polyethylene) insulation under accelerated field and laboratory conditions that were originally reported in EPRI 1009017 [25]. There were two sets of field cables. One set was aged at normal voltages and the second set was aged at $2.5V_o$ ⁴. The laboratory aging was performed submerged at $2.5V_o$ and with water in the conductor to attempt to accelerate aging. The bath was kept at temperatures similar to that of the monitored temperature of the field specimens.

The five EPR cables and one TR-XLPE 15 kV rated cable had similar designs. A different manufacturer made each cable during the 1994 -1995 time frame. The nominal construction was 107 mm² (4/0 AWG), 19-strand compressed copper conductor, 0.38 mm extruded semiconducting conductor shield, 4.45 mm (175 mils) EP or TR-XLPE insulation (100% insulation level), 0.75 mm extruded semiconducting shield, and 20 - 5.25 mm² (10 AWG) tin-coated copper concentric neutrals. These cables did not have overall jackets, as would be commonly used in nuclear applications. In addition, these 15 kV cables have higher operating voltage stresses than would occur in 5 kV or 8 kV rated cables. These cables have 4.45 mm of insulation and operate at 8 kV phase to ground. Cables in 4160 V applications have 2.29 mm (90 mils) (100% insulation level) and operate at 2.4 kV phase to ground. The 15 kV rated cables operate at 1800 V/mm (45.7 V/mil) and 5 kV cables operate at 1048 V/mm (26.7V/mil). Accordingly, the results described here with respect to insulation capability are very conservative when applied to 5 kV-rated cables.

The EPR insulations included those currently in common use as replacement cables in nuclear power plants.⁵ The commonly used nuclear insulations are represented by Cables E and F in the discussions. The cables were purchased through a utility. The manufacturers were unaware that the cable was to be used in a research program. Approximately 3,000 meters (10,000 feet) of each cable type were acquired for the program.

Each of the laboratory specimens consisted of a 27.5 m coil placed horizontally in a water-filled tank. Each tank had 10 coils. Water was also placed in the conductor interstices. As previously stated, the temperature of the water bath was controlled to reflect temperatures similar to those monitored at the field site operating at $2.5V_o$. The applied voltage was 20 kV, which is approximately 2.5 times that of phase-to-ground voltage (8 kV) on a 13.8 kV circuit. Twice a month $1.5 \times 50 \mu s$, 80 kV impulse surges were applied to simulate lightning and exaggerated switching surges that could occur under actual conditions. For the field-installed specimens, temperature of the earth, cable, and conduit were measured. Phase voltages and currents were continuously

⁴ V_o is the system operating phase to ground voltage.

⁵ Okonite and Kerite specimens were included in the 6 cable types tested.

monitored. Events such as sags, swells, and impulses were monitored along with the time of the event. Two major events were recorded: a lightning arrester failure and a snow plow striking the associated transformer pole. (Note: Most nuclear plant cables are not subject to either of these events given that they are terminated within well-shielded buildings and do not have aerial runs.)

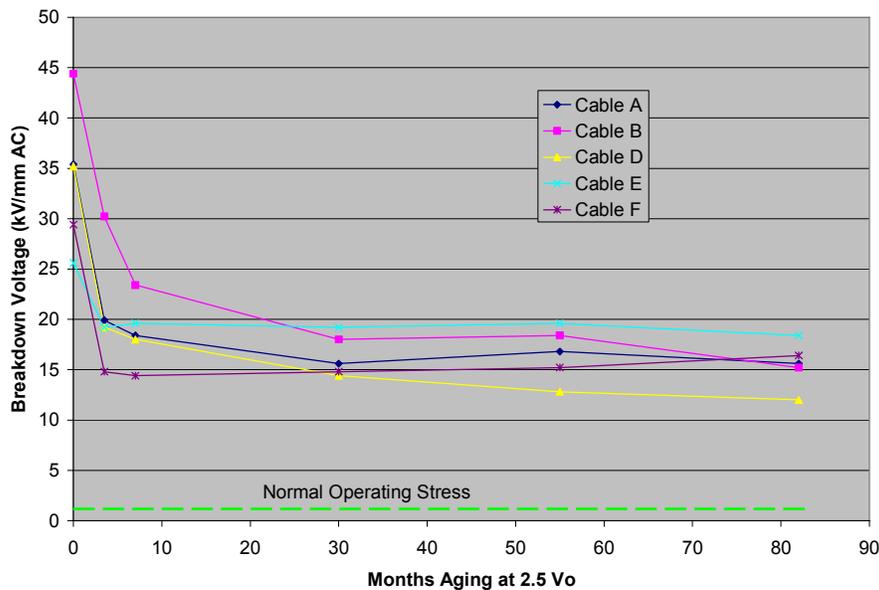
Longevity under Test Conditions

The entire group of field-aged cable (both one times V_o ($1 V_o$) and 2.5 times V_o ($2.5 V_o$)) functioned through the entire 82-month (6.8 year) period without failure. One EPR-insulated cable type that is not used in nuclear applications failed six times in the laboratory exposure. The failures appeared to be from localized imperfections. The remaining laboratory specimens sustained no failures.

