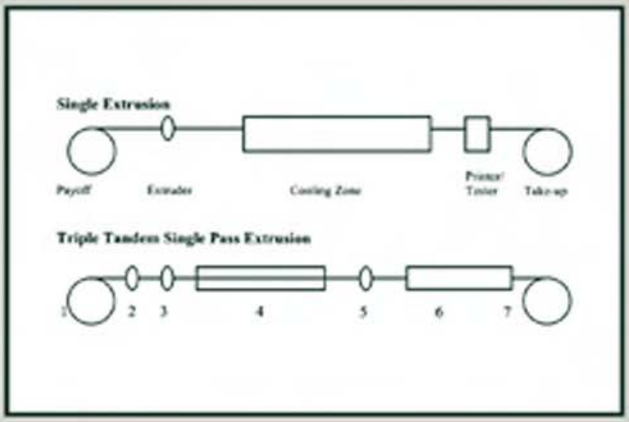
Electrical Power Cable Engineering

Second Edition, Revised and Expanded



edited by
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Electrical Power Cable Engineering

POWER ENGINEERING

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SERIES INTRODUCTION

Power engineering is the oldest and most traditional of the various areas within electrical engineering, yet no other facet of modern technology is undergoing a more dramatic revolution in both technology and industry structure. Among the most important electrical technologies for the 21st century is power cable engineering. Insulated cable has become a staple of modern power engineering and operations, where underground power transmission keeps facilities out of sight and largely protected from external damage. Increasingly, the use of insulated cable rather than air-insulated overhead conductor is the only acceptable way for electric utilities to move power in both heavily congested urban cores and environmentally or esthetically important areas. And increasingly, the maintenance, care, and condition assessment of older cable, cable that has been in service for twenty or thirty years, is a particular concern to modern utilities. That, among other topics, is part of the expanded focus of *Electric Power Cable Engineering, Second Edition*.

This second edition is a thorough, well-organized treatment of modern power cable engineering, applications, and practices, as was the first. But this second edition has grown in company with both the electric industry itself and the field of cable engineering, and consequently it provides new focus on condition assessment, lifetime extenuation, and cable characteristics and applications. As before, the book focuses on practical, rigorous engineering and operation of low-and medium-voltage cables, that constitute the vast majority of industry need. As before, the book is organized and well cross-referenced so that it makes an excellent reference for practicing engineers, yet has a very modular and serial development of its content in order to be an excellent text for engineering courses or for self-paced tutorial study.

As the editor of the Power Engineering Series, I have always been proud that William Thue’s book was included in the series, and it is particularly satisfying to see the important books in the series keep pace with the industry and technology through a constant process of revision and expansion. Like the other volumes, *Power Cable Engineering, Second Edition,* continues to put modern technology in a context of proven, practical application as a reference, for self-study, and for advanced classroom use. The Power Engineering Series includes books covering the entire field of power engineering, in all its specialties and subgenres, all aimed at providing practicing power engineers with the knowledge and techniques they need to meet the electric industry’s challenges in the 21st century.

H.Lee Willis

FOREWORD

Electrical cable might be considered to be just a conductor, overlying insulation, and often an exterior shield or jacket. Perhaps this naive, simplistic concept is part of the reason that cable engineering, especially for power cable, has been largely neglected by recent electrical engineering education in the United States with its emphasis on computers, electronics, and communication. But power cable does electrically connect the world! The history, so interestingly presented, shows how the subject evolved with both great success and sometimes unexpected failure.

As this book emphasizes, cable engineering is technically very complex. Certainly electrical, mechanical, and even to some extent civil engineering are involved in interrelated ways. Many other disciplines—physics, inorganic chemistry, organic (primarily polymer) chemistry, physical chemistry, metallurgy, corrosion with tests and standards in all of these areas—are of concern. Of course, it is impossible in one book to deal with all of these aspects in a completely comprehensive way. However, the various components of power cables are considered with sufficient detail to provide an understanding of the basic considerations in each area. Reference to detailed sources provides a means for those with greater interest to pursue specific subjects.

The importance of factors involved in different types of cable installation is stressed. Long vertical cable runs have special problems. Installation in ducts may lead to problems with joints, terminations, elbows, and pulling stresses. At first, cable with extruded insulation was buried directly in trenches without recognizing the then unknown problem of “water treeing” in polyethylene, which was originally thought to be unaffected by moisture. After massive field failures, well over a thousand papers have been written on water treeing! Field failures can involve many factors, e.g., lightning, switching surges, repeated mechanical stressing, and swelling of voltage grading shields in contact with organic solvents such as oil and gasoline. It is important to recognize how such diverse factors can affect the performance of cable in the field.

Electrical Power Cable Engineering, Second Edition meets a need to consider its complex subject in a readable fashion, especially for those with limited background and experience. Yet, sufficient detail is provided for those with greater needs in evaluating different cables for specific applications. Most of all, the supplier of materials for cables can obtain a better understanding of overall problems. On the other side, the experienced cable engineer will learn the parameters of materials with which he or she was not fully familiar.

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PREFACE

A course entitled Power Cable Engineering Clinic was presented at the University of Wisconsin—Madison from the early 1970s until the emphasis and title was changed in 1999. The course has been reorganized and is now “How to Design, Install, Operate, and Maintain Reliable Power Cable Systems.” It is divided into two sessions: “Understanding Power Cable Characteristics and Applications” and “Assessing and Extending the Life of Shielded Power Cable Systems.” Numerous lecturers have produced copious class notes that form the basis for much of the material that is contained in this book. The contributors hope that their team effort will provide a useful addition to the library of all dedicated cable engineers.

The dynamics of the cable industry produces many new materials, products, and concepts that are incorporated in this second edition. Several new chapters have been prepared (Thermal Resistivity of Concrete, Underground System Fault Locating, Armor Corrosion of Submarine Cables, and Semiconducting Jackets) and others have been greatly expanded and revised from the first edition (Electrical Insulating Materials and Field Assessment of Power Cables).

The emphasis of this book is on low and medium voltages since they comprise the greatest quantity of cable in service throughout the world. Transmission cables have the greater sophistication from an engineering standpoint, but all the basic principles that apply to transmission cables also apply to the lower-voltage cables.

This second edition covers the up-to-date methods of design, manufacture, installation, and operation of power cables. The audience that would benefit from the highly knowledgeable writings and diversity of backgrounds of the contributors to this book includes:

> Cable engineers and technicians employed by investor-owned utilities, rural electric cooperatives, industrial users, and power production personnel
>
> Universities that offer electrical power courses
>
> Cable manufacturers that would like to provide their employees with an overview and understanding of power cables

The text provides the information that is required to understand the terminology and engineering characteristics and background of power cables and to assist in making sound decisions for specifying, purchasing, installation, maintenance, and operation of electrical power cables.

William A.Thue

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Electrical Power Cable Engineering

CHAPTER 1

HISTORICAL PERSPECTIVE OF ELECTRICAL CABLES

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1.0 DEVELOPMENT OF UNDERGROUND CABLES

In order to trace the history of underground cable systems, it is necessary to examine the early days of the telegraph [1-1,1-2]. The telegraph was the first device utilizing electrical energy to become of any commercial importance and its development necessarily required the use of underground construction. Experimentation with underground cables accordingly was carried on contemporaneously with the development of the apparatus for sending and receiving signals. Underground construction was planned for most of the earliest commercial lines. A number of these early installations are of considerable interest as marking steps in the development of the extensive underground power systems in operation around the world.

2.0 EARLY TELEGRAPH LINES

In 1812, Baron Schilling detonated a mine under the Neva River at St. Petersburg, Russia, by using an electrical pulse sent through a cable insulated with strips of India rubber. This is probably the earliest use of a continuously insulated conductor on record.

One of the earliest experiments with an underground cable was made by Francis Ronalds in 1816. This work was in conjunction with a system of telegraphy consisting of 500 feet of bare copper conductor drawn into glass tubes, joined together with sleeve joints and sealed with wax. The tubes were placed in a creosoted wooden trough buried in the ground. Ronalds was very enthusiastic over the success of this line, predicting that underground conductors would be widely used for electrical purposes, and outlining many of the essential characteristics of a modern distribution system.

The conductor in this case was first insulated with cotton saturated with shellac before being drawn into the tubes. Later, strips of India rubber were used. This installation had many insulation failures and was abandoned. No serious attempt was made to develop the idea commercially.

In 1837, W.R.Cooke and Charles Wheatstone laid an underground line along the railroad right-of-way between London’s Euston and Camden stations in London for their five-wire system of telegraphy. The wires were insulated with cotton saturated in rosin and were installed in separate grooves in a piece of timber coated with pitch. This line operated satisfactorily for a short time, but a number of insulation failures due to the absorption of moisture led to its abandonment. The next year, Cooke and Wheatstone installed a line between Paddington and Drayton stations, but iron pipe was substituted for the timber to give better protection from moisture. Insulation failures also occurred on this line after a short time, and it was also abandoned.

In 1842, S.F.B.Morse laid a cable insulated with jute, saturated in pitch, and covered with strips of India rubber between Governor’s Island and Castle Garden in New York harbor. The next year, a similar line was laid across a canal in Washington, D.C. The success of these experiments induced Morse to write to the Secretary of the Treasury that he believed “telegraphic communications on the electro-magnetic plan can with a certainty be established across the Atlantic Ocean.”

In 1844, Morse obtained an appropriation from the U.S. Congress for a telegraph line between Washington and Baltimore. An underground conductor was planned and several miles were actually laid before the insulation was proved to be defective. The underground project was abandoned and an overhead line erected. The conductor was originally planned to be a #16 gage copper insulated with cotton and saturated in shellac. Four insulated wires were drawn into a close fitting lead pipe that was then passed between rollers and drawn down into close contact with the conductors. The cable was coiled on drums in 300-foot lengths and laid by means of a specially designed plow.

Thus, the first attempts at underground construction were unsuccessful, and overhead construction was necessary to assure the satisfactory performance of the lines. After the failure of Morse’s line, no additional attempts were made to utilize underground construction in the United States until Thomas A.Edison’s time.

Gutta-percha was introduced into Europe in 1842 by Dr. W.Montgomery, and in 1846 was adopted on the recommendation of Dr. Werner Siemens for the telegraph line that the Prussian government was installing. Approximately 3,000 miles of such wire were laid from 1847 to 1852. Unfortunately, the perishable nature of the material was not known at the time, and no adequate means of protecting it from oxidation was provided. Insulation troubles soon began to develop and eventually became so serious that the entire installation was abandoned.

However, gutta-percha provided a very satisfactory material for insulating telegraph cables when properly protected from oxidation. It was used extensively for both underground and submarine installations.

In 1860, vulcanized rubber was used for the first time as insulation for wires. Unvulcanized rubber had been used on several of the very early lines in strips applied over fibrous insulation for moisture protection. This system had generally been unsatisfactory because of difficulties in closing the seam. Vulcanized rubber proved a much better insulating material, but did not become a serious competitor of gutta-percha until some years later.

3.0 ELECTRIC LIGHTING

While early telegraph systems were being developed, other experimenters were solving the problems connected with the commercial development of electric lighting. An electric light required a steady flow of a considerable amount of energy, and was consequently dependent upon the development of the dynamo. The first lamps were designed to utilize the electric arc that had been demonstrated by Sir Humphry Davy as early as 1810. Arc lights were brought to a high state of development by Paul Jablochkoff in 1876 and C.R.Brush in 1879. Both men developed systems for lighting streets by arc lamps connected in series supplied from a single generating station

Lighting by incandescence was principally the result of the work of Edison, who developed a complete system of such lighting in 1879. His lights were designed to operate in parallel instead of in series, as had been the case with the previously developed arc-lighting systems. This radical departure from precedent permitted the use of low voltage, and greatly simplified the distribution problems.

4.0 DISTRIBUTION OF ENERGY FOR LIGHTING

Edison planned his first installation for New York City, and decided that an underground system of distribution would be necessary. This took the form of a network supplied by feeders radiating from a centrally located dc-generating station to various feed points in the network. Pilot wires were taken back to the generating station from the feed points in order to give the operator an indication of voltage conditions on the system. Regulation was controlled by cutting feeders in, or out, as needed. At a later date, a battery was connected in parallel with the generator to guard against a station outage.

Gutta-percha, which had proved a satisfactory material for insulating the telegraph cables, was not suitable for the lighting feeders because of the softening of the material (a natural thermoplastic) at the relatively high operating temperature. Experience with other types of insulation had not been sufficient to provide any degree of satisfaction with their use. The development of a cable sufficiently flexible to be drawn into ducts was accordingly considered a rather remote possibility. Therefore, Edison designed a rigid, buried system consisting of copper rods insulated with a wrapping of jute. Two or three insulated rods were drawn into iron pipes and a heavy bituminous compound was forced in around them. They were then laid in 20-foot sections and joined together with specially designed tube joints from which taps could be taken if desired. The Edison tube gave remarkably satisfactory performance for this class of low voltage service.

The low voltage and heavy current characteristics of dc distribution were limited to the area capable of being supplied from one source if the regulation was to be kept within reasonable bounds. The high first cost and heavy losses made such systems uneconomical for general distribution. Accordingly, they were developed in limited areas of high-load density such as the business districts of large cities.

In the outlying districts, ac distribution was universally employed. This type of distribution was developed largely as a result of the work, in 1882, of L.Gaulard and J.D.Gibbs, who designed a crude alternating current system using induction coils as transformers. The coils were first connected in series, but satisfactory performance could not be obtained. However, they were able to distribute electrical energy at a voltage considerably higher than that required for lighting, and to demonstrate the economics of the ac system. This system was introduced into the United States in 1885 by George Westinghouse, and served as the basis for the development of workable systems. An experimental installation went in service at Great Barrington, Massachusetts, early in 1886. The first large scale commercial installation was built in Buffalo, New York, the same year.

The early installations operated at 1,000 volts. Overhead construction was considered essential for their satisfactory performance and almost universally employed. This was also true of the street-lighting feeders, which operated at about 2,000 volts. In Washington and Chicago, overhead wires were prohibited, so a number of underground lines were installed. Many different types of insulation and methods of installation were tried with little success. Experiments with underground conductors were also carried out in Philadelphia. The 1884 enactment of a law forcing the removal of all overhead wires from the streets of New York mandated the development of a type of construction that could withstand such voltages. It was some time, however, before the high-voltage wires disappeared. In 1888, the situation was summarized in a paper before the National Electric Light Association [1-1] as follows:

> “No arc wires had been placed underground in either New York or Brooklyn. The experience in Washington led to the statement that no insulation could be found that would operate two years at 2,000 volts.
>
> In Chicago, all installations failed with the exception of lead covered cables which appeared to be operating successfully. In Milwaukee, three different systems had been tried and abandoned. In Detroit, a cable had been installed in Dorsett conduit, but later abandoned. In many of the larger cities, low voltage cables were operating satisfactorily and in Pittsburgh, Denver and Springfield, Mass., some 1,000 volt circuits were in operation.”

5.0 PAPER INSULATED CABLES

The first important line insulated with paper was installed by Ferranti in 1890 between Deptford and London for single-phase operation at 10,000 volts [1-3]. Some of these mains were still in use at the original voltage after more than 50 years. The cables consisted of two concentric conductors insulated with wide strips of paper applied helically around the conductor and saturated with a rosinbased oil. The insulated conductors were forced into a lead pipe and installed in 20-foot lengths. These mains were not flexible and were directly buried in the ground. This system operated successfully for 43 years and may be the source of the “40 year life” of power cables [1-4].

Soon after, cables insulated with narrow paper strips saturated in a rosin compound and covered with a lead sheath (very similar in design to those in use at the present time) were manufactured in the United States by the Norwich Wire Company. These were the first flexible paper-insulated cables, and all subsequent progress has been made through improvements in the general design.

Paper insulated cables were improved considerably with:

(a) Introduction of the shielded design of multiple conductor cables by Martin Hochstadter in 1914. This cable is still known as Type H.

(b) Luigi Emanueli's demonstration that voids due to expansion and contraction could be controlled by the use of a thin oil with reservoirs. This permitted the voltages to be raised to 69 kV and higher.

(c) The 1927 patent by H.W.Fisher and R.W.Atkinson revealed that the dielectric strength of impregnated paper-insulated cable could be greatly increased by maintaining it under pressure. This system was not used until the 1932 commercial installation of a 200 psi cable in London.

Impregnated paper became the most common form of insulation for cables used for bulk transmission and distribution of electrical power, particularly for operating voltages of 12.5 kV and above, where low dielectric loss, a low dissipation factor, and a high ionization level are important factors in determining cable life.

Impregnated paper insulation consists of multiple layers of paper tapes, each tape from 2.5 to 7.5 mils in thickness, wrapped helically around the conductor to be insulated. The total wall of paper tapes is then heated, vacuum dried, and impregnated with an insulating fluid. The quality of the impregnated paper insulation depends not only on the properties and characteristics of the paper and impregnating fluid, but also on the mechanical application of the paper tapes over the conductor, the thoroughness of the vacuum drying, and the control of the saturating and cooling cycles during the manufacturing.

Originally, most of the paper used was made from Manila-rope fiber. This was erratic in its physical properties and not always susceptible to adequate oil penetration. Increased knowledge of the chemical treatment of the wood (in order to obtain pure cellulose by the adjustment of the fiber content and removal of lignin), the control of tear resistance, and the availability of long fiber stock resulted in the almost universal use of wood pulp paper in cables after 1900.

The impregnating compound was changed from a rosin-based compound to a pure mineral oil circa 1925, or oil blended to obtain higher viscosity, until polybutene replaced oil circa 1983.

Paper insulated, lead-covered cables were the predominant power cables of all the large, metropolitan transmission and distribution systems in the United States, and the rest of the world, throughout the twentieth century. Their reliability was excellent. It was, however, necessary to have a high degree of skill for proper splicing and terminating. A shift towards extruded dielectric cables began about 1975 in those metropolitan areas, but the majority of the distribution cables of the large cities remain paper insulated, lead-covered cables as the century ends.

Considerable research has been carried out by the utilities, technical organizations, and manufacturer's of cables to obtain improved paper and laminated PPP (polypropylene-paper-polypropylene, now used in transmission cables) tapes and insulating fluids able to withstand high, continuous operating temperatures, etc.

Impregnated paper insulation has excellent electrical properties, such as high dielectric strength, low dissipation factor, and dielectric loss. Because of these properties, the thickness of impregnated paper insulation was considerably less than for rubber or varnished cambric insulations for the same working voltages. Polyethylene and cross-linked polyethylene cables in the distribution classes are frequently made with the same wall thickness as today’s impregnated paper cables

6.0 EXTRUDED DIELECTRIC POWER CABLES

The development of polyethylene in 1941 triggered a dramatic change in the insulation of cables for the transmission and distribution of electrical energy. There are two major types of extruded dielectric insulation in wide use today for medium voltage cables:

(a) Cross-linked polyethylene or tree-retardant cross-linked polyethylene.
(b) Ethylene propylene rubber.

Thermoplastic polyethylene (PE), which was widely used through the 1970s, was introduced during World War II for high-frequency cable insulation. By 1947, PE was furnished as 15 kV cable insulation. Large usage began with the advent of underground residential distribution (URD) systems early in the 1960s.

7.0 URD SYSTEMS

The development of modern URD systems may be viewed as the result of drastically lowering first costs through technology.

Post-war URD systems were basically the same as the earlier systems except that there were two directions of feed (the loop system.) System voltages rose from 2400/4160 to 7620/13,200 volts. The pre-1950 systems were very expensive because they utilized such items as paper insulated cables, vaults, and submersible transformers. Those systems had an installed cost of $1,000 to $1,500 per lot. Expressed in terms of buying power at that time, you could buy a luxury car for the same price! Underground service was, therefore, limited to the most exclusive housing developments.

But for three developments in the 1960s, the underground distribution systems that exist today might not be in place. First, in 1958–59, a large midwestern utility inspired the development of the pad-mounted transformer; the vault was no longer necessary nor was the submersible transformer. Second, the polyethylene cable with its concentric neutral did not require cable splicers, and the cable could be directly buried. While possibly not as revolutionary, the loadbreak elbow (separable connector) allowed the transformer to be built with a lower, more pleasing appearance.

The booming American economy and the environmental concerns of the nation made underground power systems the watchword of the Great Society. In a decade, URD had changed from a luxury to a necessity. The goal for the utility engineer was to design a URD system at about the same cost as the equivalent overhead system. There was little or no concern about costs over the system’s life because that PE cable was expected to last 100 years!

8.0 TROUBLE IN PARADISE

During the early part of the 1970s, isolated reports of early cable failures on extruded dielectric systems began to be documented in many parts of the world. “Treeing” was re-introduced to the cable engineer’s vocabulary. This time it did not have the same meaning as with paper insulated cables. See Chapter 17 for additional information on treeing.

By 1976, reports from utilities [1-5] and results of EPRI research [1-6] confirmed the fact that thermoplastic polyethylene insulated cables were failing in service at a rapidly increasing rate. Cross-linked polyethylene exhibited a much lower failure rate that was not escalating nearly as rapidly. Data from Europe confirmed the same facts in a report prepared by UNIPEDE-DISCAB.

The realization of the magnitude and significance of the problem led to a series of changes and improvements to the primary voltage cables:

□ Research work was initiated to concentrate on solutions to the problem
□ Utilities began replacing the poorest performing cables
□ Suppliers of component materials improved their products
□ Cable manufacturers improved their handling and processing techniques

9.0 MEDIUM VOLTAGE CABLE DEVELOPMENT

In the mid 1960s, conventional polyethylene became the material of choice for the rapidly expanding URD systems in the United States [1-7]. It was known to be superior to butyl rubber for moisture resistance, and could be readily extruded. It was used with tape shields, which achieved their semiconducting properties because of carbon black. By 1968, virtually all of the URD installations consisted of polyethylene-insulated medium voltage cables. The polyethylene was referred to as “high molecular weight” (HMWPE); this simply meant that the insulation used had a very high “average” molecular weight. The higher the molecular weight, the better the electrical properties. The highest molecular weight PE that could be readily extruded was adopted. Jacketed construction was seldom employed at that time.

Extruded thermoplastic shields were introduced between 1965 and 1975 leading both to easier processing and better reliability of the cable

Cross-linked polyethylene (XLPE) was first patented in 1959 for a filled compound and in 1963 for unfilled by Dr. Frank Percopio. It was not widely used because of the tremendous pressure to keep the cost of URD down near the cost of an overhead system. This higher cost was caused by the need for additives (cross-linking agents) and the cost of manufacturing based on the need for massive, continuous vulcanizing (CV) tubes. EPR (ethylene propylene rubber) was introduced at about the same time. The significantly higher initial cost of these cables slowed their acceptance for utility purposes until the 1980s.

The superior operating and allowable emergency temperatures of XLPE and EPR made them the choice for feeder cables in commercial and industrial applications. These materials did not melt and flow as did the HMWPE material.

In order to facilitate removal for splicing and terminating, those early 1970-era XLPE cables were manufactured with thermoplastic insulation shields as had been used over the HMWPE cables. A reduction in ampacity was required until deformation resistant and then crosslinkable insulation shields became available during the later part of the 1970s.

A two-pass extrusion process was also used where the conductor shield and the insulation were extruded in one pass. The unfinished cable was taken up on a reel and then sent through another extruder to install the insulation shield layer. This resulted in possible contamination in a very critical zone. When cross-linked insulation shield materials became available, cables could be made in one pass utilizing “triple” extrusion of those three layers. “True triple” soon followed where all layers were extruded in a single head fed by three extruders.

In the mid 1970s, a grade of tree-retardant polyethylene (TR-HMWPE) was introduced. This had limited commercial application and never became a major factor in the market.

Around 1976 another option became available—suppliers provided a grade of “deformation resistant” thermoplastic insulation shield material. This was an attempt to provide a material with “thermoset properties” and thus elevate the allowable temperature rating of the cable. This approach was abandoned when a true thermosetting shield material became available.

By 1976, the market consisted of approximately 45% XLPE, 30% HMWPE, 20% TR-HMWPE and 5% EPR.

In the late 1970s, a strippable thermosetting insulation shield material was introduced. This allowed the user to install a “high temperature” XLPE that could be stripped for splicing with less effort than the earlier, inconsistent materials.

Jackets became increasingly popular by 1980. Since 1972–73, there had been increasing recognition of the fact that water presence under voltage stress was causing premature loss of cable life due to “water treeing.” Having a jacket reduced the amount of water penetration. This led to the understanding that water treeing could be “finessed” or delayed by utilizing a jacket. By 1980, 40 percent of the cables sold had a jacket.

EPR cables became more popular in the 1980s. A breakthrough had occurred in the mid-1970s with the introduction of a grade of EPR that could be extruded on the same type of equipment as XLPE insulation. The higher cost of EPR cables, as compared with XLPE, was a deterrent to early acceptance even with this new capability.

In 1981, another significant change took place: the introduction of “dry cure” cables. Until this time, the curing, or cross-linking, process was performed by using high-pressure steam. Because water was a problem for long cable life, the ability to virtually eliminate water became imperative. It was eventually recognized that the “dry cure” process provided faster processing speeds as well as elimination of the steam process for XLPE production.

Another major turning point occurred in 1982 with the introduction of tree-resistant cross-linked polyethylene (TR-XLPE). This product, which has supplanted conventional XLPE in market volume today, shows superior water tree resistance as compared with conventional XLPE. HMWPE and TR-HMWPE were virtually off the market by 1983.

By 1984, the market was approximately 65 percent XLPE, 25 percent TR-XLPE and 10 percent EPR. Half the cable sold had a jacket by that time.

During the second half of the 1980s, a major change in the use of filled strands took place. Although the process had been known for about ten years, the control of the extruded “jelly-like” material was better understood by a large group of manufacturers. This material prevents water movement between the strands along the cable length and eliminates most of the conductor’s air space, which can be a water reservoir.

In the late 1980s, another significant improvement in the materials used in these cables became available for smoother and cleaner conductor shields. Vast improvements in the materials and processing of extruded, medium voltage power cables in the 1980s has led to cables that can be expected to function for 30, 40, or perhaps even 60 years when all of the proper choices are utilized. In 1995, the market was approximately 45 percent TR-XLPE, 35 percent XLPE, and 20 percent EPR.

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CHAPTER 2
BASIC DIELECTRIC THEORY OF CABLE

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1.0 INTRODUCTION

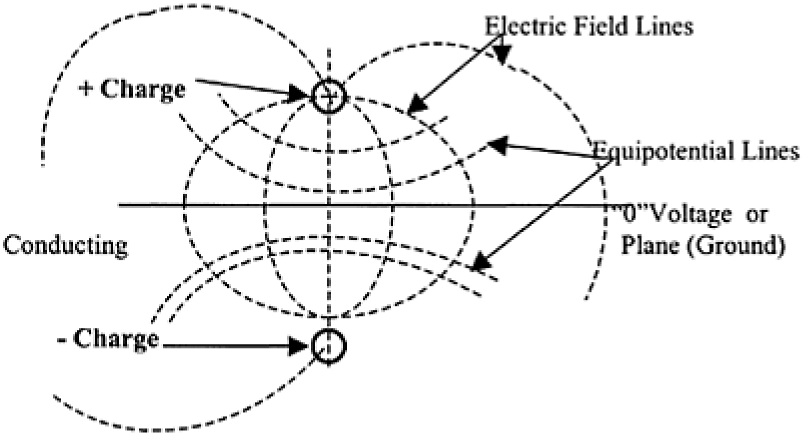
Whether being used to convey electric power or signals, it is the purpose of a wire or cable to convey the electric current to the intended device or location [2-1]. In order to accomplish this, a conductor is provided which is adequate to convey the electric current imposed. Equally important is the need to keep the current from flowing in unintended paths rather than the conductor provided. Electrical insulation (dielectric) is provided to largely isolate the conductor from other paths or surfaces through which the current might flow. Therefore, it may be said that any conductor conveying electric signals or power is an insulated conductor.

2.0 ELECTRIC FIELDS AND VOLTAGE

Current flow is charge in motion. We might consider the simple case of a conductor carrying current out to a load and then a return conductor as two separated parallel cylinders of charge. If we neglect conductor diameter (line of charge) there are electric field lines represented by circles of diameters such that the center of the circles are on the “0” line and each circle passes through the center of the cylinders. Everywhere perpendicular to the electric field lines are equipotential (equal voltage) lines due to each charge. The voltage at any location is the sum of the voltages due to each charge. Since the circle centers lie on the straight line equally distant from the charges, the equipotential lines from each charge exactly cancel on this line and the net voltage is “0”. See Figure 2-1.

If now the “0” voltage line is replaced with a conducting plane (such as the earth) and only the conductor above the plane remains, the location of the electric field lines and equipotential lines are not changed. However, the portion below the “0” voltage line is simply an image of that above the line (method of images). This then, neglecting conductor diameter, represents the electric field lines and equipotential (equal voltage lines) for an energized, current carrying conductor above ground. Of course, in this case the insulation (dielectric) is air.

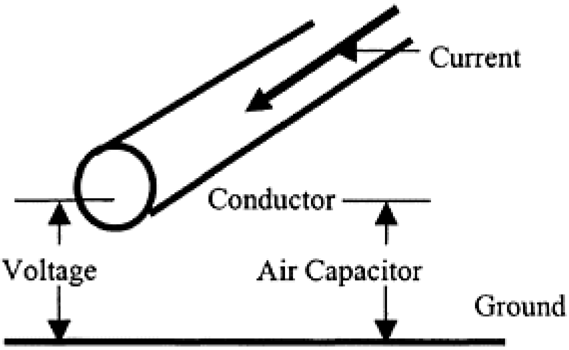
Figure 2-1 Electric field lines and equipotential lines for two lines of charge or a line of charge above a conducting plane.



2.0 AIR INSULATED CONDUCTORS

A metallic conductor suspended from insulating supports, surrounded by air, and carrying electric signals or power may be considered as the simplest case of an insulated conductor. It also presents an opportunity to easily visualize the parameters involved.

Figure 2-2 Location of voltage and current.



In Figure 2-2, the voltage is between the conductor and the ground [2-2,2-3] where ground is at "0" potential as shown in Fig. 2-1. The charge separation between the conductor and ground, results in a capacitor and because there is some (generally very small) conduction from conductor to ground, a large resistance also exists between the conductor and ground. As long as ground is well away from the conductor, the electric field lines leave the conductor outer surface as reasonably straight lines emanating from the center of the conductor. We know that all the electric field lines bend to ultimately terminate at ground. See Figure 2-1.

Air is not a very good insulating material since it has a lower voltage breakdown strength than many other insulating materials. It is low in cost and if space is not a constraint is a widely used dielectric. As the voltage between the conductor and ground is increased, a point is reached where the electric stress at the conductor exceeds the voltage breakdown strength of air. At this point, the air literally breaks down producing a layer of ionized, conducting air surrounding the conductor. The term for this is corona. It represents power loss and can cause interference to radio, TV, and other signals. It is not uncommon for this condition to appear at isolated spots where a rough burr appears on the conductor or at a connector. This is simply because the electric stress is locally increased by the sharpness of the irregularity or protrusion from the conductor. In air or other gasses, the effect of the ionized gas layer surrounding the conductor is to increase the electrical diameter of the conductor to a point where the air beyond the ionized boundary is no longer stressed to breakdown for the prevailing temperature, pressure, and humidity. This ionized air might be considered as an unintentional conductor shield. The unlimited supply of fresh air and the conditions just mentioned precludes the progression of the ionization of air all the way to ground. It is possible that the stress level is so high that an ionized channel can breach the entire gap from conductor to earth, but this generally requires a very high voltage source such as lightning.

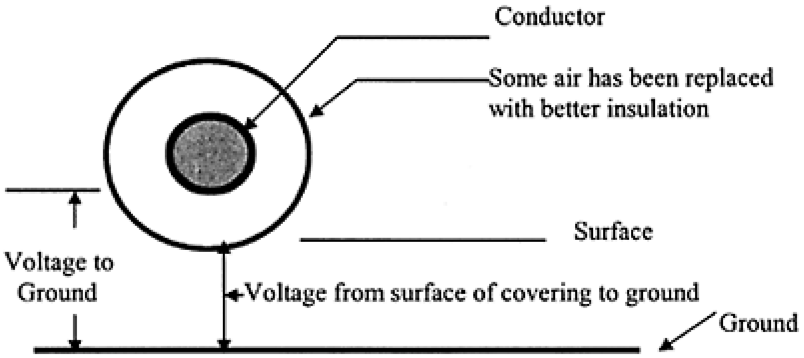
This raises another important fact about dielectrics. That is, their ability to not break down under voltage is thickness dependent. In Chapter 6, the breakdown strength of air is given as 79 volts for a 1/1,000 inch (1-mil) thickness. However, as thickness increases, the breakdown strength does not increase proportionately. If it did, a case could be made that lightning could not occur in the usual case.

3.0 INSULATING TO SAVE SPACE

Space is a common constraint that precludes the use of air as an insulator. Imagine the space requirements to wire a house or apartment using bare conductors on supports with air as the insulation. Let’s consider the next step where some of the air surrounding the previous conductor is replaced with a better insulating material (dielectric).

In Figure 2-3, we see that the voltage from conductor to ground is the same as before. A voltage divider has been created that is made up of the impedance from the conductor to the outside covering surface and another impedance from the covering surface to ground. The distribution of voltage from conductor to the surface of the covering and from the covering surface to ground will be in proportion to these impedances. It is important to note that with ground relatively far away from the covered conductor, the majority of the voltage exists from the covering surface to ground. Putting this another way, the outer surface of the covering has a voltage that is within a few percent of the voltage on the conductor (95 to 97% is a common value).

Figure 2-3 “Covered” conductor.



The amount of current that can flow from an intact covering to ground in the event of contact by a grounded object is limited by the thickness, dielectric constant and surface impedance of the covering as well as the area of contact. If the covering is made of an excellent insulation, the majority of the current will be due to capacitive charging current that can be released from the covering surface by the contacting object.

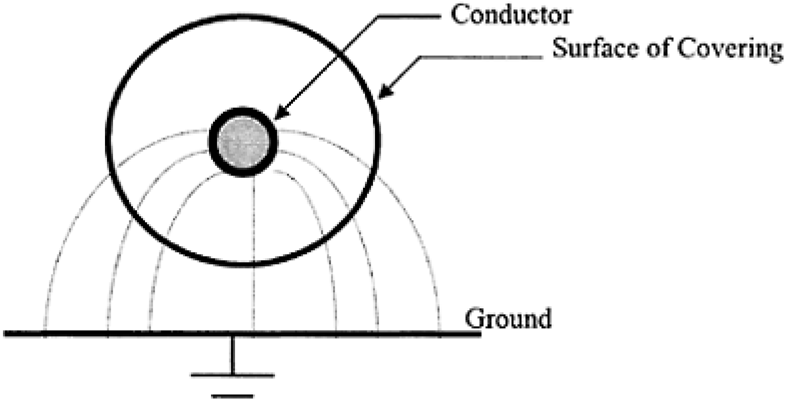
So little current is available at the covering surface from a low voltage covering (600 volts or less), that it is imperceptible. When this condition exists with some level of confidence, the “covering” is then considered to be “insulation” and suitable for continuous contact by a grounded surface as long as such contact does not result in chemical or thermal degradation. The question arises as to what is considered to be low voltage. The voltage rating of insulated cables is based on the phase-to-phase voltage. Low voltage is generally considered to be less than 600 volts phase-to-phase. See Chapters 4 and 9 for additional information.

Because of the proximity and contact with other objects, the thickness of insulating materials used for low voltage cables is generally based on mechanical requirements rather than electrical. The surrounding environment, the need for special properties such as sunlight, or flame resistance, and rigors of installation often make it difficult for a single material to satisfy all related requirements. Designs involving two or more layers are commonly used in low voltage cable designs. The outer layer, though commonly insulating, may sacrifice some of the insulating quality to achieve toughness, sunlight resistance, flame resistance, chemical resistance and more. In this case, the outer layer may serve as both insulation and jacket.

4.0 RISING VOLTAGE

Return to the metallic conductor that is covered with an insulating material and suspended in air. When the ground plane is brought close or touches the covering, the electric field lines depicted in Fig. 2-1 must bend more sharply to terminate at right angles to the ground plane.

Figure 2-4 Electric field lines bend to terminate at ground plane.



In Figure 2-4, we see considerable bending of the electric field lines. Recognizing that equipotential lines are perpendicular to the field lines, the bending results in potential difference on the covering surface. At low voltages, the effect is negligible. As the voltage increases, the point is reached where the potential gradients are sufficient to cause current to flow across the surface of the covering. This is commonly known as "tracking." Even though the currents are small, the high surface resistance causes heating to take place, which ultimately damages the covering. If this condition is allowed to continue, the erosion may progress to significant covering damage, and if in contact with ground, failure.

It is important to note that the utilization of spacer cable systems and heavy walled tree wires depend on this ability of the covering to reduce current flow to a minimum. When sustained contact with branches, limbs, or other objects occurs, damage may result with time—hence such contacts may not be left permanently, but must be removed from the cable periodically as a maintenance practice.

At first, it might be thought that the solution is to continue to add insulating covering thickness as the operating voltage increases. Cost and complications involved in overcoming this difficulty would make this a desirable first choice. Unfortunately, breakdown strength, surface erosion and personnel hazards are not linear functions of voltage versus thickness and this approach becomes impractical.

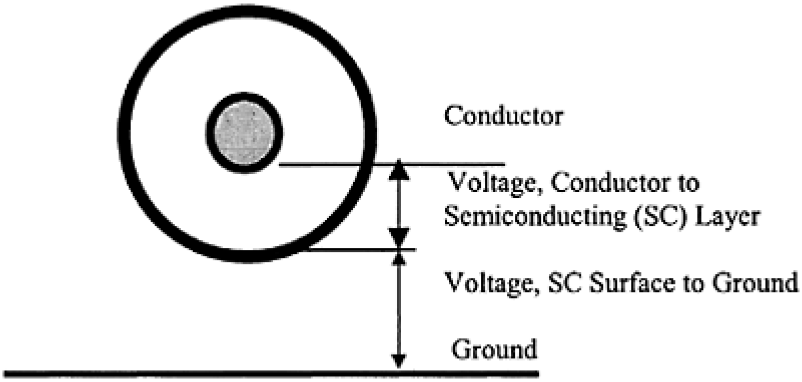
4.1 The Insulation Shield

In Figure 2-1, imagine that the ground plane were "wrapped" around the conductor "with the same thickness of air" separating the two. Barring surface irregularities at the conductor or ground, the electric field lines would be straight lines taking the shortest path from conductor to ground and the equipotential lines would be concentric cylinders around the conductor. This would form a cylindrical capacitor and would make the most effective use of the dielectric.

In order to make this ground contact possible, a semiconducting or resistive layer may be placed over the insulation surface. This material forces the bending of the field lines to occur in the semiconducting layer. This layer creates some complications, however.

In Figure 2-5, it is clear that a cylindrical capacitor has been created from the conductor to the surface of semiconducting layer, and a non-cylindrical capacitor from the semiconducting layer to ground. A great deal of charge can be contained in the capacitor involving ground because the outer plate is semiconducting allowing for greater charge mobility in the layer. This charging current must be controlled so that a path to ground is not established along the surface of the semiconducting layer. This path can lead to burning and ultimate failure of that layer. Accidental human contact would be a very serious event. It is clearly necessary to provide a continuous contact with ground that provides an adequate path to drain the capacitive charging current to ground without damage to the cable. This is done by adding a metallic path in contact with the semiconducting shield and making a relatively low resistance connection to ground.

Figure 2-5 Conductor with insulation and insulation shield.



Once a metallic member has been added to the shield system, there is simply no way to avoid its presence under ground fault conditions. This must be considered by either providing adequate conductive capacity in the shield to handle the fault currents or to provide supplemental means to accomplish this. This is a critical factor in cable design.

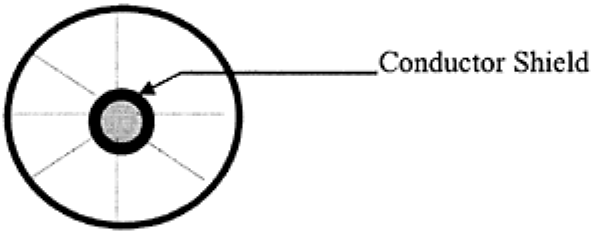
Electric utility cables have fault current requirements that are sufficiently large that it is common to provide for a neutral in the design of the metallic shield. These cables have become known as underground residential distribution (URD) and underground distribution (UD) style cables. It is important that the functions of the metallic shield system are understood since many serious errors and accidents have occurred because the functions were misunderstood.

4.2 A Conductor Shield Is Needed

The presence of an insulation shield creates another complication. The grounded insulation shield results in the entire voltage stress being placed across the insulation.

Just as in the case of the air-insulated conductor, there is concern about exceeding maximum stress that the insulating layer can withstand. The problem is magnified by stranded conductors or burrs and scratches that may be present in both stranded and solid conductors.

Figure 2-6 A conductor shield is added to provide a smooth inner electrode.



In Figure 2-6, a semiconducting layer has been added over the conductor to smooth out any irregularities. This reduces the probability of protrusions into the insulating layer. Protrusions into the insulation or into the semiconducting layer increase the localized stress (stress enhancement) that may exceed the long-term breakdown strength of the insulation. This is especially critical in the case of extruded dielectric insulations. Unlike air, there can be no fresh supply of insulation. Any damage will be progressive and lead to total breakdown of the insulating layer. There will be more discussion about “treeing” in Chapters 6 and 17.

4.3 Shielding Layer Requirements

There are certain requirements inherent in shielding layers to reduce stress enhancement. First, protrusions, whether by material smoothness or manufacturing, must be minimized. Such protrusions defeat the very purpose of a shield by enhancing electrical stress. The insulation’s shield layer has a further complication in that it is desirable to have it easily removable to facilitate splicing and terminating. This certainly is the case in the medium voltage (5 to 35 kV). At higher voltages, the inconveniences of a bonded insulation shield can be tolerated to gain the additional probability of a smooth, void-free insulation-insulation shield interface for cable with a bonded shield.

4.4 Insulation Layer Requirements

At medium and higher voltages, it is critical that both the insulation and insulation-shield interfaces be contamination free. Contamination at the interface results in stress enhancement just as a protrusion that can increase the probability of breakdown. Voids can do the same with the additional possibility of capacitive-resistive (CR) discharges in the gas-filled void as voltage gradients appear across the void. Such discharges can be destructive of the surrounding insulating material and lead to progressive deterioration and breakdown.

4.5 Jackets

In low voltage applications, jackets are commonly used to protect underlying layers from physical abuse, sunlight, flame, or chemical attack. In medium voltage shielded cables chemical attack includes corrosion of underlying metallic layers for shielding and armoring. In multi-conductor designs, overall jackets are common for the same purposes. For medium and high voltage cables, jackets have been almost universally used throughout the history of cable designs. They are used for the same purposes as for low voltage cables with special emphasis on protecting underlying metallic components from corrosion. The only exceptions were paper-insulated, lead-covered cables and early URD/UD designs that were widely used by the electric utility industry. Both “experiments” were based on the assumption that lead, and subsequently copper wires, was not subject to significant corrosion. Both experiments resulted in elevated failure rates for these designs. Jackets are presently used for these designs. The ability of jackets to reduce the ingress of moisture that has been shown to have a deleterious effect on most dielectrics causes them to be mentioned here.

5.0 TERMINOLOGY

To better understand the terminology that will be used throughout this book, a brief introduction of the terms follows.

5.1 Non-Shielded Power Cable

A cable non-shielded cable may consist of one or several conductors and one or several insulating layers. The cable may contain a jacket. The cable may also include a conductor shield. A cable is not considered fully shielded until both conductor and insulation shields are present. Non-shielded cables are common in the 0 to 5 kV voltage range although non-shielded power cables through 8 kV have been available.

5.2 Medium Voltage Shielded Cables

Medium voltage cables generally are fully shielded (having both conductor and insulation shield) cables in the 5 kV through 35 kV voltage range.

5.3 Conductor

Conductors may be solid or stranded. Metals used are commonly copper or aluminum. An attempt to use sodium was short-lived. The strand can be concentric, compressed, compacted, segmental, or annular to achieve desired properties of flexibility, diameter, and current density. The introduction of steel strands, higher strength aluminum alloys, hard drawn copper, Alumoweld and Copperweld are common in overhead applications requiring greater tensile strength or other applications with the same requirements.

Assuming the same cross-sectional area of conductor, there is a difference in diameters between solid and the various stranded conductors. This diameter differential is an important consideration in selecting methods to effect joints, terminations, and fill of conduits.

5.4 Electrical Insulation (Dielectric)

The insulation (dielectric) provides sufficient separation between the conductor and the nearest electrical ground to adjacent phase to preclude dielectric failure. For low voltage cables, (2,000 volts and below), the required thickness of insulation to physically protect the conductor is more than adequate for required dielectric strength.

5.5 Electric Field

Emphasis will be on 60Hz alternating current fields. In all cables, regardless of their kV ratings, there exists an electric field whenever the conductor is energized. This electric field can be visualized as electric field lines and lines of equipotential. See Figure 2-1.

5.6 Equipotential Lines

Equipotential lines represent points of equal potential difference between electrodes having different electrical potentials.

6.0 REFERENCES

[2-1] Landinger, Carl, adapted from class notes for “Understanding Power Cable Characteristics and Applications,” University of Wisconsin—Madison, 2001.

[2-2] Clapp, Allen, Landinger, C.C. and Thue, W.A., “Design and Application of Aerial Systems Using Insulating and Covered Wire and Cable,” *Proceedings of the 1996 IEEE/PES Transmission and Distribution Conference,* 96CH35968, Los Angeles, CA, Sept. 15–20, 1996.

[2-3] Clapp, Allen, Landinger, C.C. and Thue, W.A., “Safety Considerations of Aerial Systems Using Insulating and Covered Wire and Cable,” *Proceedings of the 1996 IEEE/PES Transmission and Distribution Conference,* 96CH35968, Los Angeles, CA, Sept. 15–20, 1996.

CHAPTER 3
CONDUCTORS

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1.0 INTRODUCTION

The fundamental concern of power cable engineering is to transmit current (power) economically and efficiently. The choice of the conductor material, size, and design must take into consideration such items as:

□ Ampacity (current carrying capacity)
□ Voltage stress at the conductor
□ Voltage regulation
□ Conductor losses
□ Bending radius and flexibility
□ Overall economics
□ Material considerations
□ Mechanical properties

2.0 MATERIAL CONSIDERATIONS

There are several low resistivity (or high conductivity) metals that may be used as conductors for power cables. Examples of these as ranked by low resistivity at 20°C are shown in Table 3-1 [3-1].

Table 3-1 Resistivity of Metals at 20°C

Metal	**Ohm-mm^2/m×10^{-8}**	**Ohm-cmil/ft×10^{-6}**
Silver	1.629	9.80
Copper, annealed	1.724	10.371
Copper, hard drawn	1.777	10.69
Copper, tinned	1.741–1.814	10.47–10.91
Aluminum, soft, 61.2% cond.	2.803	16.82
Aluminum, 1/2 hard to full hard	2.828	16.946
Sodium	4.3	25.87

Nickel	7.8	46.9

Considering these resistivity figures and cost of each of these materials, copper and aluminum become the logical choices. As such, they are the dominant metals used in the power cable industry today.

The choice between copper and aluminum conductors should carefully compare the properties of the two metals, as each has advantages that may outweigh the other under certain conditions. The properties most important to the cable designer are shown below.

2.1 DC Resistance

The conductivity of aluminum is about 61.2 to 62.0 percent that of copper. Therefore, an aluminum conductor must have a cross-sectional area about 1.6 times that of a copper conductor to have the equivalent dc resistance. This difference in area is approximately equal to two AWG sizes.

2.2 Weight

One of the most important advantages of aluminum, other than economics, is its low density. A unit length of bare aluminum wire weighs only 48 percent as much as the same length of copper wire having an equivalent dc resistance. However, some of this weight advantage is lost when the conductor is insulated, because more insulation volume is required over the equivalent aluminum wire to cover the greater circumference.

2.3 Ampacity

The ampacity of aluminum versus copper conductors can be compared by the use of many documents. See Chapter 9 for details and references, but obviously more aluminum cross-sectional area is required to carry the same current as a copper conductor as can be seen from Table 3-1.

2.4 Voltage Regulation

In ac circuits having small conductors (up to #2/0 AWG), and in all dc circuits, the effect of reactance is negligible. Equivalent voltage drops result with an aluminum conductor that has about 1.6 times the cross-sectional area of a copper conductor.

In ac circuits having larger conductors, however, skin and proximity effects influence the resistance value (ac to dc ratio, later written as ac/dc ratio), and the effect of reactance becomes important. Under these conditions, the conversion factor drops slightly, reaching a value of approximately 1.4.

2.5 Short Circuits

Give consideration to possible short circuit conditions, since copper conductors have higher capabilities in short circuit operation. Caution, when making this comparison the thermal limits of materials in contact with the conductor (shields, insulation, coverings, jackets…) must be considered.

2.6 Other Important Factors

Additional care must be taken when making connections with aluminum conductors. Not only does the metal tend to creep, but it also oxidizes rapidly. When aluminum is exposed to air, a thin, corrosion-resistant, high dielectric strength film quickly forms.

When copper and aluminum conductors are connected together, special techniques are required in order to make a satisfactory connection. See the discussion in Chapter 12.

Aluminum is not used extensively in generating station, substation, or portable cables because the lower bending life of small strands of aluminum does not always meet the mechanical requirements of those cables. Space is frequently a consideration at such locations also. However, aluminum is the overwhelming choice for aerial conductors because of its high conductivity to weight ratio and for underground distribution for economy where space is not a consideration. The 8000 series alloys of aluminum have found good acceptance in larger size conductors used in large commercial, institutional and some industrial applications in accordance with the NEC.

Economics of the cost of the two metals must, of course, be considered, but always weighed after the cost of the overlying materials is added.

3.0 CONDUCTOR SIZES

3.1 American Wire Gauge

Just as in any industry, a standard unit must be established for measuring conductor sizes. In the United States and Canada, electrical conductors are sized using the American wire gauge (AWG) system. This system is based on the following definitions:

- The diameter of size #0000 AWG (usually written #4/0 AWG and said as “four ought”) is 0.4600 inches for a solid conductor.
- The diameter of size #36 AWG is 0.0050 inches.
- There are 38 intermediate sizes governed by a geometric progression.

The ratio of any diameter to that of the next smaller size is:

$$\sqrt[39]{\frac{0.4600}{0.0050}} = 1.122932 \qquad (3.1)$$

3.1.1 Short Cuts for Estimations.

The square of the above ratio (the ratio of diameters of successive sizes) is 1.2610. Thus, an increase of one AWG size yields a 12.3% increase in diameter and an increase of 26.1% in area. An increase of two AWG sizes results in a change of 1.261 (or 26.1%) in diameter and 59% increase in area.

The sixth power of 1.122932 is 2.0050, or very nearly 2. Therefore, changing six AWG sizes will approximately double (or halve) the diameter. Another useful short-cut is that a #10 AWG wire has a diameter of roughly 0.1 inch, for copper a resistance of one ohm per 1000 feet and a weight of about 10 π, or 31.4 pounds per 1000 feet.

Another convenient rule is based on the fact that the tenth power of 1.2610 is 10.164, or approximately 10. Thus, for every increase or decrease of ten gage numbers (starting anywhere in the table) the cross-sectional area, resistance, and weight are divided or multiplied by about ten.

From a manufacturing standpoint, the AWG sizes have the convenient property that successive sizes represent approximately one reduction in die size in the wire drawing operation.

The AWG sizes were originally known as the Brown and Sharpe gage (B&S). The Birmingham wire gage (BWG) is used for steel armor wires. In Britain, wire sizes were specified by the standard wire gage (SWG), and were also known as the new British standard (NBS).

3.2 Circular Mil Sizes

Sizes larger than #4/0 AWG are specified in terms of the total cross-sectional area of the conductor and are expressed in circular mils. This method uses an arbitrary area of a conductor that is achieved by squaring the diameter of a solid conductor. This drops the π/4 multiplier required for the actual area of a round conductor. A circular mil is a unit of area equal to the area of a circle having a diameter of one mil, (one mil equals 0.001 inch). Such a circle has an area of 0.7854 (or π/4) square mils. Thus, a wire 10 mils in diameter has a cross-sectional area of 100 circular mils. Likewise, one square inch equals 4/π times 1,000,000=1,273,000 circular mils. For convenience, this is usually expressed in thousands of circular mils and abbreviated kcmil. Thus, an area of one square inch equals 1,273 kcmil.

$$A=\pi r^2 \tag{3.2}$$

where A=area in circular mils

π=3.1416

r=radius in 1/1000 of an inch

The abbreviation used in the past for thousand circular mils was MCM. The SI abbreviations for million, M, and for coulombs, C, is easily confused with the older term. The preferred abbreviation is kcmil for “thousand circular mils.”

The AWG and circular mil systems are basically limited to the United States with the remainder of the world using metric designations such as mm^2.

3.3 Metric Designations

All of the world, except for North America, uses the SI unit of square millimeters (mm^2) to designate conductor size. The International Electrotechnical Commission has adopted IEC 280 to define these sizes. An important consideration is that these are not precise sizes. For instance, their 50 mm^2 conductor is actually 47 mm^2. To accommodate everyone, the IEC standard allows as much as a 20% variation in conductor area from the size designated.

A comparison of the two systems can be seen in the tables in Chapter 23. Compression connectors, especially for aluminum, are sensitive to size variations. A #1/0 AWG is not close enough to any of the SI sizes so that a direct substitution is possible without changing the necessary connector and dies for either the 50 or 70 mm^2 sizes. Even the 1000 kcmil (1974 mm^2) size is slightly smaller than the standard SI size of 2000 mm^2.

In Canada, metric designations are used for all cable dimensions except for the conductor size! The variations in the two systems are too great to use any of the SI sizes as a direct substitution for standard sizes.

4.0 STRANDING

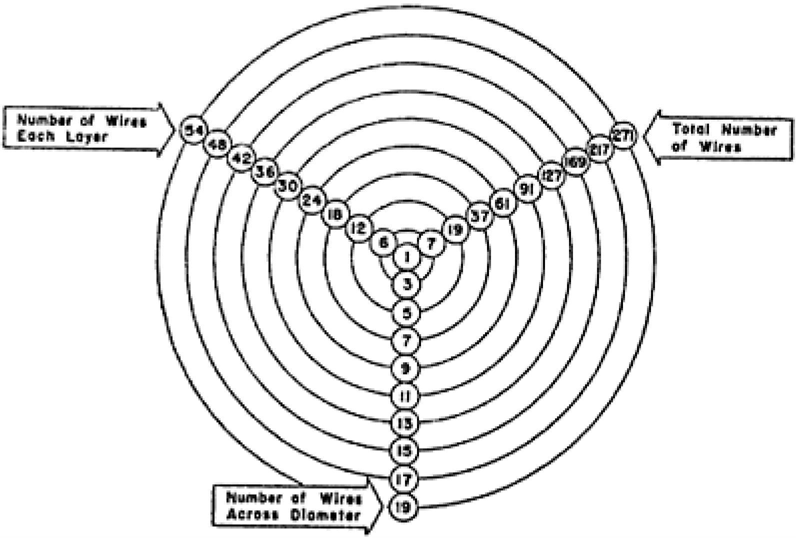
Larger sizes of solid conductors become too rigid to install, form, and terminate. Stranding becomes the solution to these difficulties. The point at which stranding should be used is dependent on the type of metal as well as the temper of that metal. Copper conductors are frequently stranded at #6 AWG and greater. Aluminum, in the half-hard temper, can be readily used as a solid conductor up to a #2/0 AWG conductor.

4.1 Concentric Stranding

This is the typical choice for power cable conductors. This consists of a central wire or core surrounded by one or more layers of helically applied wires. Each additional layer has six more wires than the preceding layer. Except in unilay construction, each layer is applied in a direction opposite to that of the layer underneath. In the case of power cable conductors, the core is a single wire and all of the strands have the same diameter. The first layer over the core contains six wires; the second, twelve; the third, eighteen; etc. The distance that it takes for one strand of the conductor to make one complete revolution of the layer is called the length of lay. The requirement for the length of lay is set forth in ASTM specifications, [3-5], to be not less than 8 times nor more than 16 times the overall diameter (OD) of that layer.

In power cables, the standard stranding is Class B. Specifications require that the outermost layer be of a left hand lay. This means that as you look along the axis of the conductor, the outermost layer of strands roll towards the left as they recede from the observer. More flexibility is achieved by increasing the number of wires in the conductor. Class C has one more layer than Class B; Class D one more layer than C. The Class designation goes up to M (normally used for welding cables, etc.). These are covered by ASTM specifications [3-2,3-3,3-4].

Figure 3-1 Concentric stranding relationships.



Classes C and D have approximately the same weight as Class B and an OD within 3 mils of Class B conductors. Examples of Class B (standard), Class C (flexible) and Class D (extra flexible) are shown below with the number of strands and diameter of each strand:

Table 3-2 Examples of Class B, C, and D Stranding

Size	Class B	Class C	Class D
#2 AWG	7×0.0974	19×0.0591	37×0.0424
#4/0 AWG	19×0.1055	37×0.0756	61×0.0589
500 kcmil	37×0.1162	61×0.0905	91×0.0741
750 kcmil	61×0.1109	91×0.0908	127×0.0768

The following formula may be used to calculate the number of wires in a concentric stranded conductor:

$$n=1+3N(N+1) \tag{3.3}$$

where n=total number of wires in stranded conductor

N=number of layers around the center wire

4.2 Compressed Stranding

This is the term that is used to describe a slight deformation of the layers to allow the layer being applied to close tightly. There is no reduction in conductor area. The diameter of the finished cable can be reduced no more than 3% of the equivalent concentric strand. A typical reduction is about 2.5%. Examples of gaps in the outer layer for concentric stranded cables are shown in Table 3-3.

Table 3-3 Gaps in Outer Layer of a Stranded Conductor

Total Number of Strands	Angle of Gap at 16×OD
19	8.3°
37	10°
61	10°

Shortening the length of lay on the outer layers could solve the problem but would result in higher resistance and would require more conductor material.

The reason that compressed stranding is an excellent construction is that concentric stranding with its designated lay length creates a slight gap between the outer strands of such a conductor. Lower viscosity materials that are extruded over such a conductor tend to “fall in” to any gap that forms. This results in surface irregularities that create increased voltage stresses and makes it more difficult to strip off that layer.

4.3 Compact Stranding

This is similar to compressed stranding except that additional forming is given to the conductor so that the reduction in diameter is typically 9% less than the concentric stranded conductor. This results in a diameter nearing that of a solid conductor. Some air spaces are still present that can serve as channels for moisture migration. The main advantage of compact conductors is the reduced conductor diameter.

4.4 Bunch Stranding

This term is applied to a collection of strands twisted together in the same direction without regard to the geometric arrangement. This construction is used when extreme flexibility is required for small AWG sizes, such as portable cables. Examples of bunch-stranded conductors are cords for vacuum cleaners, extension cords for lawn mowers, etc. Examples are:

Table 3-4 Examples of Class K and M Stranding

Conductor Size	Class K	Class M

#16 AWG	26×0.0100	65×0.0063
#14 AWG	41×0.0100	104×0.0063
#12 AWG	65×0.0100	168×0.0063

Note in Class K and M that the individual wire diameters are constant and area is developed by adding a sufficient number of wires to provide the total conductor area required.

4.5 Rope Stranding

This term is applied to a concentric-stranded conductor, each of whose component strands is stranded. This is a combination of the concentric conductor and a bunch stranded conductor. The finished conductor is made up of a number of groups of bunched or concentric stranded conductors assembled concentrically together. The individual groups are made up of a number of wires rather than a single, individual strand. A rope-stranded conductor is described by giving the number of groups laid together to form the rope and the number of wires in each group.

Classes G and H are generally used on portable cables for mining applications. Classes I, L, and M utilize bunch stranded members assembled into a concentric arrangement. The individual wire size is the same with more wires added as necessary to provide the area. Class I uses #24 AWG (0.020 inch) individual wires, Class L uses #30 AWG (0.010 inch) individual wires, and Class M uses #34 AWG (0.0063 inch) individual wires. Class I stranding is generally used for railroad applications and Classes L and M are used for extreme portability such as welding cable and portable cords.

4.6 Sector Conductors

They have a cross-section approximately the shape of a sector of a circle. A typical three-conductor cable has three 120° segments that combine to form the basic circle of the finished cable. Such cables have a smaller diameter than the corresponding cable with round conductors, lower ac resistance due to a reduction of the proximity effect, and mechanical considerations.

For paper-insulated cables, the sector conductor was almost always stranded and then compacted in order to achieve the highest possible ratio of conductor area to cable area. The precise shape and dimensions varied somewhat between manufacturers.

PVC insulated cables in Europe were used in some cases with sector shaped conductors that were “solid” (one strand), but they are no longer made.

Figure 3-2 Outline of typical compact sector.

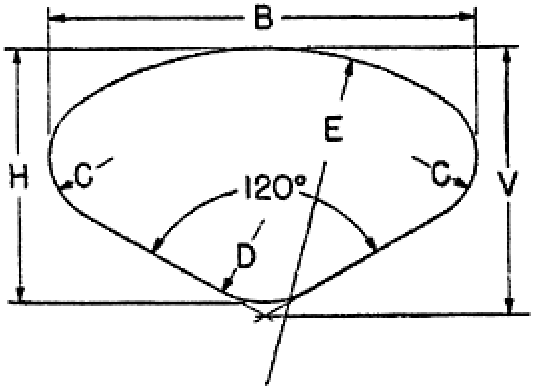


Table 3-5 Nominal Dimensions of 3/c Compact Sector Conductor

Cond. AWG/kcmil	V-Gage Inch	V-Gage* Inch	B Inch	C Inch	D Inch	E Inch
1/0	0.288		0.462	0.080	0.080	0.504
2/0	0.323		0.520	0.085	0.085	0.540
3/0	0.364		0.592	0.100	0.100	0.584
4/0	0.417		0.660	0.111	0.090	0.595
4/0		0.410	0.660	0.117	0.090	0.770
250	0.455		0.720	0.118	0.220	0.635
250		0.447	0.720	0.125	0.220	0.812
300	0.497		0.784	0.130	0.179	0.678
300		0.490	0.784	0.138	0.179	0.852
350	0.539		0.834	0.151	0.259	0.718
350		0.532	0.834	0.151	0.259	0.890
400	0.572		0.902	0.147	0.244	0.754
400		0.566	0.902	0.158	0.244	0.928
500	0.642		1.018	0.155	0.207	0.820
500		0.635	1.018	0.167	0.207	1.000
600	0.700		1.120	0.165	0.210	0.882
600		0.690	1.120	0.178	0.210	1.050
750	0.780		1.280	0.163	0.284	0.970

750		0.767	1.280	0.185	0.284	1.140
800	0.806		1.324	0.164	0.224	0.890
800		0.795	1.324	0.176	0.224	1.083
900	0.854		1.405	0.170	0.236	1.040
900		0.842	1.405	0.180	0.236	1.110
1000	0.900		1.500	0.137	0.300	1.008
1000		0.899	1.500	0.192	0.300	1.266

Note: * Denotes the column that applies for insulation thickness over 200 mils.

For calculations of capacitance, for instance, an “equivalent round conductor” is required. Over the 2/0 to 750 kcmil size range, the following formula holds:

$$D = 1.337\sqrt{A} \tag{3.4}$$

where D=equivalent round diameter in mils

A=area of sector conductor in circular mils

Sector conductors that are solid rather than stranded have been used for lowvoltage cables on a limited basis. There is interest in utilizing this type of conductor for medium voltage cables, but they are not available on a commercial basis at this time.

4.7 Segmental Conductors

They are round, stranded conductors composed of three or more sectors that are electrically separated from each other by a thin layer of insulation around every other segment. Each segment carries less current than the total conductor and the current is transposed between inner and outer positions in the completed cable. This construction has the advantage of lowering the skin effect ratio and hence the ac resistance by having less skin effect than a conventionally stranded conductor. This type of conductor should be considered for large sizes such as 1,000 kcmil and above that are to carry large amounts of current. The diameters of four segment conductors are the same as concentric stranded conductors.

4.8 Annular Conductors

These are round, stranded conductors whose strands are laid around a core of rope, fibrous material, helical metal tube, or a twisted I-beam. This construction has the advantage of lowering the total ac resistance for a given cross-sectional area of conductor by eliminating the greater skin effect at the center of the completed cable. Where space is available, annular conductors may be economical to use for 1,000 kcmil cables and above at 60 hertz and for 1,500 kcmil cables and above for lower frequencies such as 25 hertz.

4.9 Unilay Conductors

Unilay has, as the name implies, all of its strands applied with the same direction of lay. A design frequently used for low-voltage power cables is the combination unilay where the outer layer of strands are partially composed of strands having a smaller diameter than the other strands. This makes it possible to attain the same diameter of a compact stranded conductor. The most common unilay conductor is a compact, 8000 series aluminum alloy.

5.0 PHYSICAL AND MECHANICAL PROPERTIES

5.1 Conductor Properties

Although high conductivity is one of the important features of a good conductor material, other factors must be taken into account. Silver is an interesting possibility for a cable conductor. Its high cost is certainly one of the reasons to look for other candidates. Silver has another disadvantage of lack of physical strength that is necessary for pulling cables into conduits.

5.1.1 Copper.

Impurities have a very deleterious effect on the conductivity of copper. The specified purity of copper for conductors is 100%. Small amounts of impurities, such as phosphorous or arsenic, can reduce the conductivity to as low as 80%.

5.1.2 Aluminum.

Electrical conductor (EC) grade aluminum is also low in impurities—9.5% purity or better. ASTM B 233 specifies the permissible impurity levels for aluminum [3-5].

5.2 Properties

Table 3-6 Properties

Property	**Unit**	**Copper, Annealed**	**Alum, Hard Drawn**
Density at 20°C	Pounds/in^3	0.32117	0.0975
	Grams/cm^3	8.890	2.705
Linear Temp. Coef of Expansion	per °F	9.4×10^{-6}	12.8×10^{-6}
	per °C	17.0×10^{-6}	23.0×10^{-6}
Melting Point	°F	1981	1205–1215

Melting Point	°C	1083	652–657

5.3 Temper

Drawing metal rod into wire results in work hardening of the wire for both copper and aluminum. This work causes the soft temper metal to change to a slightly lower conductivity as well as a higher temper. Stranding and compacting also increases the temper of the metal. If a more flexible conductor is required, annealing the metal may be desirable. This can be done while the strand is being drawn or the finished conductor may be annealed by placing a reel of the finished conductor in an oven usually having a nitrogen atmosphere and at an elevated temperature for a specified period of time.

5.3.1 Copper.

ASTM specifications B-1, B-2, and B-3 cover three tempers for copper conductors: soft (annealed), medium-hard-drawn, and hard-drawn. Softdrawn is usually specified for insulated conductors because of its flexibility and ease of handling in the field. Medium-hard-drawn and hard-drawn are usually specified for overhead conductors.

5.3.2 Aluminum.

ASTM covers aluminum conductors with Specifications B-230, B-231 (concentric lay), and B-400 (compact round). ASTM has five designations for aluminum tempers as shown below. Note that some of the values overlap. Half-hard aluminum is usually specified for solid and for 8000 series alloy conductors because of the need for greater flexibility. Three-quarter and full-hard are usually specified for stranded cables.

Table 3-7 Aluminum Temper

1350 Aluminum Tempers		$PSI \times 10^3$
Full Soft	(H-0)	8.5 to 14.0
1/4 Hard	(H-12 or -22)	12.0 to 17.0
1/2 Hard	(H-14 or -24)	15.0 to 20.0
3/4 Hard	(H-16 or -26)	17.0 to 22.0
Full Hard	(H-19)	22.5 to 29.0

It is important to consider two facts before deciding what temper should be specified:

□ It costs money to provide the energy and equipment to anneal conductors.
□ The stiffness of the rest of the insulated cable may overwhelm the flexibility issue.

Overhead conductors and cables that will be pulled in long lengths frequently utilize higher tempers in order to increase the tensile strength of the conductor. Examples of cables that might require high tensile strength conductors are bore hole cables, mineshaft cables, or extremely long pulls of large conductors.

6.0 STRAND BLOCKING

Moisture in the conductor of an insulated conductor has been shown to cause several problems. Aluminum, in the presence of water and in the absence of oxygen, will hydrolyze. Thus, if water enters an insulated cable having an aluminum conductor, the aluminum and water combine chemically to form aluminum hydroxide and hydrogen gas. This condition is aggravated by a deficiency in oxygen in the insulated conductor. The chemical reaction is:

$$2\,Al + 6\,H_2O \rightarrow 2\,Al\,(OH)_3 + 3\,H_2 \uparrow$$

Aluminum hydroxide is a white, powdery material that is a good insulator. Many users of stranded aluminum conductors are now requiring filled conductors for this reason. Filled conductors prevent the passage of moisture along the conductor and thus help to retard this form of deterioration.

Regardless of the conductor material and degree of compaction of a stranded conductor, there is some air space remaining. This space can be a reservoir for moisture to collect and hence a source of water for water treeing. Water blocked stranded conductors are frequently specified for underground cables to reduce the possibility of this happening. (Solid conductors, of course, are specified for the same reason for #2/0 AWG aluminum and smaller cables.)

7.0 ELECTRICAL CALCULATIONS

7.1 Conductor dc Resistance

$$R_{dc} \text{ at } 25°\text{C}=1000\,\rho/A \tag{3.5}$$

where R_{dc}=direct current resistance of the conductor in ohms per 1000 feet at 25°C

ρ=resistivity of metal in ohms per circular mil foot

ρ for copper=10.575 ohms/cmil-foot at 25°C

ρ for aluminum=17.345 ohms/cmil-foot at 25°C

A=conductor area in circular mils

The resistance of a stranded conductor is more difficult to calculate. It is generally assumed that the current is evenly divided among the strands and does not transfer from one strand to the next one. For that reason, the dc resistance is based on:

□ Multiply the number of strands by the cross-sectional area taken perpendicular to the axis of that strand. The product is then the cross-sectional area of the conductor.

□ Compare the length of each strand to the axial length of the conductor. This increased length is arithmetically averaged.

□ The dc resistance of a solid conductor having the same effective cross-sectional area is multiplied by the average increase in length of the strand. The result is the calculated resistance of the stranded conductor.

Since resistance is based on temperature, the following formulas correct for other temperatures in the range most commonly encountered:

$$\text{Copper:} \qquad R_2 = R_1 \frac{234.5+T_2}{234.5+T_1} \tag{3.6}$$

$$\text{Aluminum:} \qquad R_2 = R_1 \frac{228.1+T_2}{228.1+T_1} \tag{3.7}$$

where R_2=conductor resistance at temperature T_2 in °C

R_1=conductor resistance at temperature T_1 in °C

These formulas are based on the resistance coefficient of copper having 100% conductivity and of aluminum having 61.2% conductivity (international annealed copper standard).