Breakdown Voltages

Figure 3 shows the change in breakdown voltage for the laboratory-aged cables. After the initial drop, the breakdown voltages stabilized and remained essentially constant during the exposure for cables A, E, and F, while cables B and D showed a slight continued decreasing trend. The figure is presented in terms of kV/mm ac. The normal stress level is between 1/10th and 1/13th of the breakdown voltages that the specimens exhibited for the bulk of the exposure. Cable E retained the highest breakdown strength for EPR cables. Cable C is the TR-XLPE cable and its data are not shown in the figure. Cables E and F have the same insulations as two of the most common EPR insulations used in the nuclear industry.

Figure 3. EPR Cable Steady Voltage Breakdown Testing (Wet) at $2.5V_o$ (20 kV)



Note: In addition to $2.5V_o$, 80 kV ($1.2 \times 50 \mu s$) impulses were applied twice a month to simulate lightning and exaggerated switching surges.

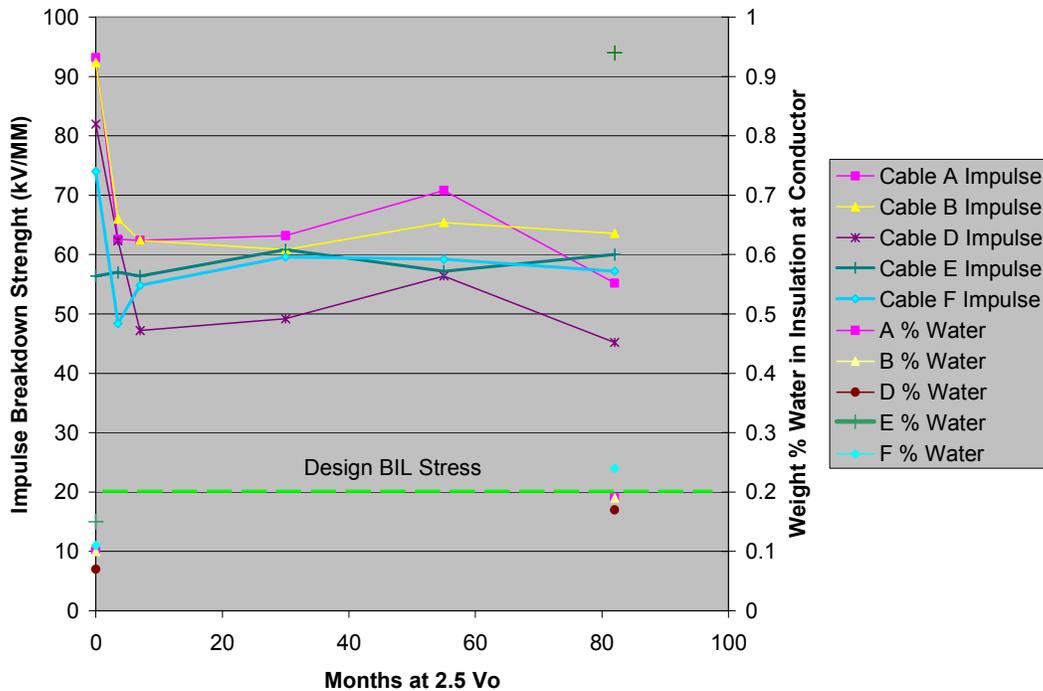
For the field test specimens, all of the cables except B and E exhibited less than 5 pC partial discharge at voltages up to 35 kV AC. Cable B exhibited 100 pC at the 75-month aging point, which was found to be associated with pitting on the insulation shield on a nine-meter section of the cable. At 20 kV, cable E exhibited 5 pC when tested between 26 to 84 months. At 35 kV, cable E exhibited between 15 and 25 pC when tested between 26 and 84 months. It should be noted that these partial discharge results do not appear to indicate a significant problem for this particular EPR insulation, in that its breakdown strength was the highest of all of the insulations as shown in Figure 2 and it has a discharge resistant characteristic.