7.2 Conductor ac Resistance

A conductor offers a greater resistance to a flow of alternating current than it does to direct current. This increased resistance is generally expressed as the ac/dc resistance ratio. The two major factors for this increase are the skin effect and the proximity effect of closely spaced current carrying conductors. Other magnetic effects can also cause an additional increase in ac/dc resistance ratios.

$$R_{ac}=ac/dc \text{ ratio}\times R_{dc} \tag{3.8}$$

The ac/dc resistance ratio is increased by larger conductor sizes and higher ac frequencies.

7.3 Skin Effect

In ac circuits, the current density is greater near the outer surface of the conductor. The current tends to crowd toward the outer surface. This is called skin effect. A longitudinal element of the conductor near the center of the axis is surrounded by more lines of magnetic force than near the rim. This results in an increase in inductance toward the center. The decreased area of conductance causes an apparent increase in resistance. At 60 hertz, the phenomenon is negligible in copper sizes of #2 AWG and smaller and aluminum sizes #1/0 AWG and smaller. As conductor sizes increase, the effect becomes more significant.

The following formula can be used to give an approximation of skin effect for round conductors at 60 hertz, another approximation will be given in Chapter 13:

$$Y_{CS} = \frac{11.18}{R_{dc}^{2} + 8.8} \tag{3.9}$$

where Y_{CS}=skin effect expressed as a number to be added to the dc resistance
R_{dc}=dc resistance of the conductor in micro-ohms per foot at operating temperature

7.4 Proximity Effect

In closely spaced ac conductors, there is a tendency for the current to shift to the portion of the conductor that is away from the other conductors of that cable. This is called proximity effect. The flux linking the conductor current in one conductor is distorted by the current in a nearby conductor. This in turn causes a distortion of the cross-sectional current distribution.

Since skin and proximity effects are cumbersome to calculate, tables have been established to give these values for common modes of operation [3-5].

7.5 Cables in Magnetic Metal Conduit

Due to excessive hysteresis and eddy current losses, individual phases of an ac circuit should not be installed in separate magnetic metal conduits under any circumstances. This is because of the high inductance of such an installation. In fact, separate phases should not pass through magnetic structures since overheating can occur in such a situation. All phases should pass through any magnetic enclosure simultaneously so that maximum cancellation occurs of the resultant magnetic field. This greatly reduces the magnetic effect. However, even under these conditions, an increase in skin and proximity effect will occur because of the proximity of the magnetic material. There can be significant losses when large conductors are simply placed near magnetic materials.

Cables in 50 or 60 hertz ac circuits should not be installed with each phase in a separate non-magnetic metal conduit when their size is #4/0 AWG or larger due to high circulating currents in the conduit. This causes a significant de-rating of the cable ampacity.

7.6 Resistance at Higher Frequencies

Cables operating at frequencies higher than 60 hertz may need to be evaluated for ampacity and ac/dc ratios because they can cause higher voltage drops than might be anticipated. Also at higher frequencies, an increase in the inductive reactance may affect voltage drops. Insulated conductors should not be installed in metallic conduits nor should they be run close to magnetic materials.

For frequencies other than 60 hertz, a correction factor is provided by:

$$x = 0.027678 \sqrt{f / R_{dc}} \tag{3.10}$$

where f=frequency in hertz

R_{dc}=conductor dc resistance at operating temperature, in ohms per 1000 feet

For additional information on the effects of higher frequency, see the ICEA Report in reference [3-3] and cable manufacture's manuals [3-4 and 3-5].

8.0 REFERENCES

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[3-4] "Engineering Data for Copper and Aluminum Conductor Electrical Cables," The Okonite Company, Bulletin EHB-90, 1990.
[3-5] *Southwire Company Power Cable Manual,* Second Edition, 1997, Carrollton, GA, USA.
[3-6] American Society for Testing and Materials, *Annual Book of ASTM Standards,* Vol. 02.03: Electrical Conductors. Section 2: Nonferrous Metal Products, Philadelphia, PA, ASTM, 2002 (revised annually).

CHAPTER 4
CABLE CHARACTERISTICS: ELECTRICAL

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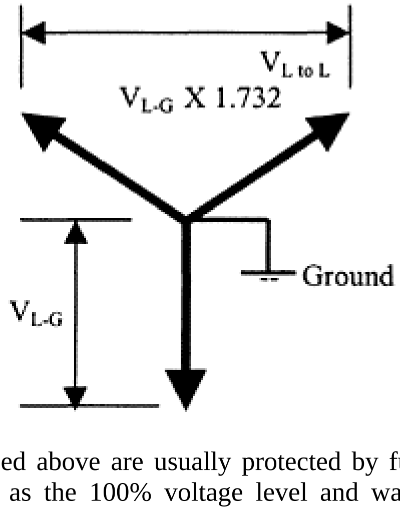
1.0 VOLTAGE RATINGS OF CABLES

The rating, or voltage class, of a cable is based on the phase-to-phase voltage of the system even though it is in a single or three phase circuit. For example, a 15 kV rated cable (or a higher value) must be specified on a system that operates at 7,200 or 7,620 volts to ground on a grounded wye 12,500 or 13,200 volt system. This is based on the fact that the phase-to-phase voltage on a wye system is 1.732 (the square root of 3) times the phase-to-ground voltage. Another example is that a cable for operation at 14.4 kV to ground must be rated at 25 kV or higher since 14.4 times 1.732 is 24.94 kV

Figure 4-1 Voltage rating.



The wye systems described above are usually protected by fuses or fast acting relays. This is generally known as the 100% voltage level and was previously known as a "grounded" circuit. Additional insulation thickness is required for systems that are not grounded, such as found in some delta systems, impedance or resistance grounded systems, or systems that have slow-acting isolation schemes. The following voltage levels are found in AEIC specifications [4-1].

1.1 100 Percent Level

Cables in this category may be applied 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. While these cables are applicable to the great majority of cable installations that are on grounded systems, they may be used also on other systems for which the application of cables is acceptable provided the above clearing requirements are met in completely de-energizing the faulted section.

1.2 133 Percent Level

This insulation level corresponds to that formerly designated for “ungrounded” systems, Cables in this category may be applied in those situations where the clearing time requirements of the 100 percent category cannot be met, and yet there is adequate assurance that the faulted section will be de-energized in a time not exceeding one hour. Also, they may be used when additional insulation strength over the 100 percent level category is desirable.

1.3 173 Percent Level

Cables in this category should be applied on systems where the time required to de-energize a section is indefinite. Their use is recommended also for resonant grounded systems. Consult the (cable) manufacturer for insulation thickness.

1.4 Cables Not Recommended

Cables are not recommended for use on systems where the ratio of the zero to positive phase reactance of the system at the point of cable application lies between −1 and −40 since excessively high voltages may be encountered in the case of ground faults.

1.5 Ratings of Low Voltage Cables

Low voltage cable ratings follow the same general rules as for the medium voltage cables previously discussed in that they are also based on phase-to-phase operation. The practical point here is that a cable that operates at say 480 volts from phase-to-ground on a grounded wye system requires an insulation thickness applicable to 480×1.732 or 831.38 volts phase-to-phase. This, of course, means that a 1,000 volt level of insulation thickness should be selected.

There are no categories for low voltage cables that address the 100, 133 and 173 percent levels. One of the main reasons for the thickness of insulation walls for these low voltage cables in the applicable Standards is that mechanical requirements of these cables dictate the insulation thickness. As a practical matter, all these cables are over-insulated for the actual voltages involved.

2.0 CABLE CALCULATION CONSTANTS

There are four main calculation constants that affect how a cable functions on an electric system: resistance, capacitance, inductance, and conductance. Conductor resistance has been addressed in Chapter 3.

2.1 Cable Insulation Resistance

The resistance to flow on a direct current through an insulating material (dielectric) is known as insulation resistance. There are two possible paths for current to flow when measuring insulation resistance:

(a) Through the body of the insulation (volume insulation resistance)
(b) Over the surface of the insulation system (surface resistivity)

2.1.1 Volume Insulation Resistance.

The volume insulation resistance of a cable is the direct current resistance offered by the insulation to an impressed dc voltage tending to produce a radial flow of leakage through that insulation material. This is expressed as a resistance value in megohms for 1000 feet of cable for a given conductor diameter and insulation thickness. *Note that this is* ***for*** *1000 feet,* ***not*** ***per*** *1000 feet!* This means that the longer the cable, the lower the resistance value that is read on a meter since there are more parallel paths for current to flow to ground. The basic formula for a single conductor cable of cylindrical geometry is:

$$IR = \mathrm{K} \log_{10} D/d \tag{4.1}$$

where IR=megohms for 1000 feet of cable
K=insulation resistance constant
D=diameter over the insulation (under the insulation shield)
d=diameter under the insulation (over the conductor shield)
Note: Both D and d must be expressed in the same units.

In order to measure the insulation resistance of a cable, the insulation must either be enclosed in a grounded metallic shield or immersed in water. Resistance measurements are greatly influenced by temperature—the higher the temperature, the lower the insulation resistance. The cable manufacturer should be contacted for the temperature correction factor for the specific insulation. Equation 4.1 is based on values at 60°F.

The values shown in Table 4-1 are also based on this temperature. The ICEA minimum requirements of IR (sometimes referred to as “guaranteed values”) are shown as well to represent values that may be measured in the field. The actual value of IR that would be read in a laboratory environment are many times higher than these “minimum” values and approaches the “typical” values shown below.

Table 4-1 Insulation Resistance

Insulation	ICEA Minimum	Typical
HMWPE	50,000	1,000,000
XLPE & EPR, 600 Volt	10,000	100,000
XLPE & EPR, Med. Voltage	20,000	200,000
PVC at 60°C	2,000	20,000
PVC at 75°C	500	5,000

2.1.2 Surface Resistivity.

One of our contributors often stated that “all cables have two ends.” These terminations or ends, when voltage is applied to the conductor, can have current flow over the surface of that material. This current adds to the current that flows through the volume of insulation which lowers the apparent volume insulation resistance unless measures are taken to eliminate that current flow while the measurements described above are being made. This same situation can occur when samples of insulation are measured in the laboratory. A “guard” circuit is used to eliminate the surface leakage currents from the volume resistivity measurement.

2.1.3 dc Charging Current.

The current generated when a cable is energized from a dc source is somewhat complicated because there are several currents that combine to form the total leakage current. These currents are:

I_L=leakage current
I_G=charging current
I_A=absorption current

The dc charging current behaves differently than the ac in that the dc value rises dramatically during the initial inrush. It decreases rather quickly with time, however. The magnitude of the charging and absorption currents is not usually very important except that it may distort the true leakage current reading. The longer the length and the larger the cable size, the greater the inrush current and the longer it will take for the current to recede. This initial current decays exponentially to zero in accordance with the following equation:

$$I_G=(E/R)\varepsilon^{-t/RC} \tag{4.2}$$

where I_G=charging current in microamperes per 1000 feet
E=voltage of conductor to ground in volts
R=dc resistance of cable in megohms for 1000 feet
ε=base of natural logarithm (2.718281…)
t=time in seconds

C=capacitance of circuit in microfarads per 1000 feet

The absorption current is caused by the polarization and accumulation of electric charges that accumulate in a dielectric under applied voltage stress. The absorption current normally is relatively small and decreases with time. Absorption current represents the stored energy in the dielectric. Short-term grounding of the conductor may not give a sufficient amount of time for that energy to flow to ground. Removing the ground too quickly can result in the charge reappearing as a voltage on the conductor. The general rule is that the ground should be left on for one to four times the time period that the dc source was applied to the cable. The absorption current is:

$$I_A=AVCt^{-B} \tag{4.3}$$

where I_A=absorption current in microamperes per 1,000 feet

V=incremental voltage change in volts

C=capacitance in microfarads per 1,000 feet

t=time in seconds

A and B are constants depending on the insulation.

A and B are constants that differ with the specific cable since they are dependent on the type and condition of the insulation. They generally vary in a range that limits the absorption current to a small value compared to the other dc currents. This current decays rather rapidly when a steady-state voltage level is reached.

The current that is of the most importance is the leakage or conduction current. The leakage current is dependent on the applied voltage, the insulation resistance of the cable insulation, and any other series resistance in the circuit. This value becomes very difficult to read accurately at high voltages because of the possibility of end leakage currents as well as the transient currents. The formula for leakage current is:

$$I_L = E \Big/ R_I \tag{4.4}$$

where I_L=leakage current in microamperes per 1000 feet

E=voltage between conductor and ground in volts

R_I=insulation resistance in megohms for 1000 feet

The total current is:

$$I_T=I_G+I_A+I_L \tag{4.5}$$

The voltage must be raised slowly and gradually because of the rapid rise of I_G and I_A with time. Also, since both of these values are a function of cable length, the longer the cable length, the slower the rise of voltage is allowable. Equation (4.5) demonstrates the reason for taking a reading of leakage current after a specified period of time so that the actual leakage current can be determined.

2.2 Dielectric Constant

Dielectric constant, relative permittivity and specific inductive capacitance all mean the same. They are the ratio of the absolute permittivity of a given dielectric material and the absolute permittivity of free space (vacuum). The symbol for permittivity is ε (epsilon). To put this in another way, these terms refer to the ratio of the capacitance of a given thickness of insulation to the capacitance of the same capacitor insulated with vacuum. (This is occasionally referred to as air rather than vacuum, but the actual dielectric constant of air is 1.0006). Since the calculations are usually not taken out to more than two decimal points, it is practical to use air for the comparison. The value of permittivity, dielectric constant, and SIC are expressed simply as a number since the dielectric constant of a vacuum is taken as 1.0000.

2.3 Dielectric Loss in Cable Insulation

The losses in the insulation of a cable may be calculated from the following equation:

$$W = 2\pi f \varepsilon C n e^2 F_p x 10^{-6} \tag{4.6}$$

where W=watts loss per foot of cable
ε=dielectric constant of the insulation
f=frequency in hertz
C=capacitance of the insulation per foot
n=number of conductors in the cable
e=voltage conductor to neutral in kilovolts
F_P=power factor of the insulation as a decimal

2.4 Cable Capacitance

The property of a cable system that permits the conductor to maintain a potential across the insulation is known as capacitance. Its value is dependent on the permittivity (dielectric constant) of the insulation and the diameters of the conductor and the insulation. A cable is a distributed capacitor. Capacitance is important in cable applications since charging current is proportional to the capacitance as well as to the system voltage and frequency. Since the charging current is also proportional to length, the required current will increase with cable length.

The capacitance of a single conductor cable having an overall grounded shield or immersed in water to provide a ground plane may be calculated from the following formula:

$$C = \frac{0.00736\varepsilon}{\log_{10}\frac{D}{d}} \tag{4.7}$$

where C=capacitance in microfarads per 1000 feet ε=permittivity of the insulating material. Permittivity (ε, epsilon), dielectric constant (K) and specific inductive capacitance (SIC) terms that are used interchangeably. The term permittivity is preferred. See Table 4-2.

D=diameter over the insulation (under the insulation shield)

d=diameter under the insulation (over the conductor shield)

Note: Both *D* and *d* must be expressed in the same units.

Table 4-2 Permittivity, Dielectric Constant, and SIC

Material	Range	Typical
Butyl Rubber	3.0–4.5	3.2
PVC	3.4–10	6.0
Varnished Cambric	4.0–6.0	5.0
Impregnated Paper	3.3–3.7	3.5
Rubber-GRS or Natural	2.7–7.0	3.5
HMWPE	2.1–2.6	2.2
XLPE or TR-XLPE	2.1–2.6	2.3
XLPE, filled	3.5–6.0	4.5
EPR	2.5–3.5	3.2
Silicone Rubber	2.9–6.0	4.0

In single conductor, low-voltage cables where there is no semiconducting layer over the conductor, a correction factor must be used to compensate for the irregularities of the stranded conductor surface as shown in Table 4-3. This measurement is based on having an insulation shield/sheath or a conducting surface over the insulation.

$$C = \frac{0.00736\varepsilon}{\log_{10}\frac{D}{kd}} \tag{4.8}$$

Table 4-3 Correction Factors for Irregularities

Number of Strands	Factor k
1 (solid)	1.0
7	0.94
19	0.97
37	0.98
61 & 91	0.985

2.5 Capacitive Reactance

The capacitive reactance of a cable is inversely dependent on the capacitance of the cable and the frequency at which it operates.

$$X_C = \frac{1}{2\pi f C} \tag{4.9}$$

where X_c=ohms per foot
f=frequency in hertz
C=capacitance in picofarads per foot

2.6 Charging Current For Alternating Current Operation

For a single conductor cable, the current may be calculated from the formula:

$$I_C = 2\pi f C E \times 10^{-3} \tag{4.10}$$

where I_C=charging current in milliamperes per 1000 feet
f=frequency in hertz
C=capacitance in picofarads per foot
E=voltage from conductor to neutral in kilovolts

Other leakage currents are also present, but the capacitive current has the largest magnitude. In addition to this, the capacitive charging current flows as long as the system is energized. The resistive component of the charging current is also dependent on the same factors as the capacitive current and is given by the formula:

$$I_R = 2\pi f C E \tan \delta \tag{4.11}$$

where I_R=resistive component of the charging current
$\tan \delta$=dissipation factor of the insulation

The tan δ of medium voltage insulation, such as cross-linked polyethylene and ethylene propylene, has values that are generally below 0.02 so the resistive component of the charging current is only a small fraction of the total charging current. The tan δ is sometimes referred to as the insulation power factor since at the small angles these values are approximately equal. Since the capacitive charging current is 90° out of phase with the resistive charging current, the total charging current is generally given as the capacitive component and leads any resistive current flowing in the circuit by 90°. The result of these ac currents generated put demands on power required for test equipment.

2.7 Cable Inductive Reactance

The inductive reactance of an electrical circuit is based on Faraday’s law. That law states that the induced voltage appearing in a circuit is proportional to the rate of change of the magnetic flux that links it. The inductance of an electrical circuit consisting of parallel conductors, such as a single-phase concentric neutral cable may be calculated from the following equation:

$$X_L=2\pi f(0.1404\ \log_{10} S/r+0.153)\times 10^{-3} \tag{4.12}$$

where X_L=ohms per 1,000 feet

S=distance from the center of the cable conductor to the center of the neutral

r=radius of the center conductor

S and r must be expressed in the same unit, such as inches.

The inductance of a multi-conductor cable mainly depends on the thickness of the insulation over the conductor.

2.7.1 Cable Inductive Reactance at Higher Frequencies.

Since the inductive reactance of an insulated conductor is directly proportional to frequency, the inductive reactance is substantially increased in higher frequency applications. Conductors must be kept as close together as possible. Due to the severe increase in inductive reactance at high frequency, many applications will require using two conductors per phase to reduce the inductive reactance to approximately one-half that of using one conductor per phase. A six-conductor installation should have the same phase conductors 180° apart.

2.8 Mutual Inductance In Cables

In single-conductor shielded or metallic-sheathed cables, current in the conductor will cause a voltage to be produced in the shield or sheath. If the shield or sheath forms part of a closed circuit, a current will flow. (Shield and sheath losses are described under Ampacity in Chapter 13).

The approximate mutual inductance between shields or sheaths is given by the following relation:

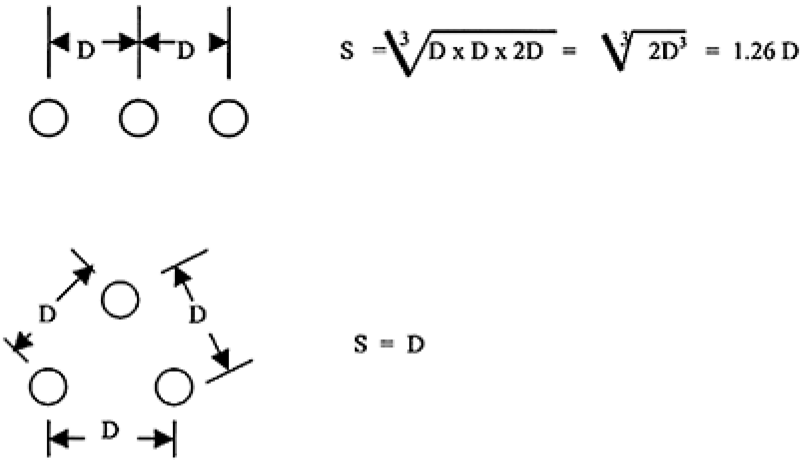
$$L_m=0.14.4\ \log_{10} S/r_m\times 10^{-3} \tag{4.13}$$

where L_m=henries to neutral per 1,000 feet

S=geometric mean spacing between cable centerlines in inches

r_m=mean shield or sheath radius in inches. See Fig. 4-2.

Figure 4-2 Geometric spacing.



2.9 Cable Conductor Impedance

Conductor impedance of a cable may be calculated from the following equation:

$$Z=R_{ac}+jX_L \tag{4.14}$$

where Z = conductor impedance in ohms per 1,000 feet

R_{ac}=ac resistance in ohms per 1,000 feet

X_L=conductor reactance in ohms per 1,000 feet

Conductor impedance becomes an important factor when calculating voltage drop. Since the power factor angle of the load and impedance angle are usually different, the voltage drop calculation can be cumbersome. The following voltage drop equation can be used for a close approximation:

$$V_D=R_{ac}\,I\cos\theta+X_L\,I\sin\theta \tag{4.15}$$

where V_D=voltage drop from phase to neutral in volts

R_{ac}=ac resistance of the length of cable in ohms

$\cos\theta$=power factor of the load

X_L=inductive reactance of the length of cable in ohms

2.10 Total Cable Reactance

The total cable reactance (X) is the vector sum of the capacitive reactance and the inductive reactance of the cable in ohms per foot.

$$X=X_C+X_L \tag{4.16}$$

2.11 Cable Dissipation Factor

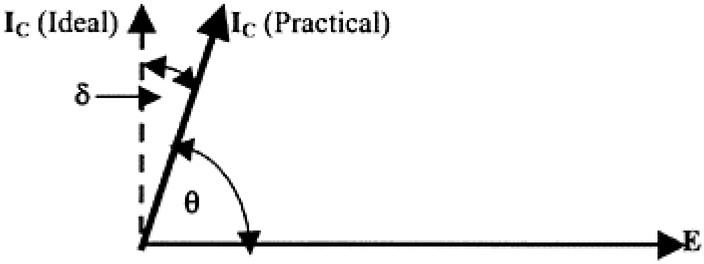
In cable engineering, the small amount of power consumed in the insulation (dielectric absorption) is due to losses. These losses are quite small in medium voltage cables, but can become more significant in systems operating above 25 kV. No insulating material is perfect.

In addition to the charging current flowing through the capacitive portion of the circuit, current also flows though the ac resistance portion of the circuit. This is the ac loss portion of the insulation circuit. The ratio of the ac resistance of the insulation to the capacitive reactance of the insulation is called the dissipation factor. This is equal to the tangent of the dissipation angle that is usually called tan δ This tan δ is approximately equal to the power factor of the insulation which is the cos θ of the complimentary angle.

In practical cable insulations and at 50 to 60 hertz, high insulation resistance and a comparatively large amount of capacitive reactance is present. There is virtually no inductive reactance. Hence the current leads the voltage by almost 90°. Since the cosine of 90° is zero, the cosine of an angle approaching 90° is small and the dissipation factor (often referred to as power factor of the insulation) also is small. Typical values for insulation power factor are 0.005 to 0.02 or slightly higher for other materials.

Dissipation factor is used in cable engineering to determine the dielectric loss in the insulation, expressed as watts per foot of cable that is dissipated as heat. It is also used to some extent to describe the efficiency or perfection of the insulation as a dielectric. Hence the term δ (delta) was chosen to represent the defect angle of the material.

Figure 4-3 Cable insulation power factor or dissipation factor (not to scale!).



Note: Tan δ is approximately equal to cos θ for the small angles involved.

The power dissipation per phase (dielectric loss, W_d) is a function of the voltage and the in-phase component of the current.

$$W_d = E_O I_C \tan \delta \ W/foot \tag{4.17}$$

The insulation parameters that determine the dielectric loss of a cable are the dielectric constant (permittivity, ε) and the dissipation factor (tan δ). The product of the permittivity and the dissipation factor is the dielectric loss factor (DLF). The lower the DLF, the better the insulation.

2.12 Insulation Parameters

2.12.1 Voltage Stress in Cables.

Voltage stress in shielded cable insulations with smooth, round conductors is defined as the electrical stress or voltage to which a unit thickness of insulation is subjected. The average stress in volts per mil is determined by dividing the voltage across the insulation by the insulation thickness in mils.

$$S_{avg}=2V/(D-d) \qquad (4.18)$$

where S_{avg}=average stress in volts per mil

V=voltage across the insulation

D=outside diameter of the insulation in mils

d=inside diameter of the insulation in mils

The stress is not uniform throughout the wall. The stress at any point in insulation wall can be calculated by the formula:

$$S=V/2.303\, r \log_{10}(D/d) \qquad (4.19)$$

where S=stress in volts per mil at a point in the insulation r mils from the cylindrical axis.

The maximum stress occurs at the surface of the conductor shield.

$$S_{max}=0.868V/d \log_{10}(D/d) \qquad (4.20)$$

where the terms and units are the same as in (4.16, 4.17 and 4.18).

2.12.2 Dielectric Strength.

Although maximum and average stresses are important, dielectric strength is usually specified as the average stress at electrical breakdown. The dielectric strength of a material depends on the dimensions and the testing conditions, particularly the time duration of the test. A thin wall of material generally withstands a higher average stress before breaking down than a thicker wall.

2.12.2.1 ac Dielectric Strength.

These measurements are made in two ways:

Quick-rise or
Step-rise.

In the quick-rise method, the voltage applied to the insulation is raised at a uniform rate until the insulation breaks down. As an example, a rate of rise of 500 volts per second is known as “quick-rise.”

In the “step-rise” method, the voltage is raised to a predetermined level and held at that level for an amount of time, such as five or ten minutes at each level, until breakdown occurs. A relatively short time, say the five or ten minutes described above, has the advantage of reaching breakdown in a shorter amount of total test time. In the real world, the time at a voltage level is much longer, so some cable engineers prefer a longer step time such as 30 minutes or one hour at each step. With the longer step times, the breakdown voltage is lower than with the quickrise or short step time methods.

2.12.2.2 Impulse Strength.

Because cable insulation is frequently subjected to lightning or switching surges, it is often desirable to know the impulse strength of the cable. Surges of “standard” wave shape, such as eight seconds to reach 90% of crest value, and 40 microseconds to drop to one-half of crest value, are frequently used in the laboratory. The increasing voltages are applied to the insulation with several surges at a negative potential and then, at the same voltage level, the same number of surges is applied with positive pulses. The average stress in volts per mil is calculated from the crest voltage of the surge on which breakdown occurs.

3.0 REVIEW OF ELECTRICAL ENGINEERING TERMS

These terms apply to all electrical engineering circuits. The actual application of these terms to cables is covered in section 2.0 of this chapter. The more important equations are:

$$E=IR \tag{4.21}$$

$$Q=It \tag{4.22}$$

$$E=-L\,dI/dt \tag{4.23}$$

$$Q=CE \tag{4.24}$$

$$P=EI=I^2R \tag{4.25}$$

$$W=EIt \tag{4.26}$$

where E=electromotive force in volts
I=current in amperes
R=resistance in ohms
Q=quantity in ohms

L=inductance in henries
C=capacitance in farads
P=power in watts
W=energy in joules
t=time in seconds

3.1 Resistance

(R) is the scalar property of an electric circuit that determines, for a given current, the rate at which electric energy is converted into heat or radiant energy. Its value is such that the product of the resistance and the square of the current gives the rate of conversion of energy.

In a direct-current circuit,

$$R = \frac{E}{I} \tag{4.27}$$

and

$$P=I^2R \tag{4.28}$$

where R=resistance in ohms
E=electromotive force in volts
I=current in amperes
P=power in watts

3.2 Conductance

(G) is the property of an electric circuit that determines, for a given electromotive force in the circuit or for a given potential difference between the terminals of a part of a circuit, the rate at which energy is converted into heat or radiant energy. This value is such that the product of the conductance and the square of the electromotive force, or potential difference, that gives the rate of conversion of energy.

$$P=E^2G \tag{4.29}$$

where P=power in watts
E=voltage, phase to ground, in kilovolts
G=conductance in mhos

The unit of conductance is the mho. Conductance is the reciprocal of resistance.

$$G = \frac{1}{R} \tag{4.30}$$

where G=conductance in mhos
R=resistance in ohms

3.3 Conductivity

Conductivity (γ) of a material is the direct-current conductance between the opposite parallel faces of a portion of the material having unit length and unit cross-section. It is the reciprocal of resistivity.

$$G = \frac{\gamma\alpha}{l} \tag{4.31}$$

where *G*=conductance
α=area
l=length

3.4 Volume Resistivity

Volume resistivity of a material is the reciprocal of conductivity. The unit for volume resistivity is ρ (rho). It is the resistance of a section of material of unit length and unit cross-section.

$$R = \frac{\rho l}{a} \tag{4.32}$$

where *R*=resistance in ohms
ρ=rho, volume resistivity
a=area
l=length

3.5 Inductance

Unit *L* represents the scalar property of an electric circuit, or two neighboring circuits, which determines the electromotive force induced in one of the circuits by a change of current in either of them.

3.5.1. Self-Inductance.

This is the property of an electric circuit that determines, for a given rate of change of current in the circuit, the electromotive force induced in the same circuit.

The unit of inductance is one henry. One henry is the self-inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current traversing the circuit varies uniformly at the rate of one ampere per second.

$$e_1 = -L\frac{d\,i_1}{d\,l} \tag{4.33}$$

where e_1 and i_1 are in the same circuit and L is the coefficient of self-inductance.

3.5.2. Mutual Inductance.

(L_m) is the common property of two associated electric circuits that determines, for a given rate of change of current in one of the circuits, the electromotive force induced in the other.

3.6 Inductance In Cables

3.6.1

Inductance in multi-conductor cables is the same as any other arrangement of conductors and follows the following equation:

$$L = 0.1404 \log_{10} \frac{GMD}{GMR} \; x \; 10^{-3} \qquad (4.34)$$

where GMD=geometric mean distance between conductors in inches
GMR=geometric radius of conductors in inches

3.6.2 Mutual Inductance in Cables

In single conductor, metallic covered cables, current flowing in the conductor will produce an electromotive force in the sheath. If by any means the sheath forms a closed circuit, current will flow in the sheath following the equation:

$$L_m = 0.1404 \log_{10} \frac{GMD}{r_m} \; x \; 10^{-3} \qquad (4.35)$$

where L_m=henries to neutral per 1,000 feet
r_m=mean sheath radius in inches

3.6.3 Inductance in Coaxial Cables

In coaxial cables, three kinds of inductance must be taken into account: space inductance, inductance within the inner conductor, and inductance within the outer conductor. Above 50 kilohertz, only space inductance needs to be considered for results with less than 0.5 percent error. The equation for a coaxial cable with a tubular outer conductor becomes:

$$L_f = 4.6 \; \log_{10} \frac{r_2}{r_1} \; x \; 10^{-9} \qquad (4.36)$$

where L_f=inductance in henries per centimeter
r_2=inner radius of outer conductor in inches
r_1=radius of inner conductor in inches

If the outer conductor is stranded or braided, the inductance is slightly higher.

3.7 Capacitance

This is the property of an electric system comprising insulated conductors and associated dielectric materials which determines, for a given time rate of change of potential difference between the conductors, the displacement currents in the system.

The unit of capacitance is the farad and it is that capacitance of a circuit whose potential difference will be raised one volt by the addition of a charge of one coulomb.

3.7.1 Capacitance of a Cable.

The electrostatic capacitance of an insulated conductor one centimeter in length, in absolute units, is:

$$C = \frac{\varepsilon}{2 \log_e \frac{D}{d}} \qquad (4.37)$$

where C=capacitance

ε=dielectric constant of the insulating material

D=outer diameter of the insulation

d=inside diameter of the insulation

In more common terms, the equation is:

$$C = \frac{7.354\ \varepsilon}{\log_{10}\ 1 + \frac{2t}{d}} \qquad (4.38)$$

3.8 Reactance

Reactance is the product of the sine of the angular phase difference between the current and potential difference times the ratio of the effective potential difference to the effective current because there is no source of power in the portion of the circuit under consideration. The total reactance of a circuit is the sum of the inductive and capacitive reactance.

3.8.1 Inductive reactance is calculated from:

$$X_L = 2\pi f L \qquad (4.39)$$

where X_L=inductive reactance in ohms/foot to neutral

f=frequency in hertz

L=inductance in henries/foot

and

$$X_L = 0.05292 \log_{10} \frac{GMD}{GMR} \qquad (4.40)$$

3.8.2

Capacitive reactance is calculated from:

$$X_C = -\frac{1}{2\pi f C} \tag{4.41}$$

where X_C=capacitive reactance in ohms/foot
C=capacitance in picofarads/foot

3.8.3

The total reactance of a circuit is the sum of the inductive and capacitive reactances:

$$X = 2\pi f L + \left(-\frac{1}{2\pi f C}\right) = X_L + X_C \tag{4.42}$$

3.9 Impedance

Impedance is the ratio of the effective value of the potential difference between the terminals to the effective value of the current, there being no source of power in the portion of the circuit under consideration.

$$Z = \frac{E}{I} = \sqrt{R^2 + X^2} \tag{4.43}$$

3.10 Admittance

(Y) is the reciprocal of impedance.

3.11 Power Factor in Power Engineering

Power factor, as used in power engineering, is not the same as “power factor” as used in cable engineering. In power engineering, power factor is the ratio of active power to apparent power. Apparent power *(S)* consists of two components; active (in-phase) power P_a, that does useful work and reactive (out-of-phase) power P_r,. Their geometric sum is the apparent power. Power factor is given by the equation:

$$F_P=P_a/S \tag{4.44}$$

In power engineering, power factor is used, among other things, to determine the amount of useful work. In a motor, for example, resistance and a comparatively large amount of inductive reactance are present so that the current lags behind the voltage. If the power factor was 1.00 (unity), and no reactance was present, then every 10 kVA delivered to the motor (neglecting losses) all the current would be in phase with the voltage and 10 kW would be applied as useful work. With a reactance present and a power factor of, say

0.80, with only part of the current (8/10) is in phase with the voltage and only 8 kW would be delivered to the motor. The out-of-phase component of current increases the total current and results in increased heat loss.

Power factor may also be described as a measure of the relationship in time phase between current and voltage in any alternating current circuit. Practically all alternating current circuits contain resistance, inductive reactance, and capacitive reactance. These characteristics determine how much the current leads of lags behind the voltage as to time during each cycle. This is usually expressed in degrees by the use of a vector diagram. The angle between them indicates the amount of lead or lag. The cosine of that angle is called the power factor of that circuit. With only capacitive reactance, the current leads the voltage by 90 degrees; with only inductive reactance, the current lags behind the voltage by 90 degrees.

4.0 STRENGTH OF PIPES

For lead pipe (sheath) and copper pipe and tubing, an adequate result may be obtained by using the following formulas.