For the laboratory-aged specimens, all cables except cable E had partial discharges that were less than 5 pC throughout the entire 82-month (6.8 year) program, with a test voltage of 35 kV AC. Cable E, the discharge resistant cable, had 5 pC during the entire period.

Impulse Breakdown Voltage

Figure 4 presents the impulse breakdown voltages for the laboratory specimens during the course of the exposure. As with the breakdown voltages, the impulse breakdown voltages initially dropped and then stabilized for the duration of the test. The figure also shows the weight percent of water in the insulation at the start and end of the test program.

Figure 4. EPR Cable Impulse Voltage Breakdown Testing (Wet) at 2.5V₀ (20 kV) (63% Probability from Weibull Distributions)



Tan Delta Measurements

Figures 5 and 6 represent the $\tan \delta$ (dissipation factor) results for cables A and E respectively, two of the EPR insulations. Results for Cables B, D and F were similar to those of Cable A. The cable E polymer design has purposefully “lossy” features to prevent charge buildup within the polymer. The significantly higher $\tan \delta$ results are representative of this design difference. For all of the cables, there is no discernable aging trend indicated by the results. The $\tan \delta$ results for these cables showed no significant change in leakage current and capacitance during the test program.

Figure 5 EPR Cable ‘A’ Dissipation Factor Laboratory Testing (Wet) at 2.5 V_o and 60 Hz

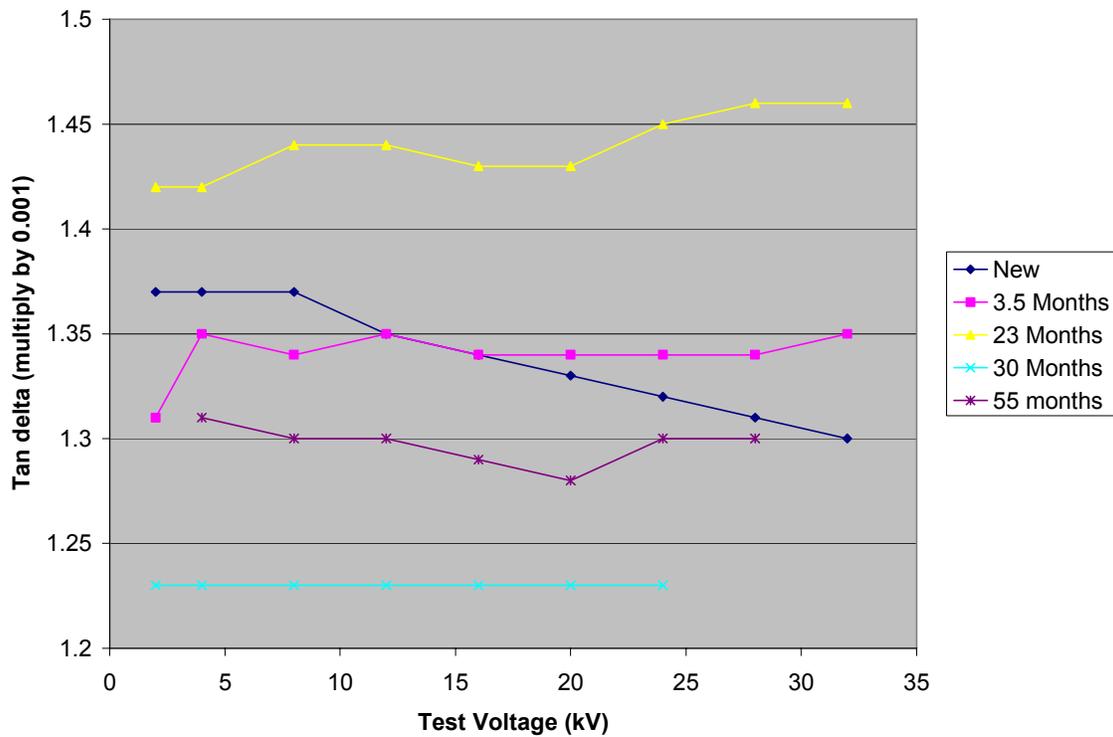
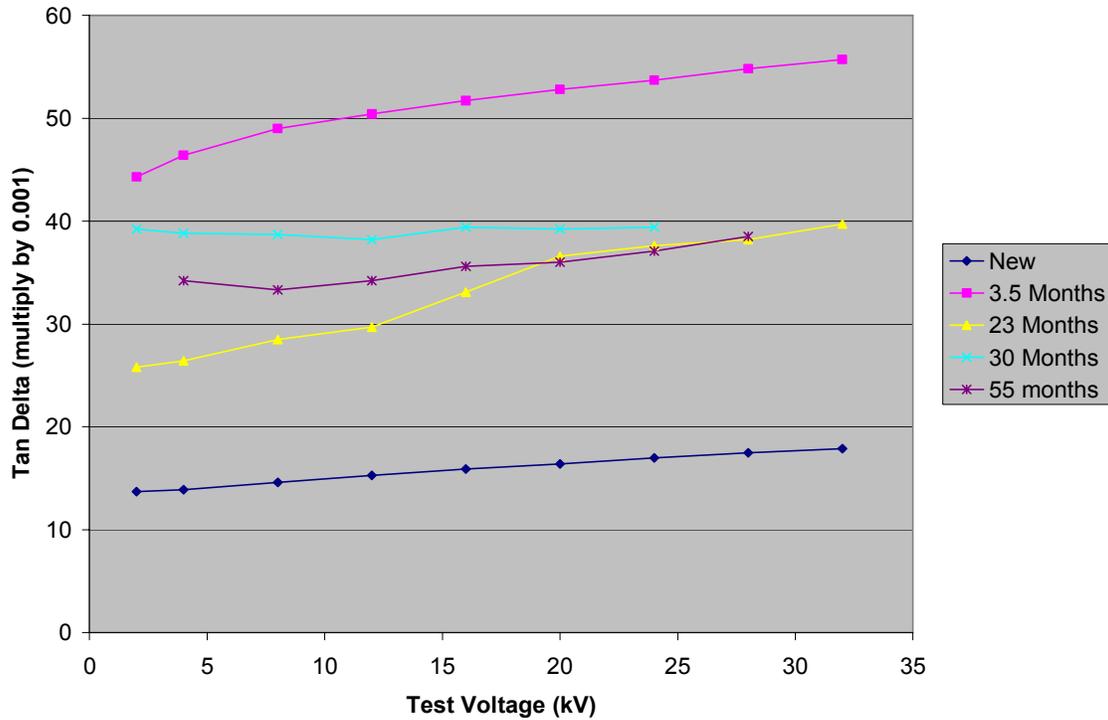