The "common" formula for lead pipe is:

$$f=1/2\ D_2\, p/t \tag{4.45}$$

where f=working stress in pounds per square inch

D_2=inside diameter of tube in inches

p=internal pressure in pounds per square inch

t=average wall thickness in inches

The value of f is obtained by assuming a safety factor based on ultimate strength. Values of f for lead sheathing are commonly used as:

Copper bearing lead	125 pounds per square inch
Arsenical lead	250 pounds per square inch

Values for other metals are:

Kind of Tube or Pipe	**Ultimate Strength in psi**
Deoxidized copper, hard	45,000
Deoxidized copper, soft	35,000
Arsenical copper, hard	45,000
Arsenical copper, soft	35,000
Electrolytic copper, hard	45,000
Steel pipe, butt-welded	40,000
Steel pipe, lap-welded	50,000
Seamless steel tube	60,000

Wrought iron pipe	28,000

5.0 REFERENCE

[4-1] Association of Edison Illuminating Companies, Specification CS8–00, 1st Ed., AEIC, P O Box 2641, 2000, Birmingham, AL, 35291–0992, USA.

CHAPTER 5
ELECTRICAL INSULATION MATERIALS

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1.0 INTRODUCTION

Electrical insulation materials are utilized to provide electrical isolation over the metallic conductors of underground cables. The insulating materials physically protect the conductor and provide a margin of safety. These materials are comprised of either synthetic or natural polymers. The polymeric insulation material selected for use may vary with the voltage class of the cable. Compatible polymeric shields are employed between the insulation and the conductor, and over the insulation to grade the voltage stress; these are comprised of flexible polymers blended with conducting carbon black that imparts the semiconducting characteristics.

Until the early 1990s, transmission class cables, defined as cables operating above 46 kV, had traditionally employed oil-impregnated paper as the insulation. This paper insulation is applied as thin layers wound over the cable core, and is later impregnated with a dielectric fluid. As the application of synthetic polymers to cable technology matured, extruded polyethylene (PE) that has been subjected to cross-linking (XLPE) gradually displaced paper as the insulation material of choice for transmission voltages up to 230 kV; XLPE is the prime extruded material used for transmission cables. XLPE is considered to be the material of choice due to its ease of processing and handling, although paper/oil systems have a much longer history of usage and much more information on reliability exists. As a result of the higher stresses associated with transmission class cables (as compared to distribution cables) extreme care and cleanliness in handling materials and during manufacturing is required. In the 1980s, a variation on paper as insulation was developed, the material being a laminate of paper and polypropylene (PPP or PPLP); this material has been employed for voltages above 230 kV.

For distribution voltage class cables (mostly 15 to 35 kV), the prime extruded material developed for use in the 1960s was conventional PE (high molecular weight polyethylene or HMWPE). However, this was replaced by XLPE as the material of choice during the late 1970s to early 1980s, as a result of unanticipated early failures in service due to the water-treeing problem (see Chapter 17). Installed PE-insulated cables are gradually being replaced (or rejuvenated in-situ for stranded constructions; see Section 4.4.1). Elastomeric ethylene-propylene co- or ter-polymers have also been used (EPR or EPDM, respectively) for medium voltage cable insulation. The term EPR (or EP) has been used to generically describe both EPR and EPDM-insulated cables and that terminology will be applied here. EPR cables have been available since the 1960s, but their use had been consistently less common as compared to HMWPE or XLPE, due to higher costs and operating losses. EPR usage started to increase in the 1970s to 1980s partly due to easier processing as a result of modification of the EPR compound to facilitate easier extrusion (hence reducing the cost). In contrast to XLPE which is a semi-crystalline polymer, EPR is an elastomer (rubber) and therefore requires the incorporation of inorganic mineral fillers in order to serve as a satisfactory functional insulation; this in turn leads to additional handling and processing requirements by materials suppliers.

Starting in the mid 1980s, XLPE has been gradually replaced by ‘tree resistant’ XLPE (TR-XLPE) as the material of choice for new distribution class cables. From the early 1980s and well into the late 1990s, a single grade of TR-XLPE was employed commercially in the North America. More recently several other grades of TR-XLPE have become available.

Although many of the older insulated cables manufactured with HMWPE, EPR, and XLPE insulations are presently still in service on many Utility systems, the insulation choices for new cables today are considered to be TR-XLPE and EPR. It should be noted here that all EPRs are not alike. All these materials will be discussed in greater detail later in this Chapter.

Paper-insulated-lead-covered (PILC) cables have been employed at distribution voltages since the early 20th century; many of these cables are also still in service, even after 60–70 (or more) years. They are highly reliable (partly due to presence of an outer lead sheath), which makes them a construction of choice for many urban locations. Although this construction is slowly being replaced by extruded cables, some utilities still prefer to employ new PILC in specific locations, particularly where existing duct size and space are limited.

Paper-insulated cables were historically one of the first types of polymer used since paper was, and is, readily available from natural sources. The special insulation paper is derived from wood pulp and is a natural polymer based on cellulose. In use, the paper is impregnated with a dielectric fluid (a synthetic oil, which is a low molecular weight hydrocarbon) so the practical insulation is actually a two-phase composition. Paper insulation is discussed in more detail in Section 8 of this chapter.

At lower operating voltages (5–15 kV), the possible choice of polymeric materials widens. Here it is possible to use polyvinyl chloride (PVC), silicone rubber (SIR), or other polymers that are readily available and easily processed. PVC was used for a time in Europe for medium voltage cables in the 10–20 kV class, but that practice has been largely discontinued. PVC is actually a tough, rigid polymer, and requires a softening agent (plasticizer) to increase flexibility and render it useful for wire and cable applications.

Before the 1960s, butyl rubber was commonly employed for distribution cables, but was eventually replaced by more modern EPR insulations. Virtually all of this installed cable has been replaced at medium voltages.

Each insulation type has certain advantages and disadvantages. An overview is provided below:

INSULATION TYPE	**KEY PROPERTY INFORMATION**
PE (Low-density polyethylene)	Low dielectric losses
	Moisture sensitive under voltage stress
XLPE (Cross-linked polyethylene)	Slightly higher dielectric losses than PE
	Ages better than PE; less moisture sensitive
EP (EPR/EPDM)	Higher dielectric losses vs. XLPE or TRXLPE
	More flexible, less moisture sensitive than XLPE or PE
	Requires inorganic filler
TR-XLPE	Similar to XLPE, but slightly more lossy
	Due to additives; losses less than for EPR.
	Ages ‘better’ than XLPE; less moisture sensitive
PILC	High reliability
	Possesses lead sheath
PVC	Must contain a plasticizer for flexibility
	Higher dielectric losses
	Does not burn but yields toxic gases

Polymers such as polyethylene, polypropylene (used as jacket material), and ethylene propylene co- and ter-polymers are hydrocarbon polymers, and are known as polyolefins. Polyethylene and polypropylene are known as homo-polymers; EPR is known as a copolymer, meaning that it is comprised of two different polymers in the chemical structure.

Polyolefins, developed shortly after World War II, have been a preferred insulation because of their generally overall superior properties:

□ Excellent electrical properties

  – Low dielectric constant
  – Low power factor
  – High dielectric strength

□ Excellent moisture resistance
□ Extremely low moisture vapor transmission
□ High resistance to chemicals and solvents
□ Ease of processing and extrusion

The dielectric losses of polyolefins are superior to those of paper/oil insulation systems and the polymers are considerably more moisture resistant than paper. A moisture resistant sheath has always been incorporated into paper cable designs.

In addition to use as primary insulation, polymers are employed as components of conductor and insulation shields. These materials are ethylene copolymers that possess quantities of carbon black (and sometimes other ingredients) to provide the semiconducting properties required for shields. The co-polymer itself can be viewed as a "carrier", but this carrier must possess the property of controlled adhesion to the insulation. It is the use of a conducting material dispersed throughout the polymer matrix that makes the mixture semi-conducting in nature; hence the term "semiconducting" is applied to shield materials.

Almost all present extruded cable constructions are covered by an outer extruded jacket. Jackets are of two types: insulating and semiconducting. They are commonly comprised of one of several polyethylene types and also contain small quantities of carbon black; insulating jackets contain a different type of carbon black compared to that used in semi-conducting shields, and it is present in much smaller quantities. The purpose of the jacket is to reduce moisture ingress, protect the cable mechanically (e.g., during installation) and provide resistance to sunlight and ultra-violet light. For semiconducting jackets, as might be expected, the carbon black used is similar to that used in shields.

Polymeric jackets are discussed in Section 9. As noted earlier, the covering use for paper/oil cables is a lead sheath.

This chapter will focus on:

(a) Properties of polyethylene, cross-linked polyethylene and tree-retardant cross-linked polyethylene from a fundamental perspective. Fundamental issues of branching, crystallinity and cross-linking are reviewed

(b) Properties of EPR and how it differs from PE, XLPE and TR-XLPE.

(c) Methodologies for inducing cross-linking of the polyolefins and the reasons for other additives; review of some practical applications relative to silicone impregnation.

(d) Introduction to manufacturing processes for polyolefins

(d) Fundamentals of cellulosic insulation and how it differs from polyolefins.

(e) Review of extruded shield and jacket technology.

The fundamental properties to be focused on here are important to understand, as they influence and control insulation and cable behavior. The properties that the electrical insulations possess and display are related to their physico-chemical structure. By understanding aspects of the chemical structure described herein, we will be defining the properties. In essence we will be providing an overview of 'structure-property relationships'.

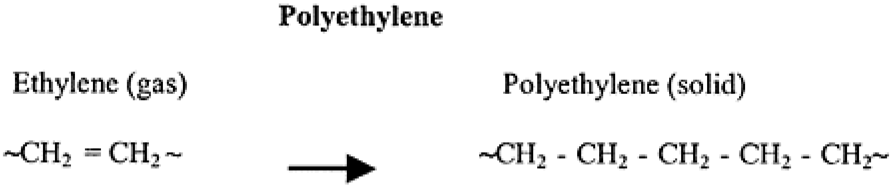
2.0 FUNDAMENTALS OF EXTRUDED POLYMERS EMPLOYED AS ELECTRICAL INSULATION

Although use of polyethylene itself as an insulation for new medium voltage cables has been essentially discontinued, the properties of this polymer will be reviewed first (as a ‘model’) as it is a homo-polymer, which makes it the base material for other cable insulations of interest. Once the basics of PE are described, it will be easier to understand the properties of EP and TR-XLPE. The chemical structure as it relates to molecular weight and chain branching will be reviewed, followed by the subjects of crystallinity and cross-linking of polyethylene. This in turn will lead to a discussion of the properties of cross-linked polyethylene. Some aspects of polyethylene manufacture will also be discussed. With this as background, the discussion will be followed by the properties of co-polymers of ethylene such as EPR, and why fillers are required. Finally, semiconducting shields and then jackets will be discussed.

2.1 Polyethylene (PE)

Polyethylene is a hydrocarbon polymer comprised exclusively of carbon and hydrogen. It is manufactured from the monomer ethylene (in turn, derived from the cracking of petroleum), as shown in Figure 5-1. Note that the chemical structure is a series of repeating -CH_2- units.

Figure 5-1 Fundamentals.



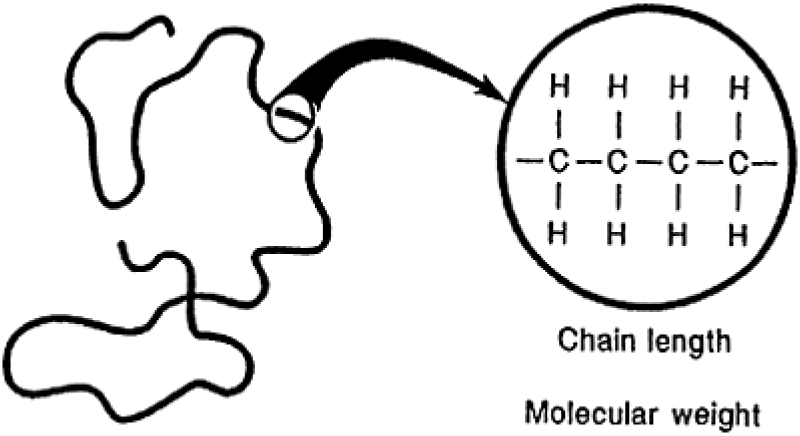
Polyethylene falls into the class of polymers known as polyolefins (polypropylene is another example). Key properties of interest relate to molecular weight, molecular weight distribution, branching, cross-linking, and crystallinity. Each will be reviewed in turn.

Polyethylene is produced by one of several processes that are summarized in Section 3.1. Manufacturing details are beyond the scope of this book. It is necessary to note, however, that the method of manufacture of the polyethylene controls whether it is ‘high density’, ‘medium density’, ‘low density’ or ‘linear low density’, terms commonly employed in the cable industry. Density is a measure of crystallinity, (discussed later in this Chapter), and is a factor that determines what makes the specific polyethylene type applicable as an insulation, semiconducting material or jacket material. Hence, the method of polyethylene manufacture controls the exact chemical structure, which in turn controls the properties.

The carbon-hydrogen structure noted above is simplified; the chemical structure of polyethylene is actually more complex than is shown here (as might be deduced from the number of key subjects noted above). For example, there are branches' hanging' off the main chains as appendages (like 'Ts'), and in addition there is always a very small amount of oxidation product (carbon-oxygen bonds) that form during the extrusion process. This is considered minor, and is not of any practical significance, as noted by the outstanding electrical properties.

For simplicity, we will depict the polymer as a wavy line as shown below in Figure 5-2.

Figure 5-2 Depiction of polyethylene chemical structure.



The wavy line is referred to as a "chain" and the length of the chain is considered significant. The chain length as depicted here is related to the molecular weight. A longer chain of polyethylene has a higher molecular weight than a shorter chain. Molecular weight increases as the number of ethylene groups in the molecule increases. Conventional polyethylene is comprised of numerous chains of this type, and the chain lengths of individual molecules vary considerably. Hence, in reality, polyethylene is comprised of polymer chains that have a distribution of molecular weights (chain lengths). Indeed, the molecular weight distribution is a means of characterizing the polyethylene. For the polyethylene insulation employed as insulation for medium voltage cables in the past, the polymeric material was described as "high molecular weight polyethylene", or HMWPE. This merely means that the "average" chain length is considered to be 'high'. Another generalization is that the higher the molecular weight, the better the overall properties. Since typical polyethylenes that have been employed for electrical insulation contain a variety of individual chains of different lengths (i.e., weights), it is easy to see that there can be a large number of commercially available grades of PE, all varying in 'average' molecular weight (and branching).

The average molecular weight can be described in several ways. The terms employed most often are "weight average" and "number average" molecular weight. These values arise from different mathematical methods of averaging the molecular weights in polymer samples possessing molecules of different sizes. The mathematical definitions of the number and weight averages are related to the smaller and larger sized molecules, respectively. Hence, the weight average molecule weight is always greater than the number average. When the polymer insulation is cross-linked (see below), the molecular weight determination becomes more complex since the cross-linked fraction can be considered to have an “infinite” molecular weight. From the perspective of the cable engineer, what is relevant to understand is that there is no single way of characterizing the polymer molecular weight. However, the higher molecular weight (average, of course) provides better overall properties in application.

2.2 Branching

As noted above, the polymer chains are not always as linear as shown in the Figures. When polyethylene is manufactured, the process always leads to side chains ‘hanging’ off the long main chain. This is called chain branching; these branches contribute to increasing the molecular weight, but do not necessarily always cause an increase in the chain length. Branches are shown in Figure 5-3; note that the chain length of the branches can also vary, and that there are both long chain-length branches and short chain-length branches. The length and distribution on the branches affects physical properties, and also influences the ability to satisfactorily extrude the polyethylene. Branching also affects the ability of the polyethylene to crystallize (see below). However, branching does not have a major influence on the electrical properties, such as dielectric losses.

It is possible to now visualize that two single molecules may have the same exact molecular weight, but one may have a longer main chain with few branches, and the other a shorter main chain with a longer branches than the first. Therefore, two different polyethylene material batches having many molecules like the two described here (if it were possible to manufacture these) could have different properties, despite having approximately the same molecular weight distributions.

A third key point to note about the polyethylene chains is that they are not ‘straight’ as shown in the circle in Figure 5-2. The polymer chains have a tendency to coil. In other words, they have a tendency to achieve a random configuration (like a bowl of spaghetti) as shown in Figure 5-4. This tendency is independent of the molecular weight, but the configuration that results is influenced by the branching.

Figure 5-3 Structure of polyethylenes depicting branches.

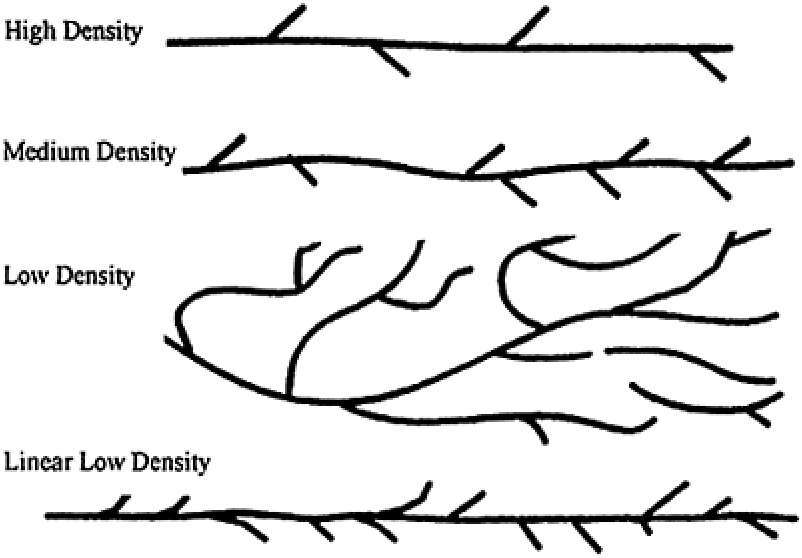
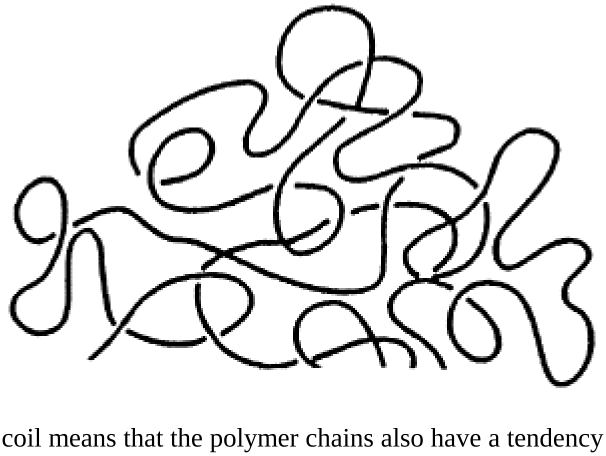


Figure 5-4 Simplified description of random coiled configuration.

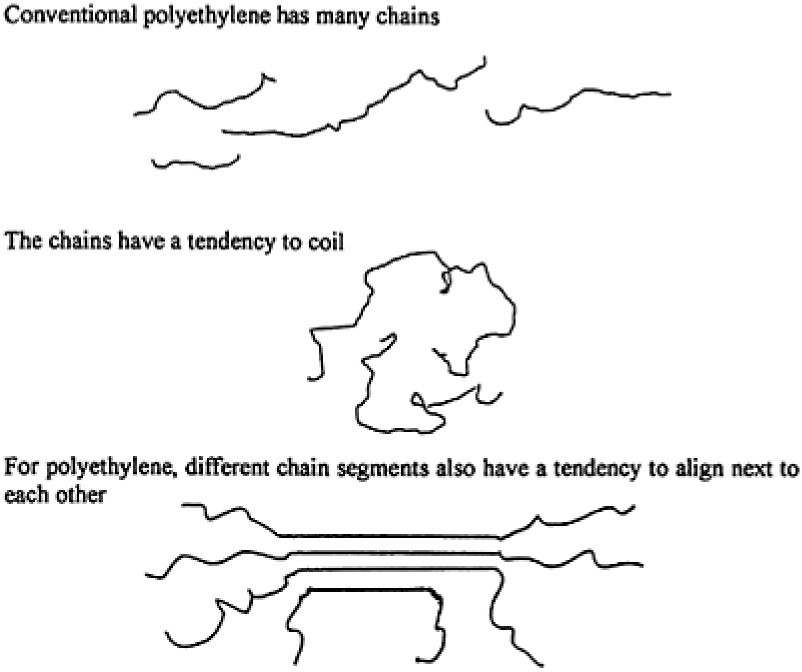


The tendency to coil means that the polymer chains also have a tendency to entangle with each other. These entanglements mean that when the chains are pulled apart (as occurs in performing a tensile strength or elongation measurement), there will be some 'resistance' to movement. Such chain entanglements influence the mechanical properties of the polymer. These entanglements contribute to the good properties of PE, but not to the qualities that make PE resistant to the penetration of water vapor. Entanglements do not have a major influence on electrical properties.

2.3 Crystallinity and Chain Motion

Molecular weight, or molecular weight distribution measurement, represent one way of describing the characteristics of polyethylene insulation; it is not the only way. Another very important characteristic is crystallinity. Polyethylene and some other polyolefins (polypropylene being an example) are known as semicrystalline polymers. This characteristic results from the fact that the polymer chains not only have a tendency to coil (as described above), but also have a tendency to align themselves relative to each other. Alignment means that there is short and long term order to the chain structure. While the nature of these alignments is quite complex, and the detailed structure is beyond the scope of this chapter, it is important to understand that the alignment contributes to the crystalline nature of the polyethylene, and therefore to the density and ultimately to properties, such as stiffness.

Figure 5-5 Chain configurations.



The aligned portions cannot coil. The portions that are not aligned will coil. The chain portions that are aligned are said to be “crystalline.” The chain portions not aligned are described as “amorphous.”

The lower portion of Figure 5-5 shows chain alignment where the polymer chain lengths differ. Some portions of the same chains align with adjacent chains, and some portions of the very same chains are not aligned. Those chain portions where alignment occurs are in regions called “crystalline.” Figure 5-5 shows that such alignment is not necessarily related to molecular weight. It is theoretically possible to have low or high molecular weight polyethylene of the same, or different, degrees of alignment.

Hence, in principle, it is possible to have several different types of polyethylenes:

□ High density, high molecular weight
□ High density, low molecular weight
□ Low density, high molecular weight
□ Low density, low molecular weight

Not all these types are of practical interest for cable (or other) applications. It is the crystalline regions that give polyethylene many good properties such as toughness, high modulus, and moisture and gas permeation resistance. Those regions that are aligned also have increased density due to “tighter” chain packing. Hence, increased crystallinity also means higher density. The alignment process means less “free” (amorphous) regions in the polymer and more polymer per unit volume. The amorphous regions increase the ductility, flexibility, and also facilitate processing.

In a sense, polyethylene can be visualized as being a ‘blend” of two materials, even though the chemical structure is comprised solely of -CH2- groups. The ‘two materials’ are the crystalline and amorphous regions.

As might be surmised, branching (as described above) influences the ability of the polyethylene chains to align. Both long chain branches and short chain branches hinder the ability of the polyethylene main chain backbone components to crystallize (but not equally). Branching, therefore, due to the ‘bulky’ nature of the chemical structure of the polymer chains, influences the crystallization process. For crystallinity to occur, non-branched regions must be able to approach each other closely. When branching is present, the ability of the main chain to come in close proximity to another main chain is hindered. Polyethylenes have historically been classified into four main categories due to this phenomenon (see Figure 5-3):

□ Low density
□ Medium density
□ High density
□ Linear low density

As the density increases, the degree of chain alignment increases and the “volume” of aligned chains increases. As noted above, the degree of branching is related to the polymerization process. It is affected since branching influences crystallinity. Crystallinity is minimally affected, if at all, by the conversion of polymer pellets as they are transformed into cable insulation.

Some further background on the nature of the crystalline and amorphous regions is of value. The nature of the crystallinity in PE has been the subject of numerous studies over the years. These studies have revealed an extremely complex relationship. Crystallites, or crystalline regions of the PE, can themselves fold (like a series of connected upright and upside-down ‘U’s), and they, in turn, align into larger structures called spherulites (which can be readily seen in high density PE under polarizing light). The size of these spherulites may vary, as can the fold dimensions of the crystallites. The folded regions are referred to as lamellae. While all these structures ‘disappear’ on melting (and reform in a qualitatively similar manner upon subsequent cooling), it is known that upon annealing below the melting temperature range, changes in the lamellae thickness occurs. It is also known that there may be numerous crystallites in a spherulite; it is possible for one polymer chain within a crystallite to cross through the amorphous region into another crystallite, becoming what is called a ‘tie molecule’. The latter are considered to influence mechanical properties.

The motion of the polymer chains in the amorphous regions has also been studied as a function of temperature below the melting region. The observed random motion of the PE chains in the amorphous regions has been divided into three varieties, traditionally referred to as alpha, beta and gamma. The first is believed due to crystallite chain twisting between amorphous phases; the second is related to chain motion at the boundaries of the crystalline/amorphous interface, and the third is believed due to motion of chains of specific lengths. This is an area of ongoing studies.

These details of the fine molecular structure are noted here to emphasize just how complex is the nature of seemingly simple polyethylene molecules (XLPE, TR-XLPE and EP are even more complex). Polyethylene’s ‘simple’ -CH2-repeating unit is far from the entire story relating to structure and properties.

2.4 Copolymers

Copolymers are insulation materials that are manufactured by incorporating more than one monomer into the polymerization process (See Section 3). Ethylene monomer is a gas. When ethylene is polymerized alone, one manufactures solid polyethylene. If a gaseous propylene monomer is mixed with the ethylene prior to polymerization, one obtains ethylene-propylene copolymer(s)—hence EPR. What should be apparent is that the ratio of ethylene to propylene employed in the polymerization process should influence the ethylene to propylene ratio in the ultimate EPR insulation material. It should be possible to manufacture a wide variety of EPR copolymers each with different ethylene to propylene (E/P) ratios, and indeed this is so. However, not all ethylene to propylene ratios are suitable as insulation materials; an E/P ratio of 50–70% may be typical for different insulations. This ratio also influences the method used to extrude the polymer as cable insulation.

Copolymerization, as described here, is different from mixing polyethylene and polypropylene after manufacture of the homopolymers. In the latter case, one does not have a copolymer, but a blend, with entirely different properties. Indeed, polymer blends are often incompatible, and phase separation of the different polymers can occur; that does not happen with true copolymers.

The same principles that apply to ethylene copolymers with propylene also apply to other monomers such as vinyl acetate or ethyl acrylate. These latter copolymers (E-VA or E-EA) are employed in shield compounds. As with PE or EP, the chain lengths may vary, and their lengths influence properties. The relative amounts of the second (co-polymerized) monomer must also be taken into consideration when evaluating properties.

3.0 MANUFACTURE OF POLYETHYLENE

3.1 Conventional Manufacturing Methods

Historically, low and medium density polyethylenes have been manufactured by a high-pressure polymerization process. This process induces polymerization of ethylene gas in a reactor vessel under rather extreme conditions of very high pressure and temperature, and leads to the branched polyethylene structures discussed above. It also employs a peroxide initiator to induce the polymerization. The polymer produced in the reactor is extruded through a die, pelletized and cooled after manufacture.

High density polyethylene is manufactured through a low pressure process using a different catalyst concept The low pressure process, developed later in time, uses non-peroxide catalysts, one of which is called “Ziegler-Natta” (named after the inventors) and allows manufacture of polyethylenes with fewer and shorter branches. This process produces a stiffer, tougher type of polyethylene, and is termed ‘high density’. Linear low density polyethylene (LLDPE), developed even more recently, is manufactured by a low pressure process; as can be seen from Figure 5-3, it has many short chain branches, rendering it more like high density polyethylene in structure. (That is why it is called ‘linear low density polyethylene’, rather than ‘high density PE’).

The different types of polyethylenes are therefore all manufactured by different processes. Recall that all these processes will provide a polymer with a variety of (different) degrees of crystallinity (hence, density) and also a variety of molecular weight distributions. The manufacturing technology is continuously improving, as discussed in the next section.

3.2 Controlled Molecular Weight Distribution Technology

Recent changes in catalyst polymerization technology have allowed materials suppliers to better control the molecular weight and molecular weight distribution; this has led to development of newer grades of polyethylene having narrower and more defined molecular weight distributions, and very low density grades. This new process has been referred to as ‘single site catalysis’ or ‘metallocene’ technology.

This area of activity for improved control of polymer properties has received much attention in recent years. Fundamental properties such as molecular weight were described in Section 2.1. It was noted there that the polyethylene or EPR (polyethylene copolymer) used for cable manufacturing do not have a single uniform molecular weight (all the molecules do not have the same length) but possess a distribution of molecular weights. This is because the catalyst technology used to manufacture conventional high-, medium- or low-density polyethylene cannot provide such an exact control of the polymerization process. This distribution of molecular weights (and branching) normally attained by use of conventional catalysts, influences the crystallinity and therefore the properties. Improved control of the molecular weight by using different catalyst technology has created much interest in the polymer industry, as better control of molecular weight distribution means better control of properties. This newer technology is applicable to manufacture of polyethylene homopolymers (for producing XLPE and TR-XLPE) and copolymers (EPR); sometimes a different monomer is used in place of the propylene in the 'EPR' (e.g., octene or butene) and this 'opens up' additional areas for property improvements. In principle, the newer materials can be potentially useful for insulation, shields and jackets.

What is relevant for insulated cable applications is that materials suppliers can attain greater control over the polymerization process to produce polymers that are more uniform in nature. The term 'metallocene' was used initially to describe these modified materials; the term is based on the nature of the catalyst, which was a metallic compound that incorporated a special chemical structure called "cyclopentadienyl". More recently, other catalysts have been developed and the general term 'single site catalysis' is more technically appropriate. What this means is that the ethylene is polymerized at one single site on the catalyst. Further details on catalyst technology are beyond the scope of this discussion. As might be expected, much of this new technology is proprietary and patented.

The ability to control the molecular structure means that the materials supplier can apply fundamental knowledge of structure-property relationships to develop products geared for a specific end use application, in this case, wire and cable. From a property perspective, the product would be fine-tuned for mechanical, physical and electrical properties. From an application perspective, these newer materials must also be capable of being processed (extruded) at the same (or faster) rates and with the same equipment existing in the cable manufacturing industry today. As a result of these base material improvements, one should expect equivalent (or better) life characteristics from cables made with these materials. Any commercial application for products developed from this newer technology will be influenced strongly by the processing and lifetime characteristics.

The advent of newer single site catalyzed polyethylenes has raised an older subject to higher visibility. In order for a polyethylene to be adequately extruded onto a wire as an insulation or shield, it must be melted in the extruder at elevated temperatures and be pushed through a die. (Extrusion is discussed in Chapter 10). A smooth surface is achieved by controlling the extrusion rate. As the extrusion rate increases, potential problems may arise: these are called 'sharkskin', and at higher rates, 'melt fracture.' 'Sharkskin' refers to a rough surface with repeated patterns of ridges. At conventional extrusion rates, the insulation surface is smooth as it emerges from the extrusion die; at higher rates, flow instability can occur. This phenomenon is related to molecular weight, molecular weight distribution and surface interfacial phenomena. This is not a problem with conventional present day polyethylenes, as it is moderated by their relatively wide molecular weight distributions at conventional extrusion rates. However, the newer polyethylenes are more prone to development of 'sharkskin,' even at relatively moderate extrusion speeds. Ongoing research is taking place to better understand the causes and mitigate the problem. 'Melt fracture' only becomes an area for consideration at significantly higher than conventional extrusion rates.

It should be noted that having a broad molecular weight distribution is not necessarily always 'bad' from a processing perspective; a balance is required between the materials properties and the extrusion ability. Thus far, the newer materials have been applied primarily for high density PE and linear low-density PE applications.

Information provided by materials suppliers suggests the following potential advantages in applying this advanced catalyst technology:

☐ Variety of co-monomer choices
☐ Controlled molecular weight distributions
☐ Better control of crystallinity
☐ Controlled long term branching
☐ Better balance of properties
☐ Improved physical properties
☐ Improved ease of installation (due to greater flexibility)
☐ Improved filled systems
☐ Superior cleanliness due to better catalyst efficiencies.

3.3 Review and Further Discussion

By now, it should be clear that polyethylene is a very complex material. Its apparent simplicity; i.e., a composition consisting solely of repeating -CH_2-functional groups, belies the fact that the actual polymer is comprised of segments imparting significantly different properties. The alignment of some of the chains imparts crystallinity. The non-aligned fractions can coil and are called the amorphous regions. The polymer itself is therefore a “mixture” of different physical segments. That is why it is referred to as “semicrystalline.”

The amorphous regions, having ‘large’ distances (on a molecular level) between the polymer chains relative to the crystalline regions, are sites where foreign ingredients can reside. Such foreign contaminants can be not only non-intended ingredients, but also ions. The crystalline regions, where aligned chains are closer together than in the amorphous regions, are the regions that resist foreign ingredients and penetration of gases. The crystalline regions provide the toughness and resistance to environmental influences. However, without the amorphous regions ‘mixed in’, it would not be possible to extrude the polymer into a functional insulation.

What causes different polyethylenes to have different ratios of crystalline to amorphous regions? Any component present on the polymer chain (backbone) that induces chain separation will decrease the degree of crystallinity. Hence, a copolymer of ethylene with propylene, ethyl acrylate or vinyl acetate (as examples), will decrease the number of consecutive methylene links in the chain and increase the tendency for the chains to be more amorphous. This suggests that EPR would be less crystalline than PE and that is exactly the case. The extent to which this occurs is dependent upon the Ethylene to Propylene ratio present. As the amount of co-monomer increases in the polymer, there is a decrease in crystallinity. One may wonder, therefore, how the “lack” of crystallinity (which imparts ‘toughness”) is compensated for in a completely or almost completely amorphous polymer. The answer is that inorganic fillers need to be added in order to provide the required “toughness” in amorphous insulations.

A second factor contributing to influencing the degree of crystallinity is, as noted earlier, the tendency for the chains in homopolymers to have branches. The older conventional high-pressure process of manufacturing polyethylene (from ethylene monomer) facilitates the formation of numerous branches on the backbone. The branches can have different chain lengths themselves. This is depicted in Figure 5-3. It is the degree and nature of the branches in conventionally manufactured polyethylene that influences tendency to align and, in turn, influences the density and crystallinity. It is for this reason that there are such a large variety of different densities available.

Until the mid 1980s, high molecular weight low-density polyethylene was the commonly used medium voltage insulation material for many users. This polymer has been superceded for new installations, first by cross-linked polyethylene, and then by other materials such as EPR and tree resistant cross-linked polyethylene. Medium- and high-density polyethylenes have traditionally been used as components for cable jackets in medium voltage cables.

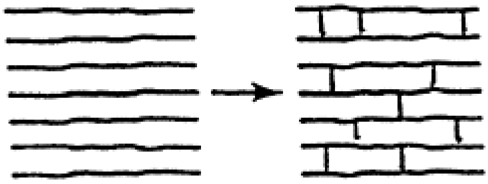
One of the properties of semi-crystalline polymers that is of great practical significance for wire and cable applications is that the crystalline regions have a tendency to “separate”, or move farther apart as the temperature is raised. Chain separation converts the crystalline regions into amorphous ones, and is referred to as crystalline melting. Such chain separation also leads to thermal expansion. This melting process actually occurs over a wide temperature range due to the fact that different crystalline regions have different degrees of “perfection”. Clearly, the ratio of crystalline to amorphous regions will change as a cable is thermally load cycled in service. Cables operating continuously at 60 C will have a larger proportion of amorphous regions than a cable operating continuously at 30 C. Also, a thermal gradient across the cable wall can mean that different amorphous/crystalline ratios will exist at different regions radially away from the conductor. The chain separation process leads to property changes such as: reduction in physical properties (tensile strength, elongation, modulus) and also a reduction in dielectric strength. This continues as the temperature is increased above 60 C. A cable operating at 90 C will have very little crystallinity remaining. When the temperature reaches 110 C, no crystallinity remains. When a cable that has been subjected to thermal overload (heated to elevated temperatures, defined in industry specifications; as 130 C or greater) is later cooled down, the crystalline regions will reform. The physical and electrical properties will now return to being closer to what they were originally. There are fine differences in the nature of the newly formed crystalline regions relative to the original structure, but the nature of these differences is beyond the scope of this book. The subject of thermal overload is relevant to cross-linked systems.

4.0 CROSS-LINKED POLYETHYLENE (XLPE)

4.1 Fundamentals

Cross-linking is the process of joining different polyethylene chains together by chemical reaction. Until now, all the PE chains discussed have been separated to various extents. This is shown in Figure 5-6. In a sense, XLPE can be considered to be a branched polyethylene where the end of the branch is connected to a different PE chain instead of just “hanging loose.” Cross-linking imparts certain desirable properties to the polyethylene; from a cable perspective, it allows the polymer to maintain its form stability at elevated temperatures. Referring to the discussion in Section 3.3, the cross-linking prevents the chains from separating ‘too far.” Other advantages of cross-linked materials include resistance to deformation and stress-cracking, and improved tensile strength and modulus. It should be noted that the electrical properties of polyethylene are not necessarily improved by cross-linking.

Figure 5-6 Simplified description of cross-linked network.



As we have seen from the previous discussion, conventional polyethylene is comprised of long chain polymers that, in turn, are comprised of ethylene groups. The individual molecules are very long. The backbone may contain 10,000 to 60,000 atoms, sometimes more. Further, we have also seen that there are branches, crystalline and amorphous regions and that any additives or impurities must be residing in the amorphous regions—not the crystalline regions. Cross-linking adds yet another dimension to the complexity of the molecular arrangement.

Figure 5-7 Crosslinking effect on chain length of polyethylene.

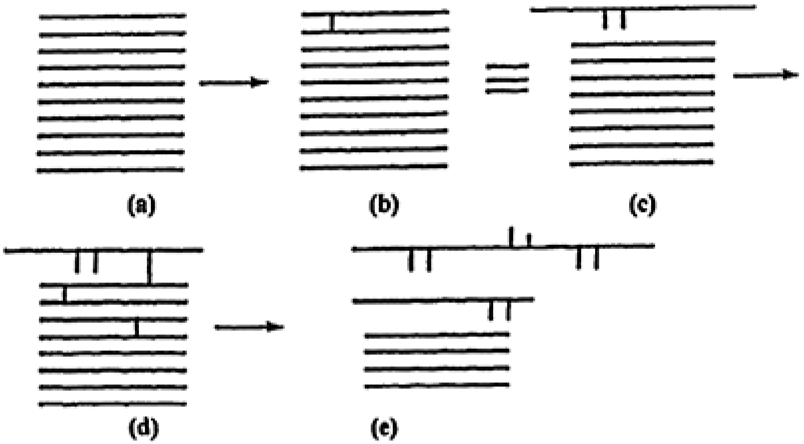


Figure 5-7 provides a description of how a conventional, non-cross-linked polyethylene "parent" is converted to the cross-linked "child." For simplicity, the chains (a) are all shown next to each other. The linear chains represent a simplified description to fit our purposes here. First, two adjacent chains link together (b). We immediately see that the molecular weight has increased. The first cross-link leads to two branches. In (c), the first two chains have been simply redrawn from (b) in a more familiar way. In (d), three additional cross-links have been (arbitrarily) added, two to different chains. The third shows that the newer (previously cross-linked) higher molecular weight chain is again linked to another chain. In (e), it has been redrawn (d) to show how the cross-linking process looks as the chains are again "stretched out" Note how the original two chains have dramatically increased in molecular weight.

It should be clear from this description that the cross-linking process is a way of increasing the molecular weight. This is exactly what occurs during this process. Note also that all the chains do not necessarily increase in molecular weight at the same rate. As the process continues (only the beginning of the process is depicted here), the molecular weight gets so great that the cross-linked polyethylene can be considered to have an "infinite" molecular weight.

One way of characterizing an extremely high molecular weight polymer as compared to a cross-linked polymer, is to check its solubility in an organic solvent such as toluene, xylene, or decalin. A conventional polyethylene, even one of very high molecular weight, will dissolve in a heated solvent of this type. The solubility results from the chains moving apart in the heated solvent. Cross-linked polyethylene will not dissolve. The chains do move farther apart when the cross-linked polymer is immersed in the warm solvent, but not so far apart so that dissolution occurs. What happens instead is that the cross-linked polyethylene merely swells in the solvent and produces a gel. Indeed, this is called the gel fraction. Another way to determine whether the polyethylene is cross-linked or not, is to subject it to heat by placing the sample in contact with a hot surface. The conventional PE will flow while the XLPE will resist flowing and behave more "rubbery."

Commercial XLPE cable insulations also have a "sol" fraction. This is the portion of the polymer chains that never got incorporated into the "infinite" network. In Figure 5-7, we see some chains in (e) not incorporated into the network. The gel fraction of a commercial XLPE is about 70 to 80%; i.e., about 70–80% of the polymer chains are incorporated into the three dimensional gel network and the remainder are not, and would be soluble in the heated solvent.

Another insulation material consideration is the number of cross-links between individual polyethylene chains. This is referred to as the molecular weight between cross-links and has some theoretical significance. However, for commercial purposes, a 70 to 80% gel fraction is an adequate description. It is also common to refer to the "hot modulus." This is a somewhat easier measurement to make than a sol fraction and does not involve the use of organic solvents. The hot modulus is directly related to the degree of cross-linking, or more correctly to the molecular weight between cross-links. It is greater as the degree of cross-linking increases or as the molecular weight between cross-links decreases.

The next issue to consider is, just how cross-linking of polyethylene (or copolymers such as EPR) is achieved.

Cross-linking of the PE chains can be induced by several different means:

- Use of organic peroxides
- Use of high energy radiation
- Modification of the backbone structure

4.2 Peroxide-Induced Cross-linking

Polyethylene that is cross-linked by peroxides (the most common method for medium voltage cables) contains a small amount of a cross-linking agent that is dispersed throughout the polymer. This agent is an organic peroxide. Organic peroxides are chemicals that are stable at room temperatures, but decompose at elevated temperatures. There are many such peroxides available. Dicumyl peroxide is used commercially for medium and high voltage cables. It has traditionally been incorporated into polyethylene pellets by the material suppliers. When the polyethylene is extruded (conversion of the pellets into cable insulation), the peroxide remains stable due to the fact that its decomposition temperature is higher than the extrusion temperature. After the extrusion process, the polyethylene insulation is now surrounding the conductor and the conductor shield and covered by the outer shield; the cable now enters the long curing tube where the temperature is raised above the temperature employed in the extruder. At this high temperature and pressure, the peroxide now decomposes and induces the cross-linking process. Peroxide-induced cross-linking uses a specific peroxide designed to intentionally decompose at a desired elevated temperature after the conversion of the pellets into cable insulation. The after-extrusion tube is called a curing tube and the terms ‘curing’ and ‘cross-linking’ are often used synonymously. Note that this process takes place in the molten state of the insulation; i.e., the polymer (polyethylene) is heated to an elevated temperature, high enough so that all the crystalline regions are melted while cross-linking is induced. The same process occurs with EPR. Cable manufacturing is discussed in more detail in Chapter 10.

When the peroxide decomposes during the curing process, it forms an active ingredient, called a ‘free radical’, that is unstable. The latter is so active that it interacts with any nearby molecule, which is virtually always the polyethylene chain. This free radical forms when the peroxide “splits” into an active oxygen-containing component that then “pulls” hydrogen atoms off the polymer chains. The polymer chain now becomes the active and unstable component and two such chains immediately combine to “cross-link”, and also to stabilize the system once again. During this process, as the peroxide decomposes, and hydrogen toms are pulled off the polymer chain, several by-products are ultimately formed. The major ones are dimethyl benzyl alcohol, acetophenone and methane.

These by-products form in the following manner. When the free radical (a cumyloxy radical) is generated, it can undergo several different types of reactions in its quest to become stabilized. It can “grab” a hydrogen atom from the polyethylene chain (as described above) and form the relatively stable dimethyl benzyl alcohol molecule. However, the unstable radical may also undergo internal rearrangement and “kick out” a methyl radical and become acetophenone. The unstable and highly reactive methyl radical may also pick off a hydrogen atom from the polymer, hence forming methane gas. Water may also be formed if the dicumyloxy radical expels a hydroxyl and hydrogen radical, to form the water; it is then converted to alpha methyl styrene in the process.

The first three by-products of cross-linking (dimethyl benzyl alcohol, acetophenone and methane) are always found in greatest quantities in XLPE. Acetophenone is a solid with a low melting point (approximately 20 degrees C) with a somewhat sweet odor. It is not soluble in water and is partially soluble in the polyolefins, the extent being dependent on the temperature. Due to its low melting point, acetophenone is a liquid at ambient temperatures. Dimethyl benzyl alcohol is also a liquid at ambient. These cross-linking agent by-products will remain in the insulation wall initially, but migrate out slowly over time. [There is some evidence that they impart some degree of water tree (and electrical tree) resistance to the insulation on aging.] Their chemical structures are shown below in Figure 5-8 along with that of alpha methyl styrene. The methane gas must be allowed to readily migrate out of freshly manufactured XLPE-insulated cable after cross-linking has been accomplished. This is easily induced by allowing the cable to “sit” for a defined time after manufacture. Heating the finished cable shortens the time that is required. Other by-products, such as alpha methyl styrene may be present in smaller concentrations. It should be noted that, at times, cumene is also found as another by product; it is believed to develop from the further reaction of alpha methyl styrene.

It should be apparent by now that the peroxide-induced cross-linking process involves rather complex chemical reactions. To achieve good cable insulation, the peroxide must be uniformly dispersed within the PE. For appropriate uniformity of the cross-linking process to take place in the cable insulation, temperature and pressure must be properly controlled throughout the curing tube, which is quite long, but obviously of finite length.

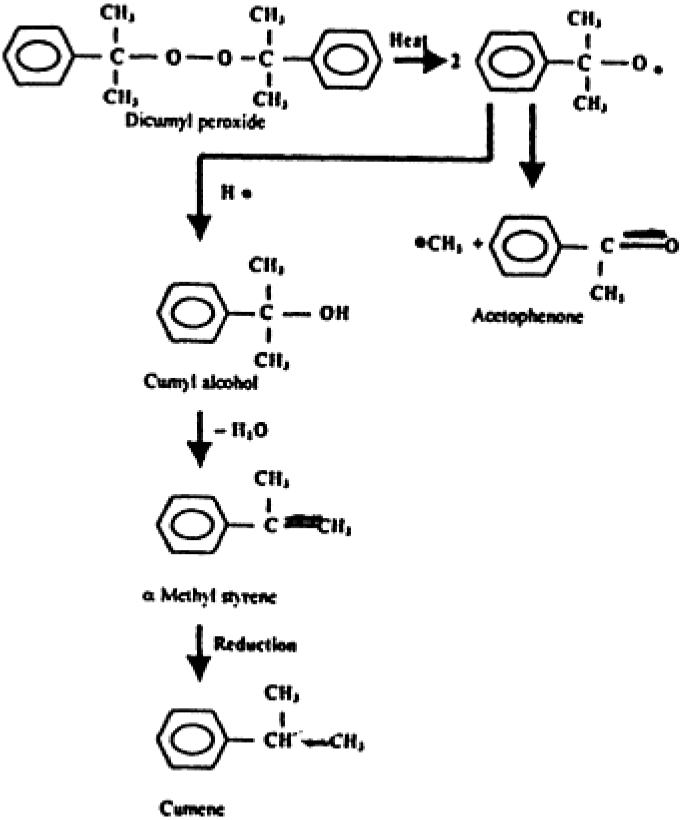
It is important to emphasize that the cross-linking process described here also applies to mineral filled EPR, TR-XLPE and cable shield materials all of which will also contain a peroxide. The same by-products are produced as long as the same peroxide is employed. It must not be forgotten that the carbon black-containing inner and outer shields are also being cross-linked concurrently along with the insulation.

Dicumyl peroxide has historically been commercially available in several forms:

- Free flowing powders that contain about 40% active materials; the inert ingredients being calcium carbonate or clay
- As a 94 to 97% active, light yellow, semicrystalline solid
- A slightly more pure 98% active grade

The choice of dicumyl peroxide form is dependent upon requirements of the type of insulation being manufactured.

Figure 5-8 Decomposition of dicumyl peroxide leads to formation of volatile by-products.



From what we have learned above, it is clear that the peroxide-induced cross-linking process must take place in the amorphous regions, since the crystalline regions cannot hold the peroxide prior to the extrusion process. This is not a complication during the extrusion and cross-linking process since the crystalline regions melt in the curing tube. By the time the peroxide induced cross-linking takes place in the heated tube after extrusion, the entire polymer is amorphous and the peroxide is considered to be relatively uniformly dispersed. It should be emphasized that the complex series of reactions described above all take place within the melted but viscous polyethylene. When the cable is cooled down after extrusion and cross-linking, recrystallization takes place. When this occurs, the newly formed by-products are ‘forced’ into the newly formed amorphous regions.

Cross-linked polyethylene gradually became the preferred insulating material of choice for medium voltage cable starting around the mid-late 1970s and early 1980s. It replaced conventional low-density polyethylene (HMWPE) due to its superior high temperature properties and perceived better resistance to water treeing. Peroxide-induced cross-linking has been the prime method of curing for medium and high voltage cables, as the process has been well developed and defined. For 69 kV transmission cables, peroxide-induced cross-linked polyethylene has also been an insulation material of choice. At higher voltages, peroxide cross-linked polyethylene has shared the market with conventional paper-fluid filled cables (These latter cables are not cross-linked.) As might be imagined, the thicker insulation walls of extruded transmission class cables require significant curing process modifications to assure proper cross-linking. Other peroxides also have been used such as “Vul-cup” which has a higher decomposition temperature than ‘Di-Cup’ (dicumyl peroxide). These higher temperature peroxides are of interest where it may be desired to extrude at higher than conventional temperatures. The use of a higher decomposition temperature peroxide reduces the possibility of premature decomposition that could cause processing problems. It should be noted that not all peroxides will decompose and induce cross-linking over the same temperature ranges. Finally, it should also be noted that most, but not all of the peroxide necessarily decomposes during the normal curing process.

For low voltage cables (less than 600 volts), peroxides may be used to induce cross-linking, but economic factors have allowed both silane and radiation induced cross-linking to share the market (see Sections 4.3 and 4.4 below). In this voltage range, it is not uncommon to employ conventional polyethylene since the voltage stresses and temperatures experienced by these cables are generally lower.

Again, although polyethylene has been use as the example for this discussion, the same principles apply to the tree-retardant cross-linked polyethylene and EPR polymers, which are cross-linked by peroxides in the same manner.

Once cross-linking has taken place, the polyethylene (which, as we have seen, was complex in nature to begin with), is now even more complex. Cross-linking typically takes place within about 70 to 80% of the polymer chains, as noted above. This means that 20 to 30% of the remaining insulation is not cross-linked. Typically this represents the low molecular weight fractions of the initial material. The insulations of such cables that are installed therefore can be viewed as a mixture of LDPE and XLPE (or cross-linked TR-XLPE and a non-cross-linked portion; or cross-linked EPR and a non cross-linked EPR portion). However, the physical and dielectric properties are clearly dominated and controlled by the cross-linked regions of the insulation. At elevated temperatures, the XLPE cable insulation clearly maintains its form stability and functions as anticipated. For EPR, the low molecular weight sol fraction is an ethylene copolymer.

4.3 High Energy Radiation-Induced Cross-linking

It is also possible to cross-link polyethylene using high energy radiation instead of a peroxide. A beam of electrons emanating from special equipment can interact with the polymer chains, causing free radicals to form; a now-reactive polymer chain interacts with another chain (as described above), and hence inducing cross-linking. The electron beam serves the same role as does the catalyst peroxide. Radioactive isotopes such as Cobalt-60 can be used for the same purpose.

In the radiation cross-linking process, energetic electrons come into contact with the polymer chain and break chemical bonds. A ~C-H or ~C-C~ bond can be cleaved. When a ~C-H bond is broken, a hydrogen atom is released, and the now-highly energized ~C. polymeric free radical seeks to stabilize itself by combining with another like radical. This provides the cross-link. The hydrogen atom can combine with another hydrogen atom to form hydrogen gas. When a ~C-C~ bond is broken it is apparent that this can, in principle, lead to a reduction in molecular weight; the shorter free radical chain can combine with another, or with a hydrogen free radical. Hence the cross-linking and degradation processes compete with each other in radiation cross-linking. In actual practice, for polyethylene, it can be generalized that three cross-links form for every polymer chain cleaved, rendering the latter of little practical significance.

Radiation cross-linking involves different processing technology as compared to peroxide-induced cross-linking, and is employed primarily for low voltage cables. The radiation process is performed at room temperature, and therefore, for polyethylene, this means (unlike with peroxides) that cross-linking takes place while the polyolefin possesses both crystalline and amorphous regions. It is possible however that the insulation temperature may rise somewhat during radiation processing, leading to some melting.

The ambient temperature radiation-induced cross-linking process leads to some changes in the insulation not experienced via peroxide-induced cross-linking. First, the distribution of cross-linked regions will differ for the two processes. Second, the nature of the crystalline regions after radiation induced cross-linking remains about the same as before (unlike the peroxide process which is performed at elevated temperature, and where re-crystallization occurs on cooling). Finally, the radiation process induces certain chemical changes within the polyethylene not experienced during peroxide-induced cross-linking; this includes as a small amount of degradation products resulting from the radiation breaking a C-C bond, and other small changes on the polymer backbone. Also, no peroxide cross-linking agent by-products are produced.

Whether there are any practical consequences as a result of these differences is not relevant for medium voltage cable, as the radiation process is not employed commercially. For low voltage wire cross-linking applications where speed of cross-linking is a key issue, radiation technology has been more applicable.

Another potential issue relating to this technology is the non-uniformity of dose (energy) absorbed for thick specimens. There is an inherent radiation dose-depth relationship that is polymer thickness (film or coated wire) related, and the energy absorbed at different regions of a wire or cable wall will differ as the item being irradiated increases in thickness. The energy absorbed increases at first, and then after reaching a maximum, will drop; the total dose absorbed is dependent upon the electron beam energy. Hence, the degree of cross-linking by electron beam technology is not uniform within the component thickness, and much depends on geometry. It is not uncommon to apply a minimum dose in this type of situation, or to irradiate from more than one side. This is in contrast to the relatively uniform degree of cross-linking that occurs with peroxides for medium voltage cables.

Use of radioactive isotopes, such as Cobalt-60, due to their greater penetrating capability (they emit gamma radiation) does not involve any non-uniform dose-absorbed issues, but Cobalt-60 usage involves a different set of manufacturing concerns, making it less useful for wire and cable cross-linking.

Radiation induced cross-linking has also been successfully used to manufacture polyolefin-based heat-shrink polymeric joints, and the crystallinity of the polymer is the key to the concept. In principle, the product is fabricated, cross-linked, and then deformed (i.e., expanded at high temperature), cooled, and marketed in the modified shape, which is quite stable. This initial deformation and cooling process after cross-linking causes crystalline melting and then is followed by re-crystallization when cooling occurs. When the cable joint is later applied in the field, externally applied heat causes the material to shrink (by inducing crystalline melting), as it seeks to regain the shape it had when it was manufactured. Cooling then facilitates the re-crystallization process again, as we have seen. The joint now conforms to the shape of the equipment it is now covering.

The basic unit of radiation dose absorbed is called the rad (which is equal to 100 ergs/gm). Commercial applications require higher doses than rads, and are referred to in terms of 'grays', with 1 Gray (Gy) being equivalent to 100 rads. Older terminology in the literature refers to Megarads, and 1 Mrad=10 kilograys. One Gray is equivalent to 1 joule/kilogram.

4.4 Silane-Induced Cross-linking

A third method of inducing cross-linking is to employ "moisture curing". This concept involves the use of organic chemicals called silanes (which are based on silicones) that react with water. In this process, cross-linking occurs at room temperature (but is accelerated by high temperatures; see below). There are several specific approaches that have been applied in the past; this method does not involve the use of a curing tube, or radiation equipment. For present day silane-induced cross-linking technology, the insulation (polyethylene) has been modified, and is not a homopolymer.

A process called 'Sioplas', the first approach to applying this concept, involves grafting a silane monomer onto the polyethylene backbone using a peroxide catalyst (in essence, inducing a special type of branch), and also preparing a separate concentrate of polyethylene, an antioxidant, and another catalyst (dibutyl tin dilaurate). These are then mixed in a specific ratio, extruded and the completed wire or cable is then immersed in water for a pre-defined time. Water induces a chemical reaction leading to cross-linking. Clearly this is an 'intensive' process, and pre-mixed components require great care in storage. Another process called 'Monosil' simplifies the overall procedure by mixing the polyethylene, catalyst, silane and antioxidant together and then extruding. The curing process is the same. The process is clearly complex, but the practical 'attraction' is that it does not require expensive equipment such as a curing tube or radiation equipment.

A third silane-based cross-linking process, called 'Si-Link" or 'Aqua-link' involves use of a polyethylene-silane copolymer (rather than a grafted material), and allows the wire/cable producer to directly procure the silane-modified polyethylene; this simplifies the handling aspects. [See Figure 5-9.] Again, the curing step is separate.

The curing process for all the technologies described above proceeds at a rate dependent on the insulation wall thickness. The water must penetrate the wall for curing to occur; hours to weeks may be required. What is unique about the overall Silane curing process, and makes it significantly different from peroxide or radiation curing, is that the cross-linking process may continue long after the cable is manufactured.

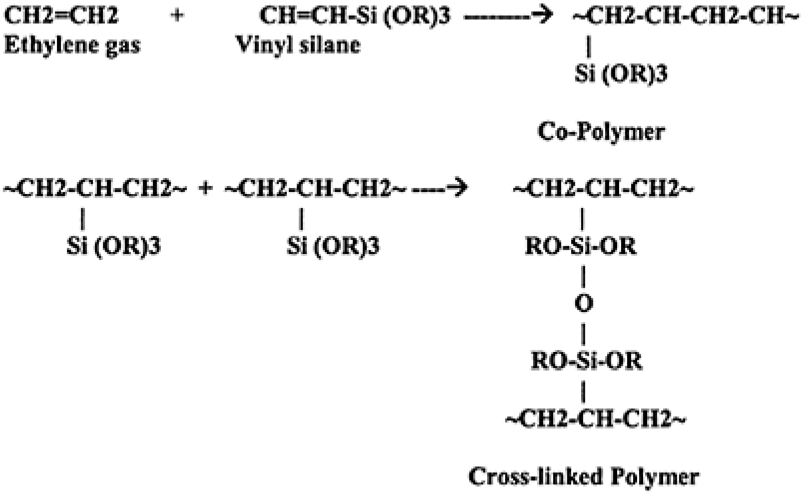
Raising the water temperature increases the water diffusion rate into the insulation, and therefore the cross-linking (curing) rate; it is obvious that thinner cable insulation walls will cure more rapidly. For this reason, silane technology has had its major impact in low voltage (secondary) cable applications.

The chemistry involves formation of ~C-Si-O~ bonds, in contrast to ~C-C~ bonds developed via the other cross-linking methods. The bond strength is therefore different for the two types of cross-links, which leads to slightly different physical properties. Actually, cross-linking is a two-step process; first the alkoxy-(O-R) hydrolyzes at a rate dependent upon the water diffusion; then condensation occurs rapidly. It should be noted that different wall thicknesses of the same insulation material will ultimately cure (cross-link) to the same level, given adequate time.

As noted above, the silane-induced cross-linking process has been commonly employed for low voltage (600V) cables. It has not been uncommon to employ an outer layer of ‘tougher’ polymer, such as high-density polyethylene over a silane-cured inner core, for certain applications where outer toughness and abrasion resistance are important.

Silane-induced cross-linking technology has also been applied for the purpose of upgrading aged, water-treed, installed polyethylene or cross-linked polyethylene cables. The silicone system is applied to the installed cables system; the liquid then migrates through the insulation wall, and curing (cross-linking) occurs by interaction with water in the degraded cable regions. The practical application of this technology is described in Section 4.4.1.

Figure 5-9 Ethylene co-polymerization with vinyl silane.



4.4.1 Practical Application Of Silane-Induced Cross-Linking Technology For Medium Voltage Cables

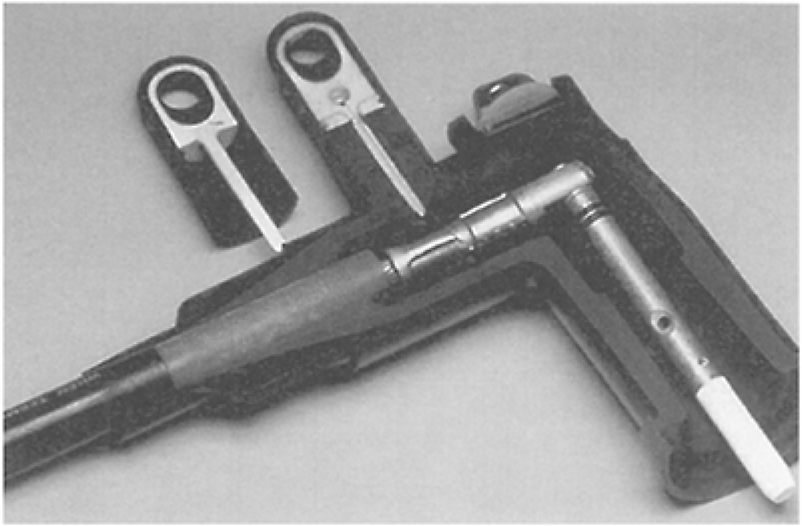
This section describes the practical application of silane cross-linking technology in the field. Many of the techniques used in reducing this technology to practice were developed by first using gas flow approaches and nonpolymerizable liquid drying procedures. These are therefore described first, and provide examples on how to apply new materials technology under service situations.

In the 1980s, as many of the earlier polyethylene cables were failing prematurely due to water treeing (Chapter 17), the industry reaction was not limited solely to improvements in new cable materials that would retard water treeing. The realization that many miles of the earlier vintage cable was in the ground and in service and would deteriorate, prompted many to seek an economic alternative to the wholesale replacement of these cables. This took an effort to understand the water treeing mechanism better, and to find ways to stop the growth of existing water trees as well as retarding the growth of new trees in cables already buried in the ground. At the time, most of these cables were direct buried with no protective jackets and water was free to migrate into the insulation. In addition, these in-service cables were terminated and spliced with polymeric accessories. Thus, any methodology developed not only had to be compatible with the cable, but also with the accessories. The initial concept was to find a way to eliminate the moisture in the buried cables and therefore limit further water treeing deterioration. This was attempted by drying aged cable with dry nitrogen and forcing the remaining moisture out of the insulation with a constant positive pressure. The process was proven in the laboratory and in the field. Further development demonstrated that air could be used in place of the nitrogen, where a constant flow not only removed resident moisture but also newly entering moisture from the ground. The limitation of this method was that adjunct mechanical drying systems had to be placed in service and routine continuous maintenance done. In addition, it was difficult to assure that no moisture would eventually re-enter the cable and continue the water treeinginduced degradation, if the drying system was interrupted or failed.

Most of the early polyethylene cables employed possessed a multi-strand core conductor, where there are longitudinal open air spaces between the circular conductors of the strands (interstices); this is the passageway used for drying gas transmission through a cable. (With a solid conductor, it would not be possible to treat a cable in this manner.) Often, the cable had to be taken out of service and the terminations modified such that there was an entry point from outside the termination directly to the cable interstices, without jeopardizing the insulation system. Overall, the application of gas drying was an on going process that required the cable to be energized and in service while this is going on. Cable elbows and stress cones were modified accordingly; special crimped connectors have to be used to allow the entering gas access to the stranded conductor.

Figure 5-10 shows a modified elbow termination with an access port. Once the gas entered the cable interstices, it would travel down the length of a section of cable as long as the other end was open to vent the moisture and contaminants inside the interstices. Quite often, this flow was impeded by a cable splice where a crimped connection squeezed off the interstices. If flow was not detected at the exit end of the cable, restricting splices were located and replaced with new splices and connectors that would allow gas flow. Another consideration was the pressures to which the cables were subjected in this process; if the pressure was raised too high (which might occur if it were necessary to overcome a temporary restriction to create flow) the termination and splice interfaces might ‘burp’, causing moisture and surrounding soil contaminants to enter the system, and deteriorate the dielectric integrity of the splice.

Figure 5-10 Modified elbow termination.



Although these gas-based drying procedures were successful in preventing growth of water trees and in extending cable life, the complexities involved, as described above, were too great for ongoing practical application. As a result, the concept was extended by filling the voids and sites where tree growth was occurring with a compatible insulating liquid. The first successful field trials were accomplished with acetophenone, one of the by-products of the cross-linking process. Laboratory tests on aged cables proved that the ac breakdown strength not only was maintained, but actually improved. Acetophenone forced out the moisture and impurities in the cable and once the exit end was capped, pressure was maintained as the fluid began to migrate radially through the insulation from the interstices to the outside of the cable. However, pressure and fluid reservoirs still had to be maintained to assure there was constant positive pressure to keep the moisture out.

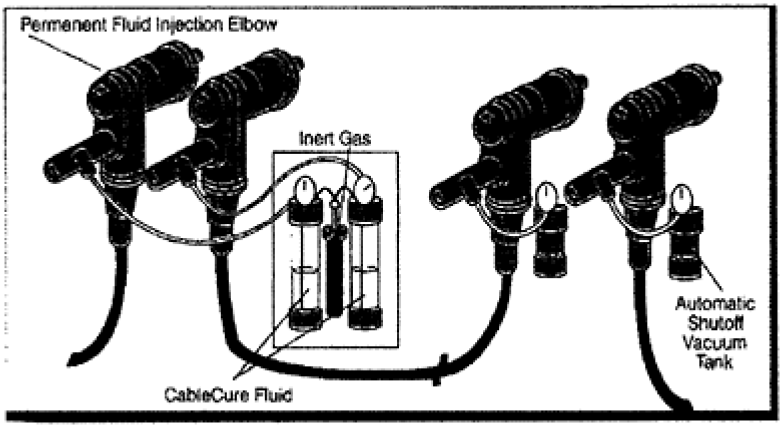
The improved more practical process that built upon this knowledge employed an insulating fluid based on silicone technology. As noted in Section 4.4, silane-induced cross-linking leads to curing of the fluid by reaction with water. In-situ silicone impregnation leads to chemical reaction with the water in the cable. Since the curing process leads to solidification, the process assures that the silane impregnant remains within the cable insulation with no need for application of external pressure. This process eliminated the need for ongoing gas transmission while employing the practical concepts developed during the earlier efforts.

As the pressurized silicone fluid flows radially through the insulation from the cable interstices to the outer regions of the cable insulation, in regions where moisture is present, it reacts with the moisture to produce a cross-linked polymer within the deteriorated regions. Not only did this process eliminate the water and stop the tree growth, but it led to improved dielectric properties.

As silicone molecules penetrate the insulation and interact with water, they polymerize, become bulkier, then exhibit reduced transmission rates, and eventually dam travel at the outer regions of the insulation. Not only does this prevent the silicone from migrating out, but it also minimizes any moisture from migrating in. Since not all the silicone fluid reacts as it penetrates the insulation, any moisture that does migrate in after a cable has been silicone-cured is also subject to reaction with water. Laboratory and field tests on aged cables demonstrated that ac breakdown strength increases and remains at elevated levels over time (hence extending life).

The polymerization of the silicone molecules within the insulation wall influences the process employed by the user. Once it is confirmed that enough fluid has been injected to penetrate the insulation thickness of the cable being treated, the fluid and exit reservoirs are removed and no further maintenance is required. Figure 5-11 shows the complete treatment setup required. In addition to applying pressure behind the fluid, vacuum may be applied at the exit end of the installation to speed the injection process. For typical URD cable sections, the entire process may take 60 days.

Figure 5-11 Silicone fluid treatment equipment.



Most of the early work in this area focused on upgrading HMWPE; the methodology has also been successfully applied to XLPE and TR-XLPE without any detrimental effects to shields or accessories. It has been used on transmission class cables up to 69 kV and large conductor size distribution feeder cables. The approach has also been studied with EPR-insulated cables.

Silicone-induced cross-linking for installed cable systems must be evaluated with caution, and from a broad perspective. It is ideally employed where it is more cost effective than installing new cable, in a new trench. However, if, for example, the outside neutral wires are corroded and near their end of service life, restoration would not be practical, even though the cable insulation itself could be upgraded.

4.5 Antioxidants

When the cable insulation temperature is raised during manufacturing, it may be subjected to oxidative degradation; this is not uncommon with polyolefins. Under these conditions, the polymeric insulation is subjected to temperatures significantly higher than it will ever see in service. Oxidative degradation, if significant, may be particularly harmful as it can lead to chemical changes within the insulation that introduce more polar materials that may, in turn, introduce changes in electrical properties and make the cable more prone to failure during aging. To prevent this potential degradation mechanism from occurring, small amounts of another material called an antioxidant are incorporated into the polymer pellets. For medium voltage cables, the common types have historically been either an organic amine or phenolic compounds. Other types, such as phosphites have also been used. The antioxidant preferentially decomposes in the extruder under the thermal environment, and inhibits or prevents decomposition of the polymer. The antioxidant can be considered to be a sacrificial component that facilitates high quality product during cable manufacturing. It also resides in the amorphous regions of the polymer at the beginning of the curing process, and when crystalline melting occurs as the temperature increases, it can migrate throughout. Upon cooling of the XLPE after manufacture, any un-reacted antioxidant would reside in the amorphous regions. Also residing in the amorphous regions will be any antioxidant degradation by-products that are not volatile. This is common for all extruded cross-linked medium voltage insulations.

There are many antioxidants available commercially; amine-types are yellowish in color, and phenolics are white. The antioxidant nature can generally be determined by obtaining an infra-red spectra of a thin film of the polymer; the antioxidant efficiency, a measure of the amount of ‘activity’ of the antioxidant, can be estimated by an oxidation induction time measurement via thermal analysis. Formation of minute amounts of oxidation in polyolefin insulation during extrusion is not completely preventable, but is kept to an absolute minimum by appropriate processing.

5.0 TREE RETARDANT CROSS-LINKED POLYETHYLENE (TR-XLPE)

Over the years, numerous attempts have been made to improve the performance of conventional polyethylene and, later, XLPE with regard to resistance to water treeing, in order to attain increased life. There are three fundamental approaches to achieving tree retardancy:

- Using a more polar copolymer in place of a polyethylene homo-polymer
- Using an additive or additives placed into the homo-polymer (or co-polymer)
- Using both of the above.

The modified XLPE is usually tested first as a pressed slab to assure that improvements have indeed occurred. However, it should be noted that much information available on cables is often focused on completed cable properties after testing or aging, rather than how these properties are achieved in compound design.

As noted earlier, one of the XLPE cross-linking agent by-products, acetophenone, has been reported to facilitate resistance to water treeing. Dodecyl alcohol was employed as a tree retardant additive to HMWPE in the past, when HMWPE was the insulation of choice for new cables. The first commercial TR-XLPE material was made available from Union Carbide (now Dow Chemical Company) in the early 1980s. The patent literature discloses that a mixture of additives is likely to be present, the additives serving the role of binding water and providing resistance to space charge. For many years this was the only TR-XLPE manufactured in North America. Another commercial tree-retardant material has been described as employing additives that immobilize water molecules when water ingress occurs, and minimize damage caused by a high electric field and space charges. The overall goal in tree retardant technology is to prevent water from damaging the insulation. Modifying the XLPE to make it more hydrophilic would facilitate ‘holding’ or ‘trapping’ the water. ‘Fillers’ may also ‘trap’ water. Silane groups, as we have seen in Section 4.4 react with water. In all cases, the water would be prevented (or slowed) from migrating to the high stress site (a fundamental event in water tree growth). TR-XLPE must still contain a peroxide cross-linking agent and an antioxidant, as do conventional XLPE and EPR.