Figure 6. EPR Cable ‘E’ Dissipation Factor Laboratory Testing (Wet) at 2.5 V_o and 60 Hz



EPR Test Conclusions

These tests indicated that under accelerated conditions, the EPR insulation used in some original cables (Kerite) and most replacement cables (Okonite) functioned well and maintained adequate electrical properties. Even continuous wet age testing at 2.5 times voltage did not result in early failure. The ac breakdown and impulse breakdown remained well in excess of the levels required for service. The tests indicate that long life can be expected from these insulations even in the presence of moisture. With the exception of Cable E, the cables did not have partial discharge levels of significance. Nonetheless, the partial discharging of Cable E, a discharge resistant insulation, in the field-aged cables did not correlate to a significant change in impulse or ac breakdown strength.

The test program provides a strong indication that modern EPR insulation configurations in use in nuclear plants will have long satisfactory service lives even when subject to wet conditions. It should be noted that the test specimens did not have jackets. Nuclear plant cables have jackets that would further aid in slowing and reducing water migration into the cable insulations.

10 OVERALL CONCLUSIONS

As indicated in the introduction, the purpose of this paper was to explore whether the EPR insulated medium voltage cables that were installed in nuclear power plants were appropriate for use in wet (i.e., submerged) applications or not. This paper does not provide a specific life nor does it draw conclusions on current condition of wet medium voltage cable.

Based on the information and analysis provided above, the following conclusions may be reached:

1. The design requirements as delineated in NRC code are adequately addressed by the nuclear industry for cable applications in wetted/submerged environments.
2. That original cable purchase specifications did consider and require cable suppliers to provide cables suitable for submerged conditions. The industry definition of “wet” includes submerged conditions.
3. Industry manufacturing standards cited in utility purchase specifications during plant construction stated the proper design requirements for the cables, and the cables that were purchased do not differ significantly from subsea/submarine cable designs with the exception that armor was not required.
4. That testing performed by both the manufacturers and EPRI indicate that the type of cable designs in use in the nuclear power industry are adequate for long term wetted or submerged environments.

The following provides a discussion of how these conclusions are reached.