Historical information from field aging combined with laboratory data justifies that TR-XLPE be considered in a separate category from conventional XLPE. However, as with EPR, it is not to be expected that all “tree retardant cross-linked polyethylenes” will respond in the same manner in laboratory aging tests or in service. Physical and electrical property data are of interest not only after cable manufacturing, but also after aging. Parameters of interest include not only retarding the growth of bowtie and vented water trees, but high retained AC breakdown strength values after wet aging, and long life under accelerated cable life testing in laboratory tanks or pipes.

Another issue that has arisen in recent year relates to the definition of TR-XLPE, or the ‘degree’ of tree retardancy. While it is generally agreed that tree growth is diminished and AC breakdown strength is increased for TR-XLPE as compared to XLPE, one question that has been raised is just how much of an improvement is required for the material to be defined as ‘tree-retardant.’ Another question is whether the decision on this matter should be determined by a materials test, or a full size cable test.

Table 5-1 shows comparative material components of conventional and tree retardant cross-linked polyethylene. The major difference is in the initial ingredients, and also potential additional by-products of the cross-linking reaction.

Table 5-1 Comparison of XLPE and TR-XLPE Insulated Cables

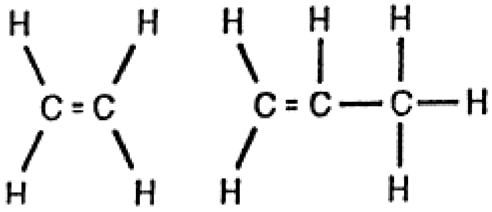
Cross-linked Polyethylene	**Tree Retardant XLPE**
	Tree retardant additives
Residual amounts of dicumyl peroxide	Residual amounts of dicumyl peroxide
Cross-linking agent by-products	Cross-linking agent by-products (same as XLPE)
Acetophenone	Acetophenone
Cumyl alcohol	Cumyl alcohol
Alpha methyl styrene	Alpha methyl styrene
Antioxidant plus some antioxidant degradation by-products	Antioxidant plus some antioxidant degradation by-products

6.0 ETHYLENE COPOLYMER INSULATIONS (EPR)

When an ethylene monomer is polymerized with propylene, the copolymer that results that is called an ethylene-propylene copolymer, or EPR. The ratio of ethylene to propylene can vary over a wide range. This copolymer has significantly different properties than PE, XLPE, or TR-XLPE while providing the dielectric characteristics required for medium voltage cables. Perhaps the most significant is the fact that the propylene segments in the polymer chain interfere with the natural tendency of the polyethylene chains to align. The result is inherently reduced crystallinity.

□ Short chain branches
□ Non crystalline-amorphous structure
□ Requires reinforcing fillers
□ Needs to be cross-linked

Figure 5-12 Copolymer of ethylene and propylene (~50/50 E/P ratio).



Single molecule structure

☐ Short chain branches
☐ Non crystalline-amorphous structure
☐ Needs reinforcing fillers (about 50%)
☐ Needs to be cross-linked

Sometimes, it is preferable to add a third monomer to the ethylene-propylene monomer blend prior to polymerization. This is called a diene monomer, and has been used to facilitate certain (non-peroxide) cross-linking processes. These materials are called EPDM. In the cable industry, it is not uncommon to refer to all ethylene co- or ter-polymers as EPRs (or EPs).

EPR materials are known as elastomers. Conventional elastomers have significantly different properties from semi-crystalline polymers. Reduced crystallinity means that the properties imparted by the crystallinity are reduced: modulus (or "toughness") and high tensile strength of the polymer are examples. It means than a functional insulation that is analogous to high molecular weight polyethylene cannot be produced with a non-cross-linked, ethylene-propylene copolymer. To achieve improved physical properties, it is necessary to incorporate inorganic mineral fillers into the EPR compound, which very effectively serve the role of improving the mechanical properties. The reduced crystallinity also imparts other differences relative to XLPE or TR-XLPE: increased flexibility, and reduced thermal expansion as the temperature of the manufactured cable is raised (see Section 3.3). The EPR resin must be crosslinked to render it suitable as an insulation material. (If it were not cross-linked, EPR would be too soft and tacky to serve as cable insulation.)

As with PE, EPR may have "high" or "low" molecular weight, and broad or narrow molecular weight distributions (prior to cross-linking). Hence, there are many grades available, each having different properties. The possible inclusion of a ter-monomer increases the choices further.

The EPR polymeric material is only one component in the eventual cable insulation. The inorganic mineral filler, as noted above, is another. However, to be useful as an insulation, additional components are also required. These are mixed in with the polymer, and the blend is now generally referred to as a "formulation" or "compound." All the additives (there may be 10 to perhaps 15 or more) are incorporated using special mixing equipment. The method of mixing the ingredients together is referred to as a compounding process. Table 5-2 below shows typical EP formulations supplied commercially in the past, up until the late 1990s. It should be noted that many EP compounds that are used as insulations for cables possess proprietary ingredients and the formulations are not published.

EP materials that have about 40–50% ethylene are considered to have little to no crystallinity. EP materials that have about 70–75% ethylene may have very small amounts of crystallinty. EP compounds that have some polyethylene incorporated will have slight crystallinity. EPRs that have the higher percentage of ethylene are pelletized; those that have lower levels of ethylene are provided as strips. Again, due to their overall lack of crystallinity, all EP compounds will have reduced thermal expansion as well as lower heat capacity and higher thermal conductivity as compared to XLPE (or TR-XLPE).

Common ingredients in EP compounds, and their purpose, are noted below.

□ Silane-treated Kaolin This inorganic mineral is a coated calcined clay that serves to improve the mechanical properties of the formulation. Since the rubber material has little or no crystallinity, the filler imparts mechanical strength. The clay is coated with a silane material to improve polymer-filler interaction at the interface; if the clay was not coated, 'gaps' could develop at the interfaces, leading to poor properties. On a microscopic level, the filler particles are large compared to the polymer chain.

□ Zinc Oxide A traditional component in EPR and EPDM compounds that improves thermal stability. It was initially incorporated into cable insulation in the past, as the compound was used in automobile tire formulations.

□ Red Lead Lead oxide (or "red lead") acts as an ion scavenger. It improves electrical properties under wet aging. It was incorporated into EPR compounds many years ago to meet low voltage cable test requirements.

□ Ethylene Propylene Co- or Ter-Polymer This is the base material that forms a continuous phase in which all the ingredients noted below are uniformly dispersed. The polymer provides flexibility and good dielectric properties.

□ Polyethylene Facilitates extrusion on conventional equipment

Table 5-2 Typical EP Insulation Compounds Employed until the Late 1990s (in parts per hundred)

Ingredient	**Amorphous**	**Semicrystalline**
Nordel 1040 (amorphous)	100.0	—
Nordel 2722 (semicrystalline)	—	100.0
Low density PE	—	5.0
Zinc oxide	5.0	5.0
Red lead (90% dispersion)	5.0	5.0
Silane treated Kaolin	120.0	60.0
Vinyl silane A-172	1.0	1.0
Process oil	15.0	

Paraffin wax	5.0	5.0
Antioxidant	1.5	1.5
Dicumyl peroxide	3.5	2.6

□ Cross-linking Agent This is typically dicumyl peroxide; it serves the same role as it does in XLPE.

□ Processing Aids A wax or an oil that acts as a lubricant, and improves the processing of the formulation during extrusion, since the inorganic additives are “abrasive” in nature.

□ Antioxidant This serves the same role as it does in PE or XLPE; to prevent polymer decomposition during extrusion.

Additional silane may be added to assure adequate polymer/filler interaction. In additional to these components, individual compound manufacturers (or cable manufacturers who do compounding) may have additional proprietary ingredients added to their commercial EPR formulations. These can serve various purposes such as to further enhance processing, enhance aging properties, or modify dielectric properties.

As noted earlier, it is possible to incorporate a third monomer into the ethylene/propylene mixture when polymerization takes place. This is sometimes referred to as “diene monomer,” and the term EPDM is used to describe the material. In the wire and cable industry, both of these types of elastomers have been generally referred to as “EPRs.” [However, EPDM is a term more commonly used for materials employed with cable joints and accessories.] The diene ter-polymer is used in formulations where the unsaturation in the polymer chain is desired, such as for specialized technology where the unsaturation of the third monomer is preferred or required. Possible examples of the ter-monomer are 1,4-hexadiene, ethylidene norbornene or dicyclopentadiene; the nature of the diene monomer can influence the cure rate.

All EPR compounds must be cross-linked to be useful as insulation, as noted above. The peroxide-induced cross-linking process is exactly the same as for medium voltage XLPE cables (although extrusion rates may differ).

For low voltage EPR insulated cables, peroxide-induced cross-linking or radiation cross-linking has been employed. It is not common to employ silane processing for EPR curing.

It should be noted that in the past, some medium voltage EPR compounds were provided with carbon black mixed as one of the ingredients in the insulation; this is not present day practice.

Processing of pelletized medium voltage EPR insulated cables is performed on the same equipment used for XLPE or TR-XLPE. Completely amorphous EPs are strip-fed into the extruder. Steam or dry curing may be employed, although steam curing has traditionally been more common for EPR.

Finally, while the added ingredients impart the desired mechanical and physical properties to the EP compound, they do have a detrimental effect on initial dielectric properties. The dielectric losses (dissipation factor and power factor) and dielectric constant all increase. This magnitude of the increase will differ as the nature of the EP compound changes.

7.0 SHIELD MATERIALS

Polymers used for shields are ethylene co-polymers. They may be co-polymers with propylene or with other monomers such as vinyl acetate or ethyl acrylate. In essence then, they are ‘elastomers’. Each of these other co-monomers imparts different properties to the polymeric shields. As with insulation, one must consider molecular weight and molecular weight distribution issues, but crystallinity is not an issue. In addition, it is necessary to incorporate an adequate amount of a conducting carbon black into the co-polymer to achieve the required semi-conducting properties. One must assure appropriate carbon particle to carbon particle contact. It is also possible to incorporate additional additives. For example, controlled strippability of insulation shields (for ease of removal) may be achieved with additional additives, but such additives would not be used for conductor shields where strippability is not desired.

The amount of carbon black required to achieve semiconducting properties depends upon the type of carbon black employed, and the degree of conductivity required for the application. Acetylene blacks, furnace blacks and, in the past, channel blacks have been employed. The goal is to achieve uniform ‘semi-conducting’ properties, where the volume resistivity is controlled within a desired range. Carbon blacks with high ‘structure’ tend to impart greater conductivity and hardness. ‘Structure’ refers to the ability of the carbon black to aggregate into small clusters (chains or networks). The structure can be disrupted when incorporating the carbon black into the elastomer, the extent being determined by the type of black and the mixing process. Conductivity is also determined by the structure, with particle-to-particle contact being a key issue. In general, the resistivity is related more to the hardness than to the concentration of the black present in the compound.

Carbon black-containing shield materials must be extrudable and cross-linkable as easily as the insulation, and under such conditions that ‘true triple’ extrusion can be effectively performed with the semi-conducting electrical properties remaining in the desired range. Factors that influence the conductivity are the carbon black type and concentration, processing conditions, as well as the base polymer type, cure system, and other components present.

Another issue relative to carbon blacks in shields is the ‘smoothness’ of the surfaces at the interfaces of the outer and inner shields with the insulation, in a completed cable. Smoothness is influenced by protrusions from the semi-conductive shields (influenced by the carbon black); protrusion geometry (the tip radius or sharpness) and the height of the protrusion are factors. Hence, the degree of dispersion of the carbon black and its ‘fineness’ in the completed cable are keys to achieving surface uniformity and smoothness.

In the past, inorganic components such as ions present in certain types of carbon blacks (resulting from prior processing) had been reported to contribute to premature cable failure; contamination occurred through the water-induced migration of such components into the insulation during aging. The issue related primarily to furnace blacks commonly employed until about the mid-1980s, and this has been resolved by improved cleaning treatment of the carbon black used for cable shields. This is noted here as many older installed cables possess this older black in their shields. (This is also an example of how the cable users, manufacturers, and material suppliers work together to correct a problem once it is identified.)

8.0 PAPER-INSULATED CABLES

The oldest type of insulation used for power cables is paper, which is based on the natural polymer, cellulose. Paper strips are impregnated with a dielectric fluid; i.e., oils obtained from cracking of petroleum. Synthetic oils have also been used. This section reviews the fundamentals of paper-based insulation.

Paper for electrical cable insulation is derived from wood. The wood consists of three major ingredients:

□	Cellulose	About 40%
□	Hemi-cellulose	About 30%
□	Lignin	About 30%

The cellulose component is what is of interest as an insulating material and must be separated from the other ingredients; this is performed by bleaching with sulfates or sulfites. The hemi-cellulose, a non-fibrous material, is more polar than cellulose and hence lossier. However, a very low level of hemi-cellulose is acceptable in the final material, and some quantity remains after the bleaching process. (It can be noted that cotton is pure cellulose; if cotton were used as a source for paper, no hemi-cellulose would be present.) Lignin is an amorphous material and serves as a binder for the other components in the wood and is removed for cable insulation applications. Details of the process of converting wood into a useful insulation material are beyond the scope of this book, but it should be noted that the process is well developed and has been used for scores of years in the paper industry.

The chemical structure of cellulose is shown in Figure 5-13. For comparison, polyethylene is also shown. The differences are apparent. Note that cellulose has a saturated cyclic structure (five carbons and one oxygen in a ring) and this is absent in polyethylene.

In contrast to polyolefins, it is more common to refer to the molecular weight of cellulose in terms of degree of polymerization, or “DP.” (DP represents the degree of polymerization of the individual components, while molecular weight, more commonly used with, polyethylene and PE copolymers, represents the weight of the individual components.)

The DP is representative of the number of individual cellulose molecules in a chain. The DP of a typical cellulose molecule in wood is about 10,000. The cellulose consists of fibrils, and as noted above, it is converted into insulating paper by the conventional processes used in the paper industry. When used as cable insulation, the paper is impregnated with dielectric fluids-low molecular weight hydrocarbons. As with polyethylene, these oils or fluids are intended to consist solely of carbon and hydrogen.

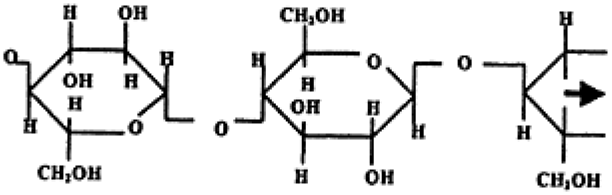
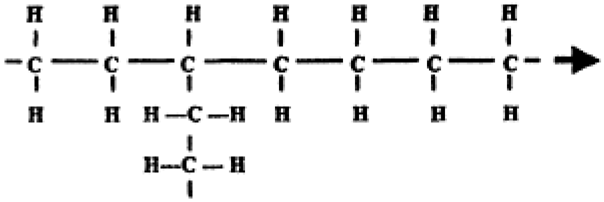


Figure 5-13 Chemical structure of cellulose.

Chemical structure of polyethylene



Cellulose can be considered to be a “polyhydric” alcohol. (A simple alcohol would be ethanol.) As seen in Figure 5-13, the polymeric chains are comprised of more complex chemical structures than those present in PE or EPR. In the latter cases one has simple methylene groups; for cellulose, one has glucose groups linked by components called ‘1,4-glycosidic’ bonds. This is an important difference as these cellulosic bonds can be cleaved (in acids, for example) and that does not happen with polyolefins. These bonds can also break under thermal stress, but the temperatures required are much higher than normally observed in service.

Cellulose molecules have a strong tendency to crystallize, and the morphology is extremely complex. This natural polymer is, as noted above, impregnated with a dielectric fluid in application. Since the cellulose is applied as a manufactured tape, there are butt spaces that overlap in the cable construction; the fluid serves to assure that an insulating medium fills any butt spaces. The dielectric fluid itself is comprised of carbon and hydrogen ~CH2~ groups, much like PE, but the molecular weight is very much lower, so it is a slightly viscous liquid rather than a solid.

As paper-insulated cable ages under load cycling and voltage stress, the fluid migrates with temperature changes. It is possible, upon high loading, for some fluid molecules to degrade and undergo a decrease in molecular weight, and other fluid molecules to increase in molecular weight. If this happens, some of the fluid is converted into a wax. (For our purposes, a wax can be considered to be a ‘high molecular weight oil,’ but not as high as in polyethylene). Solid wax in aged cables has been found in forensic examination. These waxes can restrict oil migration during load cycling, perhaps preventing effective flow and allowing detrimental micro-voids to form. These issues do not exist for extruded solid dielectric cables.

It is clear that paper-insulated cables are more complex than are their synthetic polyolefins counterparts. Both the oil and the cellulose may degrade. The fact is, however, that paper-insulated cables have an excellent history of reliability, and this is primarily attributed to the presence of an outer metallic sheath on these cables that prevents the incursion of air or water. Water can accelerate the degradation process of paper-insulated cables, just as it does with extruded cables, but the mechanism differs. Water or air that enter the paper cable system can displace the insulating fluid.

Medium voltage paper-based cables are referred to as paper-insulated lead covered (PILC) cables. Transmission cables based on paper were called high pressure oil-filled (HPOF) or low-pressure, oil-filled (LPOF). The environmentally correct term is now fluid-filled since oil is no longer used in these cables.

Because of the significantly different chemical structure of paper compared to extruded dielectric polymers, and the different response of each to external stresses (as a result of their chemical and physical structures), it should not be surprising that each type of insulation material responds differently to the same diagnostic tests that may be employed by Utilities or Industrial firms. An example is dc Hi pot (high potential) testing (see Section 10). PILC is stable to a dc application, when applied in accordance with industry guidelines, and the test can be employed to address cable integrity. XLPE, however, due to the lack of any low molecular weight oil, and the tendency to 'trap charges', may be susceptible to harmful effects when subjected to dc Hi pot testing. Much depends on the degree of degradation that the XLPE has undergone. The point is that the response of electrical insulation materials to outside influences in their application environment, both natural and imposed by the user, is intimately related to the physico-chemical structure of the insulation material.

9.0 JACKET MATERIALS

Jackets are extruded over the completed cable core and their metallic shields or neutral wires to provide abrasion and puncture resistance and to protect the cable from the local environment (moisture, light). Common jackets are insulating, and ideally, they will aid in keeping water and foreign ions out of the insulation. Jacketing materials have varying properties that are controlled by their molecular structure and compound ingredients. Good environmental stress crack resistance is also a requirement. The jackets contain small quantities on carbon black that is not conducting.

For medium-voltage cables, several polyethylene types are used as jacketing materials:

□	Low density	LDPE
□	Medium density	MDPE
□	High density	HDPE
□	Linear low density polyethylene	LLDPE

It is clear by now that the differences between the first three are in the degree of "chain alignment" that takes place, and that HDPE is more crystalline than is LDPE. As the name implies, MDPE is in-between the others in the degree of crystallinity. HDPE is manufactured by a different process than are the low and medium polyethylenes. The higher the degree of crystallinity, the greater the toughness and abrasion resistance, but the extrusion process is more complex. LLDPE is manufactured in such a manner that it approaches HDPE in properties, but by a less expensive method. Properties considered during processing of jacket materials include abrasion resistance, stress crack resistance, melt flow rate and prevention of shrinkage. In practice, LDPE was commonly employed in the past and has gradually been replaced by LLDPE.

More recently, polypropylene (PP) has come into usage as a cable jacket. PP has a significantly different architectural structure from PE and as a result, possesses lower density. Because of its increased toughness, it is a good jacket material. PP extrusion requirements are also different also.

The moisture resistance of the different PE types will vary with the degree of crystallinity. See Table 5-3.

PVC (polyvinyl chloride) is a material that was used as a jacket. Although PVC by itself is a very rigid material, it becomes quite flexible when plasticizers are added. A typical PVC plasticizer could be 2-ethyl hexyl phthalate. Plasticized PVC, while providing some degree of protection against dig-ins and corrosion protection, has poor abrasion resistance and poor resistance to water migration.

PVC is now rarely used as a cable jacket for underground distribution cables even though it is relatively inexpensive compared to other materials. For low voltage cables, it has been common to use other materials such as Neoprene (polychloroprene) or Hypalon (chlorsulphonated polyethylene).

Table 5-3 Moisture Vapor Transmission Rates

Material	**Density**	**Relative Moisture Vapor Transmission Rates**
LDPE	0.92	1.16
MDPE	0.93	0.51
HDPE	0.94	0.58
HDPE	0.95	0.32
LLDPE	0.92	0.74
PVC	1.30	10.0
Semiconducting PE	1.15	5.00

In some applications, semi-conducting jackets have also been used. These are polyethylene-based jackets with conducting carbon black dispersed throughout to provide uniform semi-conductivity from the neutral or ground shield to the outer environment. Hence the carbon black in semi-conducting jackets differs in nature and amount from that employed in insulating jackets

10.0 COMPARISON OF INSULATING MATERIALS

Since paper insulation was used first in the power industry, and was later replaced for low and medium voltage applications, any comparison of properties usually employs the paper-fluid system as the standard.

Table 5-4 Major Differences Between Paper and Polyolefinic Insulations

Paper/Cellulose	**Polyethylene**
Natural	Synthetic
Carbon/hydrogen/oxygen	Carbon/hydrogen/oxygen
More polar/medium losses	Less polar, low losses
Chains linear	Chains branched
Fibrils	Non-fibrils
Partially crystalline/Relatively constant	Partially crystalline/Varies with grade employed
No thermal expansion on Heating	Significant thermal expansion
Not cross-linked	Not cross-linked
Thermal degradation via cleavage at weak link sites	Degrades at weak link sites

Table 5-4 provides a comparison of the properties of paper, polyethylene, crosslinked polyethylene, tree-retardant cross-linked polyethylene and ethylene propylene (and EPDM) rubber insulations. Only the paper is a natural polymer and is therefore processed differently. Paper, as noted earlier, is obtained from a wood (or cotton) source and the synthetic polymers are produced by polymerization of monomers derived from cracking of petroleum.

Table 5-5 Major Differences Between Cross-linked Polyethylenes and EPRs

Cross-linked Polyethylene and Tree-Retardant Cross-linked Polyethylene	**Ethylene Propylene and Ethylene-Propylene-Diene Monomer Rubber**
Synthetic	Synthetic
Carbon/hydrogen	Carbon/hydrogen

Less polar, low losses	Losses due to additives
Chains branched, cross-linked	Chains branched, cross-linked
Non-fibril	Non-fibril
Slightly less crystalline vs. PE	Least crystalline of all
Same thermal expansion as PE	Slight thermal expansion
Cross-linked	Cross-linked
Degrades at weak links	Same as XLPE

All consist of carbon and hydrogen, but paper also contains oxygen. The latter is present as functional hydroxyl or ether groups. They contribute a measure of polarity that is absent in the synthetic polymers (polarity implies increased dielectric losses). Of special note is the concept of thermal expansion during heating (load cycling). While all of the synthetic polymers undergo varying degrees of thermal expansion during heating of the cable, this does not occur with cellulose—although the fluid will do so. How these insulations respond to aging is a heavily studied subject since it is directly related to reliability of the cable after installation and energization.

When cellulose degrades, it does so at a “weak link,” the region of the oxygen linkage between the ‘rings’. Water accelerates the ‘normal’ degradation mechanism; the DP is reduced. On the other hand, polyolefins degrade by a completely different mechanism—degradation at specific sites that are not necessarily related to the inherent nature of the polymer. Water induces degradation of extruded polymers by a mechanism of ‘water treeing’ that is, again, not related to the inherent chemical structure of the polymeric insulation, but is related to ‘imperfections. In addition, wet aging of extruded polymeric insulation induces degradation by a different mechanism than does a dry aging environment (which induces oxidative degradation). Protection against thermal degradation is imparted to polyolefins by adding an antioxidant to the pellets prior to extrusion. Note that adding antioxidants to a fluid to prevent it from degrading is not uncommon.

One further point needs to be strongly emphasized: the different response of the different insulation types to any single diagnostic tool. The example discussed here is DC testing. DC testing of cables (Chapter 16) has traditionally been performed to ascertain the state of the cable at specific times during their use. It is used for factory testing of new cables, after installation (acceptance testing), after a repair has been made (proof testing) or periodically during the life of the cable (maintenance testing). Industry standards and guidelines exist for each type of testing procedure. DC testing was a technique originally adapted for PILC cables many years ago, and was later carried over to extruded dielectric cables. Research in recent years has shown that PE and XLPE may be harmed by the use of a DC test, but there is no evidence that this occurs with paper-oil systems. The potential harm is a result of aged XLPE becoming more susceptible to space charge trapping after aging. Damage may occur despite conventional industry guidelines. [EPR and TR-XLPE-insulated cables have not been studied to the same extent and no conclusions can be drawn at this time about the effect of DC testing on those types of insulated cables.] The point is that a diagnostic tool adopted for one insulation type should not be applied to a different insulation type without adequate consideration of all factors involved. This applies to all diagnostic tests involving electrical property measurements.

To summarize:

□ Advantages of polyethylene:

- Low permittivity (low dielectric constant)
- Low tan delta (low dielectric losses)
- High initial dielectric strength

□ Advantages of cross-linked polyethylene (in addition to the ones above):

- Improved mechanical properties at elevated temperature
- No melting above 105°C but thermal expansion occurs
- Reduced susceptibility to water treeing

□ Advantages of tree-retardant cross-linked polyethylene

- Even better resistance to water treeing

□ Advantages of EPR:

- Reduced thermal expansion relative to XLPE
- Reduced sensitivity to water treeing
- Increased flexibility

□ Advantages of PILC:

- Lack of sensitivity to dc testing
- Known history of reliability

Particular advantages of synthetic polymer insulations over PILC:

- Reduced weight
- Accessories more easily applied
- Easier to repair faults
- No hydraulic pressure/pumping requirements
- Reduced risk of flame propagation
- Reduced initial cost

Some of these advantages relate to electrical properties, and some do not.

Care must be taken in seeking to compare EPR to XLPE and TR-XLPE. There are many different EPR formulations, an all do not necessarily respond in the same manner on aging. The nature of the non-polymeric additives, including fillers, plays a major role in influencing properties as well as does the nature of the mixing process. What is clear is that any EPR formulation will have higher intrinsic losses than a non-mineral filled PE or XLPE system. Some EPR systems may have very high losses; this may favorably influence resistance to water treeing. However, EPR systems are generally “softer” due to their lack of crystallinity and therefore easier to handle in the field—especially at very low temperatures.

Disadvantages of PILC include the fact that lead is usually used as an outer sheath and the motivation not to use lead for new installations is very high. Paper cable systems are also highly susceptible to deterioration from moisture, once the lead sheath is breached.

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CHAPTER 6
ELECTRICAL PROPERTIES OF INSULATING MATERIALS

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1.0 INTRODUCTION

Electrical properties of interest for insulation materials can be classified into two major categories:

- Those of significance at low voltage operating stresses
- Those of significance at high voltage operating stresses

At low stresses, the properties of interest relate to dielectric constant, dissipation or power factor, and conductivity (resistivity). From an insulation materials perspective, dielectric constant can be visualized as representing the ability of the insulation to "hold charge." Dissipation factor represents a measure of the amount of energy lost as heat rather than transmitted as electrical energy. A good dielectric (insulation) material is one that holds little charge (low dielectric constant) and has very low losses (low dissipation factor). Polyolefins such as polyethylene (PE), cross-linked polyethylene (XLPE) and non-mineral-filled ethylene co- and ter-polymers (EP or EPR) represent examples of polymers that possess excellent combinations of these properties. This is discussed in depth in Chapter 5. [In this chapter, the terms 'power factor' and 'dissipation factor' will be used interchangeably.]

At high stresses (greater than operating stress), the characteristic of importance is dielectric strength. Here, the insulation must be resistant to partial discharges (decomposition of air in voids or microvoids within the insulation). Also of interest is the inherent ability of the polymeric insulation material to resist decomposition under voltage stress. Unfortunately, the data generated from the dielectric strength measurement does not provide constant values, but can vary depending upon how the measurement is performed. This will be discussed later in this chapter. In any event, the dielectric strength must be "high" for the insulation to be functional. This chapter will review factors that influence electrical properties at both low and high voltage stresses.

2.0 STRUCTURE-PROPERTY RELATIONSHIPS OF INSULATION MATERIALS

The electrical properties of insulation materials at operating stress are controlled by their chemical structure. Chapter 5 reviewed the inherent chemical structure of polyolefins, and described how the structure influences physico-chemical, and therefore electrical properties. Polyethylene, polypropylene, cross-linked polyethylene, tree-retardant cross-linked polyethylene and ethylene-propylene polymers are all polyolefins. In this chapter, we shall review the electrical properties of these polymeric insulation materials, and what influences their electrical properties. The emphasis shall be on these polyolefins, which represent the major classification of polymeric materials employed as cable insulation.

Low stress electrical properties are determined by the polar/non-polar nature of the polymer chains, and their degree of polarity. Polyethylene, comprised of carbon and hydrogen or methylene chains, is non-polar in nature, and has low conductivity. If a polar component (e.g., a carbon-oxygen linkage such as a carbonyl) is on the chain, the polymer chain now becomes more polar and the characteristics that lead to low conductivity are diminished. Ethylene copolymers with propylene retain their non-polar nature since the propylene moiety is as non-polar as is the ethylene moiety. Ethylene copolymers with vinyl acetate or ethyl acrylate are slightly more polar then polyethylene homopolymers.

When a polyolefin is subjected to an electrical field, the polymer chains have a tendency to undergo motion and become polarized. Figure 6-1 shows what happens when a polymer is “stressed” between electrodes, with different polarities resulting. Figure 6-2 shows how the polymer insulation material responds. There is a tendency for the positive charges on the polymer to move toward the negative electrode, and for the negative charges on the polymer to move toward the positive electrode, hence the polymer is ‘pulled’ in two directions. This is a general description, and does not take into account the influence of chemical structure. Since polyolefins are non-polar, one would expect that under the conditions described, there would be little to no polymer chain movement toward the electrodes.

Figure 6-1 shows a schematic description of a polymer subjected to electric field so that the polymer becomes polarized.

Figure 6-1 Polarization of a polymer subjected to an electric field.

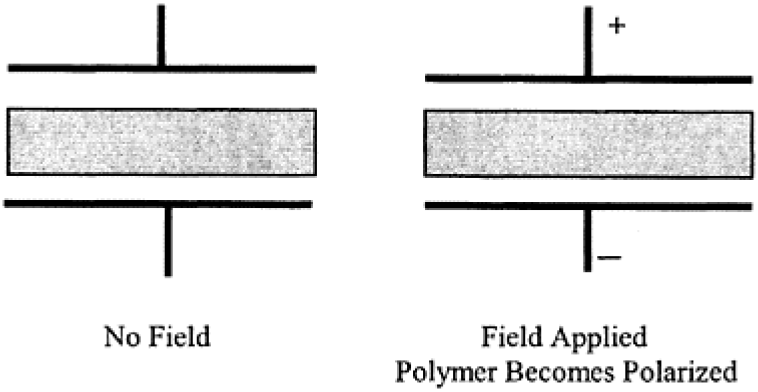


Figure 6-2 Charge migration on polymer chains subjected to an electric field.

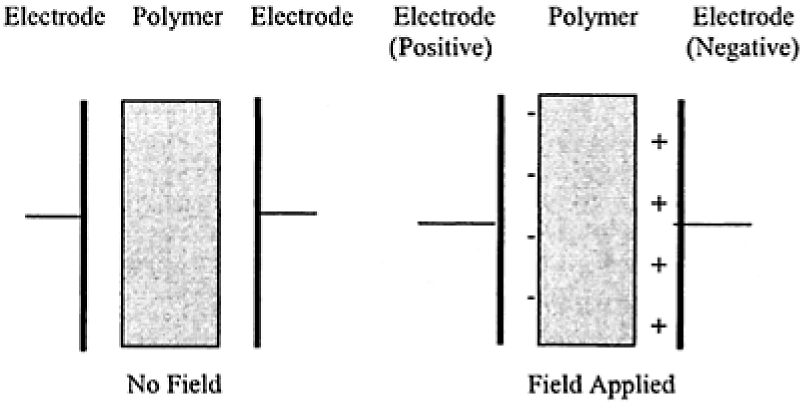
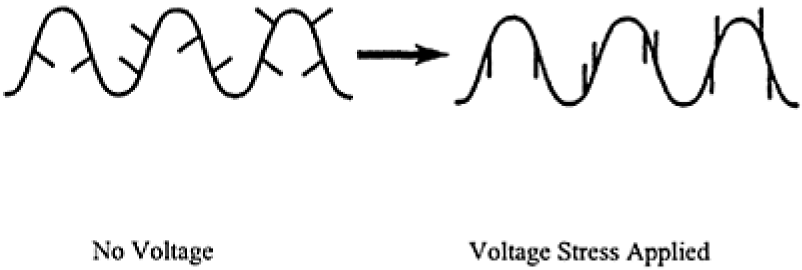


Figure 6-2 shows the insulation response to the application of the electric field. Positive charges on polymer chains migrate toward the cathode and negative charges migrate toward the anode.

Where do these charges come from? After all, the polyolefins have been described as being comprised of carbon and hydrogen, and as not being polar. This is correct when comparing the polyolefins to, say, polyamides or ethylene copolymers possessing substantial amounts of carbonyl or carboxylate groups. The fact is that such a description of polyolefins is “ideal”. While pure polyolefins are truly non-polar, in real world compositions there are always extremely small amounts of such polar materials present. This is discussed in Section 2.0. In addition, if there are polar foreign impurities present (such as ions), they will also migrate under the electric field.

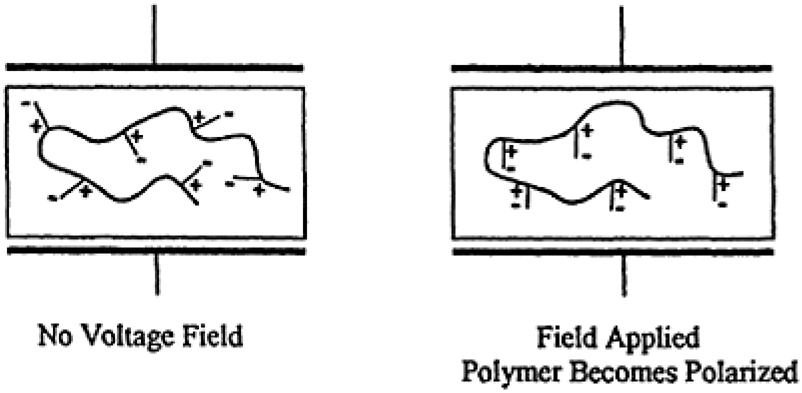
Figure 6-3 shows what may happen to a polymeric insulation material that has polar groups on the side branches, rather than on the main polymer chain. Note that in this idealized description of the “folded” chain. In this description, the main chain does not undergo any movement under voltage stress. The side chains, which were once “random,” are now aligned toward the electrodes. Figure 6-4 shows a “more realistic” coiled polymer chain with polar branches. Note how the alignment toward the positive and negative electrodes has taken place.

Figure 6-3 Schematic description of orientation of polar functionality on polymer side chains subjected to an electric field.



Under voltage stress, a polar chain orients toward the cathode or anode, depending upon the charge it possess. The non-polar portion of the chain does not migrate due to the field. However, the non-polar portion of the chain can theoretically be ‘dragged’ along by the migration of the polar portion.

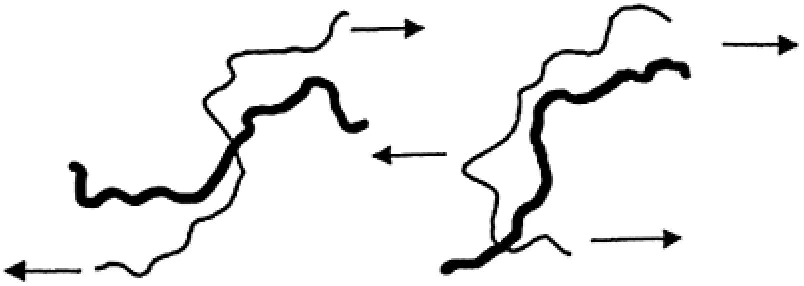
Figure 6-4 Polarization of side chains depicted on a coiled polymer.



A polymer is typically coiled, as discussed in Chapter 5. The positive charges on a polymer are attracted to the cathode. The negative charges are attracted toward the anode. The movement of these charged regions causes motion of the entire side chain.

In Figure 6-5, we show what happens to a polar main chain. Prior to this, we had considered what happened to the relatively short side chain branches. However, the entire main chain may undergo motion also, assuming it possesses polar functional groups that respond to the voltage stress. This figure shows that entire chain segments may move and rotate, in accordance with the applied field.

Figure 6-5 Main chain motion of a polymer subjected to an electric field.



Hence, when the main chain length possesses polar regions, the entire main chain may exhibit motion under the electric field. In this example, the center portion of the thin chain migrates to the left. The lower portion of the chain, depicted here as being thick, migrates toward the right. The depiction indicates that one chain is positively charged and the other is negatively charged.

It must be emphasized that this a generic description is what would happen under dc. Consider now what would happen under ac; here the polymer chain alignments will be shifting back and forth in accordance with the polarity change. Furthermore, this realignment will be taking place at a rate controlled by the frequency. In considering these points, it becomes evident that the response of a polyolefin polymer, even a slightly polar one, is quite different under ac than under dc.

The next question to consider is what happens if the movement of the chains cannot "keep up" with the change in frequency? Of course, our interest is in the 50 to 60 hertz range, but to understand the polymer response, it is desirable to review what happens over a very broad frequency range. This is reviewed in Section 3.0.

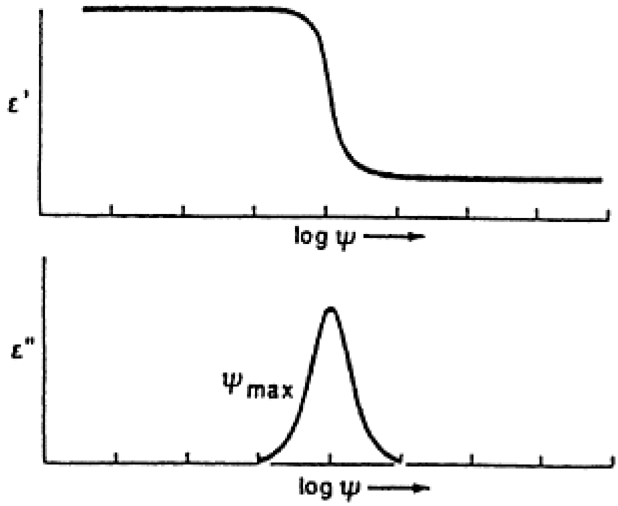
Before entering that subject however, it is necessary to recall that the polymer chains that we have been considering consist of many, many methylene groups linked together (see Chapter 5) and these are essentially non-polar in nature. However, during polymer insulation manufacture (polymerization of the monomer or monomer mixtures) and fabrication, these very long chains are always subjected to small chemical changes. These small chemical changes, known as oxidation, may occur during conversion of the monomer to the polymer, and also during conversion of the polymer to cable insulation). When extrusion is performed, the polymer is heated to very high temperatures in an extruder barrel, and is subjected to mixing and grinding due to screw motion and frictional contact against the barrel wall. As noted earlier, an effort is made to prevent any elevated-temperature-induced degradation (but more realistically, the event is kept to a minimum) by incorporating an antioxidant into the polymer. The antioxidant preferentially degrades and protects the polymer insulation. However a small degree of oxidative degradation, while controlled, cannot be prevented and always occurs. Therefore there will always be some oxidized functional groups on the polymer chains. These are important points to keep in mind when reviewing the polymer insulation response to frequency.

3.0 LOW VOLTAGE STRESS PARAMETERS

3.1 Dielectric Constant And Dissipation Factor

Different regions of the polymer chains will be sensitive to and respond differently to voltage stress. This phenomena is intimately related to the frequency. Different functional groups will be sensitive to different frequencies. When the "proper" frequency-functional group combination occurs, the chain portion will respond by moving, e.g., rotating. Since this phenomenon is frequency dependent, it should not be surprising that different responses will result from different functional group-frequency combinations. This is exactly what occurs. Referring to the top curve in Figure 6-6, we can see that at low frequencies, when stress is applied, the polar region-dipoles can respond and "accept" the charge, and re-align as described above. The dielectric constant is relatively high under these conditions. As the frequency increases, no change in this effect will occur as long as the dipoles can respond. At some point as the frequency continues to increase, the chains will have difficulty responding as fast as the field is changing. When the frequency change is occurring at so rapid a rate that no rotation can occur, the charge cannot be held and the dielectric upper portion of Figure 6-6 depicts the change in dielectric constant with frequency. The lower portion of the figure depicts the change in power factor with frequency.

Figure 6-6 Dielectric constant and power factor as a function of frequency.



For a polymer such as polyethylene, with very small amounts of polar functionality, the dielectric constant is always low [compared to a more polar polymer such as a polyamide (Nylon for example)]. However, oxidized regions will respond more readily due to their more polar nature. The reason for the change in dielectric constant with frequency is therefore apparent. It should also be noted that other parameters such as temperature will also affect this response. In essence, any change that affects motion of the polymer chain will affect the dielectric constant.

The point where the polymer chain segments undergo the rapid change in rate of rotation is of special interest. The lower curve of Figure 6-6, focusing on losses (e.g., dissipation factor), and shows a peak at this point. In considering dissipation factor, the same explanation applies; changes are affected by frequency and specific polymer nature. At low frequencies, the dipoles on the polymer chains follow variations in the ac field, and the current and voltage are out of phase; hence the losses are low. At very high frequencies as noted above, the dipoles cannot move rapidly enough to respond, and hence the losses are low here also. But where the change is taking place, the losses are greatest. This can be visualized by thinking in terms of motion causing the energy to be mechanical rather than electrical in nature. It is common to refer to the dielectric constant and power factor at 50 or 60 hertz and at 1,000 hertz.

In relating the information shown in Figure 6-6 to the earlier figures, it is to be noted that the polar functionality can be due to either motion of main chains or motion of branches, or both. Where the nature and concentration of oxidized groups are the same (such as only carbonyl or only hydroxyl functionality being present), one could expect the chains to (ideally) respond the same way at the same frequency. But what happens if there are many different functional groups present; what if there are polar groups such as carbonyl, carboxyl, or even amide or imide functionality present? One would expect different responses at any single frequency. Carrying this one step further, a main chain of a polyamide (such as Nylon) would clearly respond very differently from a main chain comprised of a polyolefin. Clearly, the nature of the polar functionality is very significant. Different functional groups will respond differently at the same frequency, whether on the main chain or a branch.

Main chain motion can be hindered due to the polymer visco-elastic nature. If the dipole is rigidly attached on the polymer backbone, then main chain motion is involved. If the dipole is on a branch, it can be considered to be ‘flexibly attached’, and the rate of motion of the branch will be expected to differ from the main chain, even if the functional group is the same.

The end result of all of this is a phenomenon called dispersion. Here, in response to the applied field, the chains will exhibit motion at different rates at any single frequency and temperature. The polymer chains may exhibit this change over a broad region rather than a sharp or localized region as the frequency and temperature is changed slightly.

For purposes of understanding power cable insulation response, the main interest is, of course, at 50 or 60 hertz. Also, our interest is in what is intended to be relatively non-polar systems. It is always necessary to remember that no system is perfect and there will be variations in degrees of polarity not only from one insulation material to another, and not only from one grade of the same material to another, but perhaps also from one batch of supposedly identical material to another. Much depends upon the processing control parameters during extrusion.

The literature reports dielectric losses of many different types of polyolefins as a function of temperature at controlled frequencies. Hence, it is known that conventional low-density polyethylene undergoes losses at various different temperatures. In addition, antioxidants, antioxidant degradation by products, and low molecular weight molecules will also respond; this complicates interpretation. With conventional cross-linked polyethylene, the situation is even more complex as there are peroxide residues and cross-linking agent by-products (see Chapter 5). These low molecular weight organic molecules, acetophenone, dimethyl benzyl alcohol, alpha methyl styrene, and smaller quantities of other compounds, will gradually migrate out of the insulation over time.

To now, we have focused on PE and XLPE. TR-XLPE possesses additives or more polar components (see Chapter 5) that lead to slightly increased dielectric constant and dissipation factors. With reference to EPR, it is necessary to distinguish between the polymers themselves, and the EPR compounds use as insulation. The properties of unfilled EPR are quite good; low dielectric constant and low dissipation factor. But unfilled EPR is not a practical insulation material (see Chapter 5). After fillers and other additives are incorporated, the dielectric constant and dissipation factor both rise. The reason is due to the additives.

Contaminants can be defined as ‘unintended non-polymeric components’ that might be present. We have already noted their influence on low operating stress parameters; they can migrate under voltage stress just as do polar portions of polymer insulation chains. [Examples are ions that can enter the cable core from the outside soil, or enter the insulation from the shields.] They also can influence other cable properties.

Interpretation of data therefore requires not only knowledge of the system, but some degree of caution is prudent.

The dielectric constant is dependent upon the temperature and frequency of testing. At constant temperature, it is reduced slightly as the frequency increases; at constant frequency, it increases with temperature. The dielectric constants of various common polymeric materials are shown in the Table 6.1.

Table 6-1 Dielectric Constants Of Various Polymers Used As Electrical Insulation

Polymer Type	Dielectric Constant (60Hz)
Polyethylene, low-density	2.25–2.35
Polypropylene	2.2–2.6
Polytetrafluoroethylene (Teflon)	2.1
Polyethylene, high-density	2.30–2.35
Ethylene-Propylene copolymer (unfilled)	2.25–2.35
Ethylene-Vinyl Acetate copolymer	2.50–3.16
Ethylene-Ethyl Acrylate copolymer	2.70–2.90
Epoxy (filled)	3.50–5.00
Nylon (unfilled)	3.90
PVC (flexible, plasticized)	5.00–9.00

The ‘classical’ definition of dielectric constant is the ratio of the capacitance (charge held) by the polymer when placed between two plates, relative to the charge held between those plates when the polymer is replaced by a vacuum. The vacuum contains no polar ingredients, and therefore is ‘pure’.

The dissipation factor represents the energy lost as heat, and is a function of the ‘efficiency’ of the insulation; it is the ratio of the resistance component of the current to the capacitive component of the current. It is commonly referred to as ‘tan delta’. [The power factor is not identical to the dissipation factor, but the values are nearly identical when the Tan delta is < 0.1]. Another term commonly used by designers is ‘loss factor,’ which represents the product of the dielectric constant and the dissipation factor.

3.2 Volume Resistivity And Insulation Resistance

Since insulating polymers are poor conductors, they have high resistance to movement of electrons. This resistance can be expressed as ‘ohms.’ Volume resistivity is a term commonly applied and represents the resistance to passage of electrons between opposite faces of a (hypothetical) cube, where the cube dimensions, distance between cube faces, and temperature are all defined; it has units of ‘ohm-cm.’ The volume resistivity is a fundamental materials parameter for insulation and semi-conducting materials.

A variation of this concept is ‘surface resistivity’, which is represented by the passage of electrons between opposite portions along the surface of a film of defined dimensions (this can be visualized one surface of the cube described above); the units here are ohms (not ohm-cm), as the width and length of the film being measured (one square cm.) are chosen to be the same. Thus, volume resistivity represents a three dimensional measurement, and surface resistivity represents a two dimensional measurement

It is important to recognize that volume resistivity (ohm-cm) is not to be confused with resistance per unit volume (or ohms per cubic centimeter). Also, volume resistivity differs from ‘insulation resistance,’ which is a term generally applied where measurements are made under a specific set of defined conditions. Insulation resistance is related to both the volume and surface resistance of the insulation material.

Volume resistivity, insulation resistance, and the other properties noted above are influenced by moisture content, voltage, time of applied voltage, and temperature. Volume resistivity increases with decreasing temperature. Clearly, the conditions of measurement are vital to understanding how to compare this property information for different insulations. It is an important parameter when considering properties of semiconducting materials

4.0 DIELECTRIC STRENGTH

The dielectric strength of an insulation material can be defined as the limiting voltage stress beyond which the dielectric can no longer maintain its integrity. The applied stress causes the insulation to fail; a discharge occurs which causes the insulation to rupture. The excess current flow (an arc) passes through the insulation. Once that happens, it can no longer serve its intended role. Dielectric strength has also been defined as the voltage gradient at which electrical failure occurs. Unfortunately, the dielectric strength is not an absolute number; the value obtained when dielectric strength is measured depends on many factors, not the least of which is how the test is performed. Therefore, it is necessary to review the issues involved, so that the value and the limitations of the term "dielectric strength" are well understood.

The dielectric strength is usually expressed in stress per unit thickness—volts per mil, or kV per mm. For full size cable, it is common to merely report the kV at which the cable has failed. Hence if a 175 mil wall cable fails at 52.5 kV (or 52, 500 volts), the dielectric strength can also be expressed as 300 V/mil (52,500/175).

Perhaps the most obvious value of dielectric strength would be the intrinsic strength. This is defined by the dielectric strength characteristics of the material itself in its pure and defect-free state, and measured under ideal test conditions that produce breakdown at the highest possible voltage stress. In practice, this is never achieved experimentally. One reason, as noted above, is the difficulty in attaining a defect-free pure insulation specimen. The closest one can come is by performing measurements of very thin, carefully prepared films with appropriate electrodes. (The thinner the film, the less the chance for a defect to exist.) Under these ideal conditions, the insulation itself would fail due to its inherent properties (bond strength rupture).

It is more likely is that failure will occur under discharge conditions; here, gas (e.g., air) present in small voids in the insulation (present due to processing characteristics or aging-induced defects), will undergo decomposition. Air is the most likely gas present for PE, XLPE, TR-XLPE or EPR (in contrast to vapors of cross-linking by products). The intrinsic dielectric strength of air is significantly less than that of any polymeric insulation. Under these conditions, the discharges that take place in these small voids leads to "erosion" of the insulation surfaces that are in contact with the air in the void, or microvoid. This in turn leads to gradual decomposition of the insulation and eventual failure. The decomposition of the air in the voids occurs at voltage stresses much lower than the inherent strength of the polymeric insulation itself. For example, the dielectric strength of a one-mil thick film of polyethylene measured under identical conditions to a layer of air (atmospheric pressure), is reported to give a dielectric strength value 200 times greater. The polyethylene dielectric strength is about 16,500 volts per mil, while that of air is about 79. The dielectric strength of air increases with pressure (that of polymer insulations do not change, as they are not compressible); however the degree of improvement is small. By increasing the pressure by a factor of 6, the dielectric strength increases by a factor of about 5—still well below that of the polymer film.

When focusing on extruded cable insulation, we are now concerned with relatively thick sections; 175 to 425 mil walls for distribution cables, and even thicker walls for transmission cables. Discharges that occur in these practical systems may not lead to immediate failure. It is possible that the discharge will cause rupture of a portion of the wall, and then cease. This could be related to the energy of the discharge, the size of the adjacent void, and, of course, the nature of the insulation material. When this occurs, a blackened needle-shaped series of defects results, sometimes resembling a tree limb; these are called electrical trees. Discharges may occur repetitively, and hence the tree will appear to grow. In time the "tree" will bridge the entire insulation wall and cause failure. Discharges may also occur on the surface of the insulation, particularly if there is poor adhesion between the insulation and shield layers. Surface discharges are not considered to be as serious as are internal discharges.

Another mechanism of failure is known as thermal breakdown. This occurs when the insulation temperature starts to increase as a result of aging under operating stress. Under voltage stress, some insulation systems will start to generate heat, due to high losses. If the rate of heating exceeds the rate of cooling (that normally occurs by thermal transfer), then thermal runaway occurs, and the insulation fails by essentially, thermally induced degradation. Several points should be kept in mind here:

- The heat transfer capability of polyolefins are low, and heat dissipation is not normally rapid.
- These events may occur in the presence or absence of discharges.
- The presence of inorganic fillers contributes to increasing the dielectric losses, and may exacerbate the situation. Also, some organic additives in the insulation may also lead to increasing the dielectric losses.

Finally, it should be noted that thermal breakdown of polylolefins is a well-studied area.

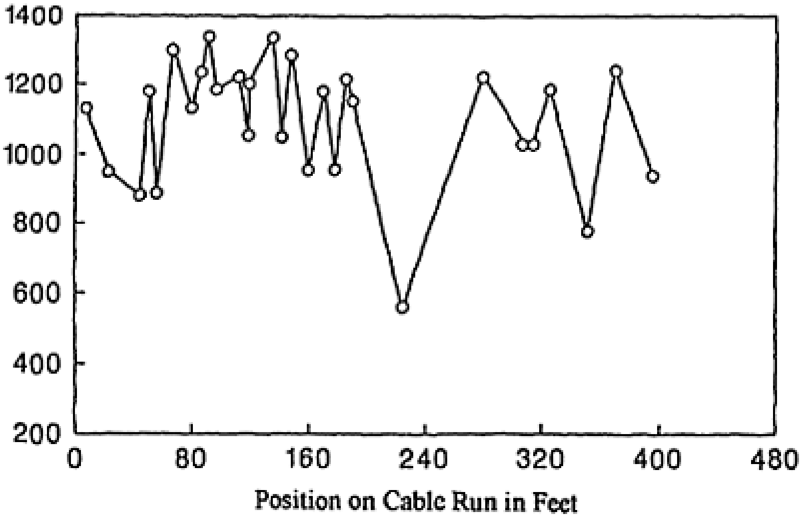
Although not a direct cause of failure, mention should be made of water treeing; water trees lead to a reduction in dielectric strength. These trees have a different shapes compared to electrical trees, and also have different causes. The differences are summarized below.

WATER TREES	**ELECTRICAL TREES**
Water required	Water not required
Fan or bush shaped	Needle or spindle shaped
Grow for years	Failure shortly after formation
Microvoids connected by tracks	Carbonized regions

Water trees grow under low (normal) operating stress, do not require the presence of “small voids,” and lead to a reduction in dielectric strength. Laboratory studies have shown that such trees can penetrate virtually the entire insulation wall yet not lead immediately to failure. As the chart shows, the “channels” or “tracks” that comprise water and electrical trees differ. Treeing is discussed in Chapter 17.

AC breakdown strength is commonly performed on full size cables as an aid in characterization. For full size cables, it is common to perform many such tests of long lengths of cables (e.g., 25 to 30 feet) and plot the data as Weibull or Log normal curves. This is done as the data always has some variation. A good example is data shown in Figure 6-7, where 5,000 feet of a 50, 000 foot run of cable was studied. In this Figure, it is seen that the dielectric strength of the full size cables vary from a low of about 600 V/mil to a maximum of about 1,350 V/mil. Figure 6-7 shows positions of breakdowns from one reel of 5,000 feet that was a portion of a 50,000 foot extrusion run.

Figure 6-7 AC breakdown (in volts per mil).



This demonstrates that although the cable was manufactured in (presumably) the same manner, significant differences can exist between cable sections. Sample lengths tested were from the same production run and from the same reel. From what has been noted above, it is likely that these variations are due to inevitable imperfections that result during processing. Variations such as these are not uncommon and are the reason for employing statistical analysis of data, such as Weibull or log normal distribution calculations.

The ac breakdown strength data shown above was obtained employing a five-minute step rise time, starting at about 50% of the anticipated breakdown strength. If the time interval between the steps is increased (e.g., from 5 to 10 minutes), the apparent ac breakdown strength will decrease. If the time interval between steps is increased again, to say 30 minutes, the apparent dielectric strength is reduced even more. In other words, the apparent dielectric strength that one obtains in performing a test increases as the voltage stress is applied more rapidly. [This is analogous to what happens during a tensile strength test for an insulation material such as polyethylene; the apparent tensile strength increases as the stress is applied more rapidly].

Therefore, the meaning of an “ac breakdown strength” value is relevant only if the manner in which the test was performed is known. In comparing AC dielectric strength values for different insulation materials, the test should always be performed in the same manner. This holds true whether one is comparing different grades of the same material (different grades of polyethylene) or different insulation materials (polyethylene versus polypropylene or EPR), for example. It is emphasized that it is particularly important, when comparing properties of different grades of an insulation, to assure that the same test conditions are employed.

It is not uncommon to test polymer films or small (miniature) cables using a different procedure; a ‘rapid-rise’ short time test that increases the voltage from zero at a predetermined speed (~100 to 3000 volts per second), until breakdown occurs. It should be apparent that the breakdown strength value(s) obtained by this approach will be greater than those from a ‘step-rise’ test procedure.

When the testing of thin films or slabs of insulation materials is performed in the laboratory, the opportunity to control the local environment during testing is easier. This should be done and should be reported. Since relatively small specimens are involved (compared to full size cables), a large number of specimens are usually tested to overcome the inherent variability in results. When working with small samples, since the opportunity to control the local environment during testing is greater, the reproducibility may be enhanced. Hence the following variables are to be controlled so that the information obtained represents a true representation of the statistical distribution in homogeneities for the material under study.

- specimen thickness
- temperature
- electrode shape and size

The reasons for controlling the thickness have been noted. This is especially of increasing importance as the thickness is reduced. Temperature control is vital, as the dielectric strength is related to the temperature of the specimen at the time breakdown occurs. The opportunity to control the temperature by using ovens is an advantage to small specimen testing.

The electrode shape and size represents a significant parameter for small sample testing. The most common electrodes are Rogowski types, where the electrode is curved and inserted into the polymer slab; this provides a uniform stress gradient and enhances the opportunity for obtaining meaningful information. If the electrode-polymer interface is sharp (instead of rounded) the voltage stress will be enhanced at this location. The failure of the test specimen will be induced at this location. Should that happen, the dielectric strength measured is related more to the manner in which the test was performed (inducing a high localized stress), rather than related to the properties of the insulation itself.

Needle tests are also performed, where a sharp, but controlled radius of curvature exists at the needle tip, and the latter is inserted into the specimen part way to the ground plane. Voltage stress is applied and the dielectric strength is measured; this approach has been used to determine the influence of additives to the insulation that are designed to increase the breakdown strength (to aid in developing superior insulation materials). A detailed description of typical arrangements of electrodes that may be used for dielectric strength testing of thin films is provided by Mathes in the references.

The frequency of measurement may be readily varied in thin film studies, much more easily than for full size cables. While most testing is performed at 60 hertz, testing has also been performed at frequencies ranging to 1,000 hertz. Again, the rate of rise of the field is vitally important, and can readily be controlled.

A less common but often applied alternate dielectric strength test is an impulse breakdown strength test. The impulse wave shape during this test is intended to simulate lightning or switching surges. Standard wave shapes are defined in industry specifications

Another parameter often measured when considering dielectric strength issues for materials is ‘arc resistance’. This parameter is usually referred to when considering films of insulation materials (rather than cables). It relates to the timed required for breakdown to occur along the surface, and is also caused by the development of a conducting path. Arc resistance is measured in time (seconds) for breakdown to occur, rather than in breakdown strength units. Cleanliness and moisture influence this measurement; the higher the value (time) the greater the resistance to surface arcing, or tracking.

5.0 PARTIAL DISCHARGE

Although not a fundamental property of insulation materials, the important subject of partial discharge is reviewed here from a materials perspective. Partial discharge results from decomposition of air in voids or microvoids that are present within the cable insulation material. The degraded air, or the decomposition products thereof, attacks the void surface.

Such voids in extruded cable insulation may result from inadequate control of the manufacturing process, or from aging-induced changes. Partial discharge testing is performed on newly manufactured cables precisely to prevent cables with voids of certain sizes (and quantities) to reach the user. Since extruded cables develop water trees on aging (see Chapter 17), small voids do develop and the can grow in size.

The discharges are a result of the very low dielectric strength of air; its dielectric strength is 2 to 3 orders of magnitude less than that of polyethylene (at atmospheric pressure). Whether any specific void undergoes discharge depends upon the void size and shape, the pressure, and the temperature. Different insulation materials will respond differently to any specific discharge event.

When discharges occur, the void surface is bombarded with electrons, and the charges can be trapped or migrate into the insulation. A polar insulation will trap electrons more readily than a non-polar one. Some discharges are so energetic that they decompose the surface of the void; cracks or “pits’ on the surface have been reported. Polyolefin degradation yields products such as low molecular weight hydrocarbons and oxalic acid. Polymeric free radicals can form and react with oxygen; in the case of polyethylene, this leads to peroxide formation and eventually to both cross-linked and degraded PE. (This is analogous to radiation effects; see Chapter 5.) Decomposition products of the nitrogen and oxygen in air can conceivably react with the attacked void surface, yielding nitrogen-containing by-products. Other insulation materials would lead to different products.

Partial discharge has been the subject of numerous studies from a phenomenological perspective. For details, see reference 6-5 (Bartnikas).

6.0 SUMMARY

Electrical properties are reviewed from the perspective of what happens when the insulation materials and cables are subjected to low and high voltage stress. Under low stress, the chemical structure of polymeric insulation materials determines the response and therefore magnitude of the dielectric constant and dissipation factor. These two properties are significant at operating stress and generally considered to be “low”. Polyolefins such as polyethylene, cross-linked polyethylene and unfilled ethylene-propylene co- or ter-polymers have low dielectric constants and low dissipation factors. Low levels of oxidation, generally resulting from processing the polymer or aging-induced changes, lead to slight increases in these properties. Insulation materials with inorganic fillers (such as EPR), or additives that are polar in nature (such as some TR-XLPE insulation materials), have increased dielectric constants and dissipation factors. Volume resistivity and insulation resistance are defined. Higher than normal operating stresses are used to determine the dielectric strength of an insulating material. Inherent (absolute) ac breakdown strength of an insulation is not possible to measure in practice; practical measurements provide values that are dependent upon the manner in which the test is designed and performed. Dielectric strength results should always be defined by the manner in which the test information was obtained. Variations in ac breakdown strength of freshly manufactured cables are not uncommon; statistical evaluation of the dielectric strength data is required. Differences between water and electrical trees are introduced. Finally, partial discharge is discussed from a materials perspective.

7.0 REFERENCES

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CHAPTER 7
SHIELDING OF POWER CABLES

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1.0 GENERAL

Shielding of an electric power cable is accomplished by surrounding the insulation of a single conductor or assembly of insulated conductors with a grounded, conducting medium. This confines the electric field to the inside of this shield. Two distinct types of shields are used: metallic and a combination of nonmetallic and metallic.

The purposes of the insulation shield are to:

1. Obtain symmetrical radial stress distribution within the insulation.
2. Eliminate tangential and longitudinal stresses on the surface of the insulation.
3. Exclude from the electric field those materials such as braids, tapes, and fillers that are not intended as insulation.
4. Protect the cables from induced or direct over-voltages. Shields do this by making the surge impedance uniform along the length of the cable and by helping to attenuate surge potentials.

2.0 CONDUCTOR SHIELDING

In cables rated over 2,000 volts, a conductor shield is required by industry standards. The purpose of the conductor shield, also called conductor screen, over the conductor is to provide a smooth cylinder rather than the relatively rough surface of a stranded conductor in order to reduce the stress concentration at the interface with the insulation.

Conductor shielding has been used for cables with both laminar and extruded insulations. The materials used are either semi conducting materials or ones that have a high dielectric constant and are known as stress control materials. Both serve the same function of stress reduction. Conductor shields for paper-insulated cables are either carbon black tapes or metalized paper tapes.

The conductor shielding materials were originally made of semi conducting tapes that were helically wrapped over the conductor. Present standards still permit such a tape over the conductor. This is done, especially on large conductors, in order to hold the strands together firmly during the application of the extruded semi conducting material that is now required for medium voltage cables. Experience with cables that only had a semi conducting tape was not satisfactory, so the industry changed their requirements to call for an extruded layer over the conductor.

In extruded cables, this layer is now extruded directly over the conductor and is bonded to the insulation layer that is applied over this stress relief layer. It is extremely important that there be no voids or extraneous material between those two layers since this is the area of maximum voltage stress in a cable.

Present-day semiconducting extruded layers are made with clean materials (a minimum of undesirable impurities) and are extruded to be very smooth and round. This has greatly reduced the formation of water trees that could originate from irregular surfaces (commonly known as protrusions) because of high electrical stress. By extruding the two layers simultaneously, the conductor shield and the insulation are cured at the same time. This provides the inseparable bond that minimizes the chances of the formation of a void at that critical interface.

For compatibility reasons, the extruded shielding layer is usually made from the same or a similar polymer as the insulation. Special carbon black is used to make the layer over the conductor semi conducting to provide the necessary conductivity. Industry standards require that the conductor semi conducting material have a maximum resistivity of 1,000 meter-ohms. Those standards also require that this material pass a long-time stability test for resistivity at the emergency operating temperature level to insure that the layer remains conductive and hence provides a long cable life. This procedure is described in reference [7-1].

A water-impervious material can be incorporated as part of the conductor shield to prevent radial moisture transmission. This layer consists of a thin layer of aluminum or lead sandwiched between semiconducting materials. A similar laminate may be used for an insulation shield for the same reason.

There is no definitive standard that describes the class of extrudable shielding materials known as “super smooth, super clean.” As will be described in Chapter 9, Standards and Specifications, It is not usually practical to use a manufacturer’s trade name or product number to describe any material. The term “super smooth, super clean” is the only way at this writing to describe a class of materials that provide a higher quality cable than an earlier version. This is only an academic issue since the older types of material are no longer used for medium voltage cable construction by known suppliers. The point is that these newer materials have tremendously improved cable performance in laboratory evaluations.

3.0 INSULATION SHIELDING FOR MEDIUM-VOLTAGE CABLES

The insulation shield for a medium voltage cable is made up of two components: (1) a semi conducting or stress relief layer and (2) a metallic layer of tape or tapes, drain wires, concentric neutral wires, or a metal tube. They must function as a unit for a cable to achieve a long service life.

3.1 Stress Relief Layer

The polymer layer used with extruded cables has replaced the tapes shields that were used many years ago. This extruded layer is called the extruded insulation shield or screen. Its properties and compatibility requirements are similar to the conductor shield previously described except that standards require that the volume resistivity of this external layer be limited to 500 meter-ohms. This lower resistivity value—as compared with the conductor shielding value—was established due to the fact that it is possible that workers could come in contact with the outer layer while the cable is energized.

The nonmetallic layer is directly over the insulation and the voltage stress at that interface is lower than at the conductor shield interface. This outer layer is not required to be bonded for cables rated through 35 kV. At voltages above that, it is strongly recommended that this layer be bonded to the insulation.

Since most users want this layer to be easily removable, the Insulated Cable Engineers Assoc. (ICEA) S-94–649–2000 [7-2] has established strip tension limits. Presently these limits are that a ½-inch wide strip cut parallel to the conductor peel off with a minimum of 3 pounds and a maximum of 24 pounds of force that is at a 90° angle to the insulation surface.

3.2 Metallic Shield

The metallic portion of the insulation shield or screen is necessary to provide a low resistance path for charging current to flow to ground. It is important to realize that the extruded shield materials will not survive a sustained current flow of more than a few milliamperes. These materials are capable of handing the small amounts of charging current, but cannot tolerate unbalanced or fault currents.

The metallic component of the insulation shield system must be able to accommodate these higher currents. On the other hand, an excessive amount of metal in the shield of a single-conductor cable is costly in two ways. First, additional metal over the amount that is actually required increases the initial cost of the cable. Secondly, the greater the metal component of the insulation shield, the higher the shield losses that result from the flow of current in the central conductor. This subject is treated more completely in Chapter 13, Ampacity.

A sufficient amount of metal must be provided in the cable design to ensure that the cable will activate the back-up protection in the event of any cable fault over the life of that cable. There is also the concern for shield losses. It therefore becomes essential that:

☐ The type of circuit interrupting equipment to be analyzed. What is the design and operational setting of the fuse, recloser, or circuit breaker?
☐ What fault current will the cable encounter over its life?
☐ What shield losses can be tolerated? How many times is the shield to be grounded? Will there be shield breaks to prevent circulating currents?

Although there are constructions such as full and one-third neutral listed in ICEA standards for single-conductor, URD and UD cables, these may not be the designs that are the most economical for a particular installation. Studies have been published on the optimum amount of metal to use in the neutral [7-3,7-4]. Documents such as these should be reviewed prior to the development of a cable design. In Chapter 13, Ampacity, there is an in-depth discussion of shield losses.

3.3 Concentric Neutral Cables

When concentric neutral cables are specified, the concentric neutrals must be manufactured in accordance with applicable ICEA standards. These wires must meet ASTM B3 for uncoated wires or B33 for coated wires. These wires are applied directly over the nonmetallic insulation shield with a lay of not less than six or more than ten times the diameter over the concentric wires.

4.0 SHIELDING OF LOW-VOLTAGE CABLES

Shielding of low voltage cables is generally required where inductive interference can be a problem. In numerous communication, instrumentation, and control cable applications, small electrical signals may be transmitted on the cable conductor and amplified at the receiving end. Unwanted signals (noise) due to inductive interference can be as large as the desired signal. This can result in false signals or audible noise that can effect voice communications. Across the entire frequency spectrum, it is necessary to separate disturbances into electric field effects and magnetic field effects.

4.1 Electric Fields

Electric field effects are those that are a function of the capacitive coupling or mutual capacitance between the circuits. Shielding can be effected by a continuous metal shield to isolate the disturbed circuit from the disturbing circuit. Even semiconducting extrusions or tapes supplemented by a grounded drain wire can serve some shielding function for electric field effects.

4.2 Magnetic Fields

Magnetic field effects are the result of a magnetic field coupling between circuits. This is a bit more complex than for electrical effects.

At relatively low frequencies, the energy emitted from the source is treated as radiation. This increases with the square of the frequency. This electromagnetic radiation can cause disturbances at considerable distance and will penetrate any “openings” in the shielding. This can occur with braid shields or tapes that are not overlapped. The type of metal used in the shield also can affect the amount of disturbance. Any metallic shield material, as opposed to magnetic metals, will provide some shield due to the eddy currents that are set up in the metallic shield by the impinging field. These eddy currents tend to neutralize the disturbing field. Non-metallic, semiconducting shielding is not effective for magnetic effects. In general, the most effective shielding is a complete steel conduit, but this is not always practical.

The effectiveness of a shield is called the “shielding factor” and is given as:

$$\mathrm{SF} = \frac{\text{Induced voltage in shield circuit}}{\text{Inducted voltage in unshielded circuit}} \tag{7.1}$$

Test circuits to measure the effectiveness of various shielding designs against electrical field effects and magnetic field effects have been reported by Gooding and Slade.

5.0 REFERENCES

[7-1] Insulated Cable Engineers Association Publication T-25–425, “Guide for Establishing Stability of Volume Resistivity for Conducting Polymeric Compounds of Power Cables,” 1981, Global Engineering Documents, 15 Inverness Way East, Englewood, CO, 80112, USA.