10CFR50 Appendix A, General Design Criteria, *Criterion 4 – Environmental and dynamic effects design bases*, states “Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents...” The remainder of Criterion 4 discusses the effects of accidents that must be considered. The criterion states that components important to safety must be designed to be compatible with the environments of service. It does not specify that a “qualification” test must be performed. General Design Criteria 17 describes redundancy requirements for electrical systems and General Design Criteria 18 states that systems shall be designed to allow functional and surveillance testing. Neither of these requires “qualification” testing to support design.

10CFR50 Appendix B, *Criterion III – Design Control*, states, *in part*: “The design control measures shall provide for verifying or checking the adequacy of design, such as by the performance of design reviews, by the use of alternate or simplified calculational methods, or by the performance of a suitable testing program.” While this criterion indicates that “performance of a suitable testing program” is a means of verifying design, it does not require that such testing be performed.

The conditions of service for underground cable are consistent with the definition for a “mild environment” as defined in 10CFR50.49, *Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants*. The definition is: “A mild environment is an environment that would at no time be significantly more severe than the environment that would occur during normal plant operation, including anticipated operational occurrences.” There is no worsening of the underground (or inaccessible) environment caused by an accident condition. Accordingly, the selection of cable for underground conditions does not require a 10CFR50.49 qualification. It should be noted that much of the cable in question does have a 10CFR50.49 qualification to allow its use in high energy line break and radiation areas within nuclear plants.

The main requirement for the design of these cables for wet/submerged environmental conditions is that a cable appropriate for the condition be selected. Review of typical procurement specifications from the period 1968 through 1982 indicated that the manufacturers of the cables were made aware that the medium voltage cables would be used in underground applications that were potentially wet. In some cases, they were specifically told that the cables could be submerged. The specifications also called for use of manufacturing standards, such as ICEA S-68-516⁶ [12], for EPR insulated cable that covers cables suitable for indoor, outdoor above and below grade, direct buried and in ducts, wet and dry, and for submarine applications. Review of the ICEA S-68-516 indicates that there is no significant difference between the cores of cables intended for plant usage and those intended for submarine (submerged) conditions. The key difference is that cables intended for submarine conditions had steel wires bedded in jute and tar for physical protection against river and sea bottom conditions. This outermost protective layer does not prevent the ingress of moisture. No sealed metal or other water proof layer is necessary or specified. Review of current manufacturers’ specifications indicates that medium voltage cables for submarine (subsea) applications have the same core as those sold for use in power plants.

Manufacturers did not arbitrarily decide their cable materials were suitable for wet conditions. A series of design tests were performed to determine if the materials were stable when immersed in water while energized. While testing for modern cable has been described here, similar tests were performed on earlier designs to assure both the manufacturers and their clients that wetting would not result in early failure. For example, Kerite and General Cable performed accelerated water treeing tests in which cables are subjected to three times operating voltage while submerged in water for periods up to one year to verify that cables are satisfactory for wet conditions. The tests include daily cyclic load variations to account for expansion and contraction from thermal loading. In General Cable’s test program, the accelerated cable life testing continued for 4.3 years without failure. Kerite cites the results for a direct buried cable that was in service for 28 years and still met original acceptance criteria.

EPRI Report 1003085 [24] describes an effort to age EPR cables to allow development of an aging model. The cables were subjected to 2.5 times normal operating voltage.

⁶ EPR cables have been covered in detail in this paper because they have the dominant insulation used in the nuclear power industry. Cross-linked polyethylene insulated cables are less dominant. The associated manufacturing standard for cross-linked polyethylene insulated cables is Reference [26]. Note that IPCEA is the earlier acronym for ICEA.

Okonite and Kerite insulations were included in the test program. Cables were aged in both field and laboratory conditions. The test was discontinued after 6.8 years because the cables were not aging. No failures occurred in the Okonite and Kerite cable specimens.

Based on the foregoing, plant designers were aware that medium voltage cable in underground (and inaccessible) areas could become wet and submerged. Their specifications to cable manufacturers indicated where the cable could be used and that those areas include wet and underground conditions. Cable manufacturers also understood that the cables could be subjected to wet conditions, including submergence. Cable manufacturers performed design tests to assure themselves and their customers that the cables would perform satisfactorily if subjected to wet conditions. These were not qualifications required by nuclear power plant requirements but rather by general conditions throughout the electrical distribution industry. These tests and further tests performed by the EPRI indicate that the medium voltage cable insulations used by the overall utility industry, industry in general, and the nuclear industry, as well, were suitable for wet service.

Accordingly, the medium voltage cables used in nuclear power plants were appropriately selected and designed for wet applications, including submergence. As stated at the beginning of this paper, the current condition of cables subjected to wetting for long-durations is a separate question. Current condition of the insulation system is not addressed by this paper.

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