[7-2] Insulated Cable Engineers Association Standard S-94–649–2000 “Standard for Concentric Neutral Cables Rated 5,000–46,000 Volts,” Global Engineering Documents, 15 Inverness Way East, Englewood, CO, 80112, USA

[7-3] EPRI EL-3014 and EL-3102, RP-1286–2: “Optimization of the Design of Metallic Shield/Concentric Neutral Conductors of Extruded Dielectric Cables Under Fault Conditions,” EPRI, P O Box 10412, Palo Alto, CA 94303–0813.

[7-4] EPRI EL-5478, RP-2839–1: “Shield Circulating Current Losses in Concentric Neutral Cables,” EPRI, Palo Alto, CA.

CHAPTER 8
SHEATHS, JACKETS, AND ARMORS

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1.0 SHEATHS

The terms “sheaths” and “jackets” are frequently used as though they mean the same portion of a cable. Sheath is properly the term that applies to a metallic component over the insulation of a cable. An example is the lead sheath of a paper insulated, lead-covered cable. See the definition of jacket in 2.0 below.

Various metals may be used as the sheath of a cable such as lead, copper, aluminum, bronze, steel, etc. A sheath provides a barrier to moisture vapor or water ingress into the cable insulation. It is necessary to use such a sheath over paper insulation, but it also has a value over extruded materials because of water ingress.

The thickness of the metal sheath is covered by ICEA and AEIC standards and specifications, but there are some constructions that are not covered. The thickness is dependent on the forces that can be anticipated during the installation and operation of the cable. Designs range from a standard tube to ones that are longitudinally corrugated. The bending radius of the finished cable is dependent on such configurations.

To fully utilize the metal chosen, one should consider first cost, ampacity requirements—especially during fault conditions, and corrosion [8-1].

2.0 THERMOPLASTIC JACKETS

The term jacket should be used for nonmetallic coverings on the outer portions of a cable. They serve as electrical and mechanical protection for the underlying cable materials.

There are many materials that may be used for cable jackets. The two broad categories are thermoplastic and thermosetting. For each application, the operating temperature and environment are important factors that must be considered.

2.1 Polyvinyl Chloride

Polyvinyl chloride (PVC) is the most widely used nonmetallic jacketing material in the wire and cable industry. Starting in 1935, when it first became available, the use of PVC grew rapidly because of its low cost, its easy processing, and its excellent combination of overall properties including fire and chemical resistance.

PVC belongs to a group of polymers referred to as vinyls. The unmodified polymer contains approximately 55% chlorine. It is fairly linear in structure (few side chains) with approximately 5 to 10% crystallinity. The material must be compounded with additives such as fillers, plasticizers, and stabilizers to attain flexibility, heat resistance, and low temperature properties. General purpose jacketing materials normally possess good physical strength, moisture resistance (but not as compared to polyethylene), adequate oil resistance, good flame resistance, and excellent resistance to weathering and to soil environments. Both flame resistance and low temperature flexibility can be improved (within limits) by the use of additives.

General purpose PVC compounds are recommended for installation at temperatures above −10°C, but specially formulated compounds may be used as low as −40°C.

One of the limitations of PVC jacketed cable is its tendency to creep under continuous pressure. For this reason, cables that are to be supported vertically with grips should not have PVC jackets. Hypalon or Neoprene are recommended for such use.

In the low voltage field, PVC is widely used as a single layer of material where it functions both as insulation and jacket. Since PVC is usually a thermoplastic material, it cannot take high temperatures. Under high current fault conditions, the insulation can be permanently damaged by melting or can emit plasticizers and become stiff and brittle over a period of time. For this reason, it is not used for utility secondary network cable. Similarly, in industries that handle large amounts of heated material, or where there is the possibility of excessive heat, the use of PVC is avoided because of its tendency to melt or deform when heated to a high temperature. Under continuous dc voltage in wet locations, as in battery operated control circuits, single-conductor PVC-insulated cables have frequently failed due to electro-endosmosis (water vapor ingress created by voltage stress).

The large percentage of chlorine can be released during a fire. When combined with moisture, hydrochloric acid may be produced. It may leach into concrete structural members and attack and weaken the steel. This situation highlights one of the major problems that can result from the use of PVC. PVC has fallen out of favor for electric utility underground medium voltage power cables because the moisture resistance is not as good as polyethylene in the common case.

2.2 Polyethylene

Polyethylene (PE) has been widely used as a jacket for underground cables since it became commercially available in large quantities in about 1950. For use as a jacket, polyethylene may be compounded with carbon black or coloring material, and with stabilizers. Carbon black gives the material the necessary sunlight protection for outdoor use. Polyethylene for jacketing is categorized under three different densities:

Low density	0.910 to 0.925 grams per cm^3
Medium density	0.926 to 0.940 grams per cm^3
High density	0.941 to 0.965 grams per cm^3

Density generally affects the crystallinity, hardness, melting point, and general physical strength of the jacketing material. In addition to density, molecular weight distribution is important since it influences the processing and properties of the polymer.

Polyethylene jackets are an excellent choice where moisture resistance is a prime design criterion since it has the best moisture resistance of any non-metallic jacket material. When polyethylene is used as a jacket material, it should be compounded with enough carbon black to prevent ultra-violet degradation. Linear, low density, high molecular weight (LLDPE) is the most popular jacket material since it has better stress-crack resistance than the high-density materials. High density provides the best mechanical properties, but may be very difficult to remove from the cable.

In evaluating fillers, both black and non-black, it has been found that although many of these materials improve the aging characteristics, carbon black is by far the best. It has also been found that the aging resistance increases with carbon black loading from 2 to 5 percent. Normally, a 2.5 to 3.0 percent loading is used.

Although PE has good moisture resistance and good aging properties in its temperature limits, it has poor flame resistance. This discourages using it as a jacket in many circumstances. Polyethylene jackets have good cold bend properties since they will pass a cold bend test at about −55°C. They are extremely difficult to bend at low temperature because of their stiffness. Like PVC, PE generally is a thermoplastic material and will melt at elevated temperatures. This temperature will vary slightly with molecular weight and density, but melt occurs at about 105 to 125°C largely depending on density.

High-density polyethylene (HDPE) has been used extensively as the second (outer) layer for “ruggedized” thermoplastic in secondary and low voltage street light cables because of its toughness.

While black polyethylene for jacketing is frequently an insulating material, with higher loadings of carbon black it can be a semiconducting material. This material has been used for over 40 years in direct-buried applications to improve the grounding of the concentric neutral.

2.3 Chlorinated Polyethylene (CPE)

Chlorinated polyethylene (CPE) can be made either as a thermoplastic or as a thermosetting jacket material. As a thermoplastic material, it has properties very similar to PVC, but with better higher temperature properties and better deformation resistance at high temperatures than PVC. CPE jackets also have better low temperature properties than PVC unless the PVC is specifically compounded for this property.

2.4 Thermoplastic Elastomer (TPE)

Thermoplastic elastomer (TPE) is a thermoplastic material with a rubber-like appearance. It is a form of crystalline polyethylene and it comes in various types. It can be compounded for use as either an insulation or a jacketing material. By use of compounding techniques, a good electrical insulation can be developed with good moisture resistance properties.

Also, a jacketing material can be compounded to provide flame resistance, low temperature performance, good abrasion resistance, and good physical properties. This material is relatively new as compared to the thermoplastics previously mentioned, but appears to be a very versatile material.

2.5 Nylon

Nylon is a thermoplastic with many properties that make it desirable for jacketing of wire and cable. Nylon has relatively high strength, tough, but rather stiff especially in cold weather. Nylon also has good impact fatigue and, within limitations, good abrasion resistance. A very important feature is the low coefficient of friction in contact with conduit materials. This is an aid in pulling cables into conduits. Nylon has excellent resistance to hydrocarbon fuels and lubricants as well as organic solvents. However, strong acids and oxidizing agents will attack nylon. The most common use of nylon in cable jacketing is the jacket on THHN and THWN building wire.

3.0 THERMOSETTING JACKETING MATERIALS

Thermosetting jackets are not widely used for underground distribution cables except for the special case of medium- or high-density crosslinked polyethylene that is used as the outer layer on two layer, ruggedized secondary cables. Thermosetting jackets are more commonly utilized in industrial and power plant applications.

3.1 Cross-linked Polyethylene

Cross-linked polyethylene, with the addition of carbon black to provide sunlight resistance, provides a tough, moisture, chemical, and weather resistant jacket material. The medium and high-density materials are especially tough and are widely used as the outer layer on two layer ruggedized secondary cables. Only limited use is found for other purposes.

3.2 Neoprene

Neoprene has been used as a jacketing material since 1950 for large power cables such as paper insulated, lead-covered cables and portable cables. Compounds of neoprene usually contain from 40 to 60% by weight of neoprene that is compounded with other ingredients to provide the desired properties such as good heat resistance, good flame resistance, resistance to oil and grease, and resistance to sunlight and weathering. Moisture resistance can be compounded into the material when required.

Properties that can be varied by compounding techniques are: improved low temperature characteristics, improved physical strength, and better moisture resistance. Most neoprene compounds have good low temperature characteristics at −30°C to −40°C. Special compounding can lower this to −60 °C, but other properties, such as physical strength, have to be sacrificed.

Because of its ruggedness, tear resistance, abrasion resistance, flame resistance, and heat resistance, neoprene is the most widely used jacketing material for the mining industry. This is probably the most severe application for cables from a physical standpoint. The thermosetting characteristics of neoprene are desirable in this application since these cables must withstand high temperature while installed on cable reels. Thermoplastic jacketing materials would soften and deform under such environments.

3.3 Chlorosulphanated Polyethylene (CSPE)

Chlorosulphanated polyethylene (CSPE) is a thermosetting jacket compound with properties very similar to neoprene. CSPE is unique in that colored compounds of this material, protected by sunlight stable pigments, have weather resistant properties similar to black CSPE compounds. Hypalon is the trade name of the most commonly used material.

CSPE compounds are superior to neoprene compounds in the areas of resistance to heat, oxidizing chemicals, ozone, and moisture. They also have better dielectric properties than neoprene. The flame resistance of both materials is excellent. The superior heat resistance of CSPE as compared with neoprene, makes it the better choice for cables rated at conductor temperatures of 90°C.

3.4 Nitrile Rubber

Nitrile rubber compounds are copolymers of butadiene and acrylonitrile. They provide outstanding resistance to oil at higher temperatures. Since this is their only outstanding feature, they are generally limited to oil well applications where temperatures up to 250°C can be encountered. Their poor oxidation resistance in air limits their use for other applications.

3.5 Nitrile-Butadiene/Polyvinyl Chloride

These jacket compounds are blends of nitrile rubber mixed with PVC to provide a thermosetting jacket similar to neoprene. The advantage of this material over neoprene is that colored jackets of nitrile-butadiene rubber (NBR)/PVC have properties comparable to black jackets and can be compounded for physical properties and tear resistance similar to that of neoprene.

3.6 Ethylene Propylene Rubber

Ethylene propylene rubber (EPR) is frequently used as an insulating material because of its balance of outstanding electrical properties. They can also be used for jackets, especially in low temperature applications where flexibility is required. These materials can be compounded for −60°C applications with reasonably good physical properties and tear resistance.

EPR is not generally used for a jacketing material in other applications. They are used as jackets in low voltage applications when flame resistance has been compounded into the material.

4.0 ARMOR

4.1 Interlocked Armor

This armor consists of a single metal tape whose turns are shaped to interlock during the manufacturing process. Mechanical protection is therefore provided along the entire cable length.

Galvanized steel is the most common metal provided. Aluminum and bronze are used where magnetic effects or weight must be considered. Other metals, such as stainless steel or copper, are used for special applications.

Interlocked-armor cables are frequently specified for use in cable trays and for aerial applications so that conduit and duct systems can be eliminated. The rounded surface of the armor withstands impact somewhat better than flat steel tapes. The interlocked construction produces a relatively flexible cable that can be moved and repositioned to avoid obstacles during and after installation.

An overall jacket is often specified in industrial and power plants for corrosion protection and circuit identification. Neither flat-taped armor nor interlocked armor is designed to withstand longitudinal stress, so long vertical runs should be avoided.

4.2 Round-Wire Armor

This construction consists of one or two layers of round wires applied over a cable core. For submarine cable applications, the wires are usually applied over a bedding of impregnated polypropylene or jute.

Round-wire armor is used where high tensile strength and resistance to abrasion and mechanical damage are desired. Vertical riser cables and borehole cables are made with round-wire armor when end-suspension from the wires is necessary for support for the longitudinal stresses. Round wires have less resistance to piercing than flat-tape armor or interlocked armor, but has superior tensile strength and abrasion resistance.

To calculate the strength of armor wires, the following calculation is suggested:

$$W=wl_n \tag{8.1}$$

where W=total weight of cable in pounds
w=weight of cable to be suspended in pounds per 1,000 ft
l_n=length of cable in thousands of feet
Strength of steel armor wires:

$$S=NA\times 50{,}000/f \tag{8.2}$$

where S=strength in pounds
N=number of armor wires
A=area of one armor wire in square inches
F=factor of safety (usually 5)

For copper or bronze, use tensile strength in ASTM Specifications instead of 50,000. If the strength is found to be less than the total weight *W*, the next step would be to select the next larger size of armor wires and recalculate the values.

For single-conductor cables, copper or aluminum wires have been used to minimized losses due to circulating currents. Such constructions sacrifice mechanical strength in order to achieve the lower losses.

Armor wires can be made with the individual wires coated with polyethylene or other corrosion resistant coverings. Since there is a portion of the circumference without metal protection, cables with such covered wires are usually made with two layers of armor wires with the second layer in the opposite lay to the first.

For installations in severe rock environments, two layers of steel wires, with no individual coverings, are applied in reverse lay. The outer layer frequently is applied with a very short lay to achieve optimum mechanical protection.

The number of armor wires for a wire-armored cable may be calculated from the following equation:

$$N = \left[\frac{\pi(D+d)}{Fd}\right] -2 \qquad (8.3)$$

where N=number or armor wires, nearest whole number

D=core diameter of cable under armor in inches

d=diameter of armor wire in inches

F=lay factor (see Table 8-2)

$D+d$=pitch diameter or armor wire in inches

Armor resistance may be calculated from the following equation:

$$R_a = \frac{r_a \bullet F}{1{,}000\ N} \qquad (8.4)$$

where r_a=dc resistance of one armor wire or tape per 1,000 feet at temperature t in ohms

F=lay factor (see Table 8-2)

N=number or armor wires

Note: For steel wire armor, increase *Ra* by 50% to obtain approximate ac resistance.

Table 8-1 Approximate DC Resistance of Armor Wire

Wire Size, BWG	Wire Diameter, inches	Galvanized Steel, ohms Per 1,000 ft	Hard Drawn Copper, ohms Per 1,000 ft	Commercial Bronze, ohms Per 1,000 ft
12	0.109	7.33	0.895	2.49
10	0.134	4.92	0.592	1.65
8	0.165	3.16	0.391	1.09
6	0.203	2.12	0.258	0.72

	4	0.238	1.53	0.188	0.52
Basis:					
Conductivity,		% IACS	12.0	97.5	40.0
Temperature Coefficient of Resistivity		(α)	0.0035	0.00383	0.00190

Table 8-2 Lay Factor for Round Wire Armor

Ratio of Length of Lay to Pitch Diameter of Armor Wire	Lay Factor
7	1.095
8	1.072
9	1.057
10	1.048
11	1.040
12	1.034

Note: Use 7 as a typical value if the ratio is unknown.

5.0 REFERENCE

[8-1] Landinger, Carl C., adapted from class notes of "Understanding Power Cable Characteristics and Applications," University of Wisconsin—Madison, October, 2001.

CHAPTER 9
STANDARDS AND SPECIFICATIONS

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1.0 INTRODUCTION

Standards and specifications for power, control, signal, instrumentation and communication cables have been prepared in the North America by various industry organizations since the early part of the twentieth century. These industry specifications are commonly referenced in user specifications and supplemented by the user to include specifics required by the user. Electrical cables are manufactured to these requirements depending on the application of the particular installation.

The power cables that are covered by these standards and specifications can be classified under three major categories:

□	Low Voltage Cables	Rated up to 2,000 volts
□	Medium Voltage Cables	Rated 2,001 through 46,000 volts
□	High Voltage Cables	Rated 69,000 volts to 500,000 volts

The most widely used documents in the North America are those issued by the American National Standards Institute (ANSI), American Standards for Testing and Materials (ASTM), Insulated Cable Engineers Association (ICEA) in conjunction with the National Electrical Manufacturers Association (NEMA), the Association of Edison Illuminating Companies (AEIC), the Rural Electrification Administration (RUS), the Aluminum Association (AA) and Underwriter’s Laboratories (UL) in conjunction with the National Electrical Code (NEC). These organizations may loosely be categorized into:

(1) manufacturers organizations
(2) user organizations
(3) consensus organizations

2.0 MANUFACTURERS ORGANIZATIONS

2.1 ICEA

This group was formerly known as IPCEA. They removed the "Power" from their name to more accurately describe a broader scope of activities. Sections in ICEA include:

Extruded Dielectric Power	EDP
Portable, Communication	COM
Control and Instrumentation	C&I

Membership is made up of technical employees of cable manufacturers in North America. They develop standards, guides, and committee reports on all aspects of insulated cable design, materials, and applications. They work with other organizations toward the development of joint standards. Many of their standards are subject to the approval of NEMA and these are published as a joint ICEA/NEMA standard.

These standards encompass the entire cable: conductor, shields, insulation, jackets, testing, etc. The only possible omission is packaging. This is considered to be an area that is not allowed by United States' law. Both ICEA and NEMA standards may be purchased from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

2.2 NEMA

NEMA's members are from cable manufacturing organizations and generally they are from the commercial side of those companies.

2.3 Aluminum Association

The aluminum association tends to impact cable standards and specifications by representation on organizations engaged in these activities. The association takes the lead in specifying ingredient and impurity levels in aluminum alloys used for conductors and has published code words for many bare, covered and insulated aluminum wires and cables. These code words are widely used to specify and purchase the wires and cables coded.

3.0 USER ORGANIZATIONS

3.1 AEIC

Cable specifications have been written by the Cable Engineering Section of the Association of Edison Illuminating Companies, a group of investor owned and municipal utility company engineers, since the 1920s. They also prepare guides that pertain to power cables.

Their first specifications were written for paper-insulated cables for medium voltage applications. Presently their specifications cover all forms of laminated cables from 5 to 345 kV such as paper-insulated, lead-covered, low-pressure oil-filled, and pipe-type. These specifications include conductors, insulations, sheaths, shields, jackets, and testing requirements.

AEIC also prepares specifications for extruded dielectric cables from 5 to 138 kV that build upon the ICEA documents (hence also on the applicable ASTM requirements). AEIC uses the ICEA standards for such items as conductors, shields, jackets, and testing requirements. A unique feature of AEIC's past extruded cable specifications is that they required a qualification test be performed on a sample of cable that represents the cable to be manufactured. This has now found its way into the ICEA Standards for utility cables [9-2,9-3].

Another feature of AEIC's specifications for extruded cables is that a checklist of the available options is presented. This can be useful for those users that are in the process of developing a user specification for themselves.

AEIC documents are available from: AEIC, 600 N. 18th St., P.O. Box 2641, Birmingham, Alabama 35291–0992, USA.

3.2 Rural Utility Systems (RUS) [previously REA]

This is also a user group of the U.S. Department of Agriculture that develops standards for the Rural Electric Cooperatives of the United States.

4.0 CONSENSUS ORGANIZATIONS

4.1 Underwriter's Laboratories

Underwriter's Laboratories (UL) has published a wide range of standards covering wires and cables specified by, and for use in accordance with the NEC. UL both lists and labels acceptable designs and acts as a third party inspector by having UL inspectors visit the manufacturers facilities to conduct tests to verify the manufacturer is meeting the standard for the product(s).

4.2 National Electrical Code

The National Electric Code (NEC) is written by a number of panels, each addressing specific sections of the NEC. Membership on the panels is carefully controlled to avoid having any single interest group gain control over the panel. The NEC covers wire, cables, and wiring methods in facilities frequented by the general public. The only specific exemption is facilities under the control of electric utilities that are not facilities used to host the general public such as customer service areas. The NEC is adopted by ANSI and is adopted in whole or part (or not at all) by governmental agencies.

4.3 American Society For Testing And Materials (ASTM)

Membership includes raw material suppliers, manufacturers, users and general interest groups. As such, ASTM is a consensus organization. ASTM is organized for “the development of standards on characteristics and performance of materials, products, systems and services.”

4.4 American National Standards Institute (ANSI)

American National Standards Institute membership and polling lists involve all interested parties. Thus, ANSI standards are consensus standards. ANSI does not develop standards, it elevates standards developed by others to a consensus level by voting procedure.

5.0 FEATURES OF STANDARDS AND SPECIFICATIONS

5.1 Conductors

5.1.1 Resistance.

Both copper and aluminum conductors are covered by ASTM and ICEA standards. Since resistance is the governing factor for establishing conductor size in most instances, they both establish a maximum resistance for each AWG and kcmil size. ICEA conductor diameters are required to meet a nominal dimension +/−2%.

5.1.2 Compressed Strand.

ASTM standards for stranded conductors give the manufacturer the option of “compressing” Class B and C conductors. This means that they can decrease the overall diameter of the conductor by a maximum of 3% from that of a concentric conductor. The need and advantages for such compression was presented in Chapter 3. Another way of saying this is that even if “concentric” stranding is requested, the manufacturer has the option of providing “compressed” strand.

5.1.3 Temper.

An important decision that must be made involves the temper of the metal. This option should be based on such factors as the pulling forces, flexibility, and also on the cost.

The harder the temper, the greater force can be applied to the conductor during installation. A half-hard aluminum conductor will withstand less force than a 3/4 or full hard conductor. On the other hand, that increase in temper produces a conductor that requires more force to bend—it is less flexible. This additional force may be negligible when compared with the bending forces of the finished cable, however. When conductors are drawn during the manufacturing process, the metal is work hardened and the temper increases. Annealing during the drawing process or after the conductor is formed will decrease the temper, but this takes energy so there is an increase in the cost of an annealed conductor. All of these points need to be weighed before a decision is reached.

5.1.4 Identification.

Cable manufacturers have the capability of indent printing on the center strand of a seven strand, or greater, Class B or C conductor. If requested at the time of the inquiry, they can print the year of manufacturer and their name at one-foot intervals on this center strand. This provides a lasting identification of the manufacturer and the year.

5.1.5 Blocked Strand.

Another consideration is to block, or fill, the strands of a Class B conductor with a compound that eliminates almost all the air from the interstices. This prevents the accumulation of moisture in the air space as well as prevents any moisture from longitudinal movement along the cable. The elimination of water in the strand reduces the treeing concerns and increases the life of cables in accelerated treeing tests. ICEA Standards contain a test for the effectiveness of this “water blocking” [9-2] [9-3].

Another method of keeping water from entering (or leaving) the strand is to install a metal barrier in the semiconducting strand shielding. The layer is a “sandwich” of the semiconducting material with a lead or aluminum overlapped tape in the center.

5.2 Conductor Shielding

Conductor shielding (either a semiconducting or a stress control layer) is required for cables rated 2,000 volts and higher by these standards. Conductor shielding normally consists of a semiconducting layer applied between the conductor and the insulation. For this layer to function properly, it should be inseparably bonded to the insulation to ensure there are no air voids between the conducting layer and the insulation.

This extruded semiconducting material is made from a polymer that will ensure compatibility with the insulation and a strong bond at the interface. Its conducting properties are obtained by adding particles of special carbon black. The present requirement for the maximum resistivity of this layer is 1,000 meter-ohms. Industry standards require this material to pass a long-time stability test for resistivity at rated emergency overload temperature of the cable. Accelerated tests have shown that the cleanliness of the material can significantly effect the life of the cable when it is in a wet environment. A "super clean" semiconducting material can improve the life of a cable in an accelerated water treeing test significantly.

The stress control layer that may be used rather than semiconducting has properties that are best describe it as having a high dielectric constant (high K) material. This means that it acts like a rather poor conductor and produces a very low voltage drop between the conductor and the insulation. It does provide the stress control that is needed for smoothing out the conductor surface.

In some applications a conducting tape may be installed over the conductor and under the semiconducting layer. This functions as a binder and is sometimes used for larger conductors.

If a semiconducting conductor stress control layer is used, the resistivity is measured between two painted silver electrodes placed at least two inches apart on the conductor stress control layer. If greater accuracy is desired, current electrodes may be placed one inch beyond each potential electrode.

The resistance shall be measured between the two potential electrodes. The power of the test circuit shall not exceed 100 milliwatts.

The volume resistivity is then calculated from the following equation:

$$P = \frac{R(D^2 - d^2)}{100L} \quad (9.1)$$

where *P*=volume resistivity in ohm-meters
R=measured resistance in ohms
D=diameter over conductor stress control layer in inches
d=diameter over conductor in inches
L=distance between electrodes in inches

5.3 Insulation

Cross-linked polyethylene (including tree retardant XLPE) and ethylene propylene rubber are the dominant materials presently being used as the insulation for medium voltage cables.

5.3.1 AEIC Specification.

AEIC has a specification for 5 through 46 kV medium voltage cable [9-4] that covers both cross-linked (thermosetting) polyethylene and ethylene propylene rubber cables. At this time, there is not any medium voltage thermoplastic polyethylene power cable [9-1] being manufactured in North America.

Both AEIC [9-4] and ICEA [9-2,9-3] require that numerous tests be performed on the material that will be used in the manufacturing process. Applicable tests, with passing requirements, include:

For filled and unfilled cross-linked polyethylene, including TRXLPE:

Physical Requirements—Unaged

Tensile strength, psi, minimum, room temperature	1, 800

Elongation, percent, minimum, room temperature	250

Physical and Electrical Requirements—Aged

After air oven test for 168 hours at 121°C	
Tensile strength, % of unaged, minimum	75
Elongation, % of unaged, minimum	75
Electrical characteristics at room temperature	
SIC at 80 V/mil, maximum	3.5
Dissipation factor at 80 V/mil, maximum, XLPE	0.1
Dissipation factor for filled or TR-XLPE	0.5
Insulation resistance constant	20,000

For ethylene propylene rubber types 1, 2 and 3:

Physical Requirements—Unaged

Tensile strength, psi, minimum at room temperature,	EPR 1	700
	EPR 2	1,200
	EPR 3	700
Elongation, percent, minimum at room temperature, all three		250

Physical and Electrical Requirements—Aged

After Air Oven Test for 168 hours at 121°C		
Tensile Strength, percent of unaged, minimum,	EPR 1	75
	EPR 2	80
	EPR 3	75
Elongation, percent of unaged, minimum,	EPR 1	75
	EPR 2	80
	EPR 3	75
Electrical characteristics at room temperature:		
SIC at 80 V/mil, maximum, all three		4.0
Dissipation factor at 80 V/mil, maximum, all three		1.5
Insulation resistance constant (K), minimum, all		20,000

5.3.2 Insulation Thickness and Test Voltages.

Both cross-linked polyethylene and ethylene propylene rubber insulated cables have the same wall thickness requirements and test voltages in accordance with ICEA [9-2] [9-3] standards. The ac test voltage in ICEA [9-2,9-3] is approximately 200 volts per mil of specified wall thickness. Two important changes from past ICEA requirements are that a dc test is no longer required for these cables. The other is that they provide two wall thickness for each voltage rating—Column A and B. See note 2 of Table 11-2 where they discuss the factors to be considered in making the choice.

RUS specifications require the use of Column B wall thickness for cables that are manufactured to their needs unless dispensation is given on the basis of selective designs.

5.4 Extruded Insulation Shields

In addition to the conductor stress control layer, medium voltage, shielded power cables require an insulation shield. The insulation shield consists of a nonmetallic covering directly over the insulation and a nonmagnetic metal component directly over or imbedded in the nonmetallic conducting covering. This outer layer is not required to be bonded to the insulation for cables rated up to 35 kV. At higher ratings, bonding is both required and recommended. The insulation and the semiconducting material must be compatible since they are in intimate contact with one another.

5.4.1 Strip Tension.

AEIC has established peel strength limits for the removal of the semiconducting layer for 5 to 35 kV cables. The lower limit is for cable performance and the upper limit is set to permit removal without damaging the surface of the insulation.

The AEIC test calls for a ½-inch wide strip to be cut parallel to the center conductor. This cut may be completely through the layer (in contrast to field stripping practices). The ½-inch strip is removed by pulling at a 90° angle to the insulation surface at a set rate of speed. The limits are shown in Table 9-1.

Table 9-1 AEIC Strip Tension Limits

Material	**Lower Limit in Pounds**	**Upper Limit in Pounds**
XLPE and TR-XLPE*	3	24
EPR	3	24

5.4.2 Resistivity.

The volume resistivity of this extruded layer shall not be greater than 500 meter-ohms when tested in accordance with ICEA procedures. This layer can be used only as an auxiliary shield and requires a metal shield in contact with it to drain off charging currents and to provide electrostatic shielding.

The volume resistivity level is half that of the conductor shield because this layer is subject to chemical action from the environment. The function of the shielding properties would be acceptable with a higher value, but concerns over long-time stability have influenced this level.

The resistivity of the extruded layer is also measured using silver painted electrodes. The outer coverings including the metallic shield are removed. Four silver-painted annular-ring electrodes are applied to the outer surface of the insulation shield. The inner two electrodes are for the potential application and are at least two inches apart. If a high degree of accuracy is required, a pair of current electrodes shall be placed at least one inch beyond each potential electrode. The resistance is measured between the two potential electrodes. The power of the test circuit is not exceed 100 milliwatts.

The volume resistivity is then calculated as follows:

$$P=\frac{2xR(D^2-d^2)}{100L} \tag{9.2}$$

where *P*=volume resistivity in ohm-meters
R=measured resistance in ohms
D=diameter over insulation shield in inches
d=diameter under insulation shield in inches
L=distance between potential electrodes in inches

5.4.3 Insulation Shield Thickness.

ICEA has established a thickness for the extruded layer of insulation shield to provide guidance for the manufacturers of molded splices and terminations [9-2][9-3].

5.5 Metallic Insulation Shields

In addition to the extruded insulation shield previously described, shielded cables must have a metallic member over and in contact with the nonmetallic layer. The following options are available for the metallic member.

Helically wrapped flat metal tape (usually copper)
Longitudinally corrugated metal tape (usually copper)
Wire shield (multiple #24 AWG or larger copper wires)
Concentric neutral wires (#14 AWG or larger to meet conductivity)
Flat straps (flat metal tapes applied with close coverage to meet conductivity)
Tape plus wires
Continuous welded corrugated metal sheath (copper, aluminum, etc.)

Wire shields and flat tapes are popular metallic shields and are almost always copper. A 5 mil copper tape with a minimum 10% overlap is generally used when tapes are specified. For wire shields, #24 to #18 AWG wires are used in proper multiples to provide a minimum of 5,000 circular mils of area per inch of cable core conductivity. These types have a limited fault current capacity and are not commonly used by electric utilities for outdoor plant for that reason.

Concentric neutral wires and flat straps are normally specified on URD and UD cables where the metal functions both as a shield and a neutral. These constructions normally use copper wires with an overall jacket applied over the wires for corrosion protection.

In higher voltage cables such as 35 kV to 138 kV, fault currents often may be greater than the capabilities of wires. In those situations, the tape plus wire construction is frequently used.

Where shields must be sized for specific fault current requirements, there are several sources of data such as:

> ICEA P-45–482, "Short Circuit Performance of Metallic Shielding and Sheaths of Insulated Cable."
>
> EPRI RP 1286–2, (EL-5478), "Optimization of the Design of Metallic Shield/Concentric Neutral Conductors of Extruded Dielectric Cables Under Fault Conditions."

5.5.1 Concentric Neutral Cables.

ICEA standards cover the number and size of concentric neutrals for this type of cable. The concentric neutral conductor shall be uncoated copper wire in accordance with ASTM B3 or tin coated wire in accordance with ASTM B33. The wires of the concentric neutral shall be applied directly over the insulation shield with a lay of not less than six or more than ten times the diameter over the concentric wires.

Although AEIC does not provide information on concentric neutrals, it is important to understand that a full or one-third neutral is not mandated by any standard. Many utilities use smaller amounts of neutral wires based on the fact that too much metal leads to increased losses. RUS standards do not require even a full neutral for URD cables.

5.6 Cable Jackets

Jackets are generally required over metallic shields for mechanical and corrosion protection during cable installation and operation.

There are many possible jacketing materials such as:

Polyethylene
Semiconducting polyethylene
Polyvinyl chloride (PVC)
Polychloroprene (Neoprene, Trade Mark)
Chlorosulphanated polyethylene
Chlorinated polyethylene

Their attributes are discussed in Chapter 8.

ICEA standards cover the thickness of these jackets. See Chapter 25 for tables.

6.0 REFERENCES

[9-1] ICEA S-61–402 (NEMA WC-5), "Thermoplastic Insulated Wire and Cable, 0 to 35 kV." Withdrawn by ICEA.

[9-2] ICEA S-94–649, "Standard For Concentric Neutral Cables Rated 5,000–46,000 Volts," 2000, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

[9-3] ICEA S-97–682, "Standard For Utility Shielded Power Cables Rated 5,000–46,000 Volts," 2001, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

[9-4] AEIC CS8–00, "Specifications for Extruded Dielectric, Shielded Power Cables Rated 5 Through 46 kV" (1st Edition), 2000, AEIC, 600 North 18th Street, P O Box 2641, Birmingham, AL 35291–0992, USA.

[9-5] AEIC CS7–93, "Specifications for Crosslinked Polyethylene Insulated, Shielded Power Cables Rated 69 through 138 kV, 3rd Edition," 1993, AEIC, 600 North 18th Street, P O Box 2641, Birmingham, AL 35291–0992, USA.

[9-6] UL Standard 1072, "MV Cables Rated 2,001 to 35,000 Volts."

[9-7] ICEA T-24–380, "Guide for Partial Discharge Test Procedures," 1994, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

[9-8] ICEA P-45–482, "Short Circuit Performance of Metallic Shielding and Sheaths of Insulated Cable," 1999, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

[9-9] ICEA T-25–425, "Guide for Establishing Stability of Volume Resistivity for Conductivity of Polymeric Compounds of Power Cables," 1981, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

[9-10] ICEA T-28–562, "Test Method for Measurement of Hot Creep of Polymeric Insulations," 1995, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

[9-11] ICEA T-22–294, "Test Method for Extended-Time Testing of Wire and Cable Insulations for Service in Wet Locations," revised 1983, Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA.

CHAPTER 10
CABLE MANUFACTURING

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1.0 INTRODUCTION

Insulated electric power cable manufacturing involves a broad range of complexity depending on the cable design to be produced. [1-1,1-2] Different cable plants may be capable of a limited or broad range of designs. Those capable of a broad range may limit operations to only a few steps in the manufacturing process. Despite this large variability in plants, the steps in the manufacture remain basically the same, whether done in one facility or a number of facilities. Conductor manufacturing, in Chapter 3, is common to all cables with metallic conductors. The manufacture of extruded dielectric power cables and laminar dielectric power cables follow.

2.0 CONDUCTOR MANUFACTURING

In Chapter 3, Conductors, it was pointed out that for efficient distribution of electric power, the conductors must be produced from a high conductivity material. It was also shown that copper and aluminum offer the best available combinations of conductivity, workability, strength, and cost to become the most popular power cable conductor materials. From the conductor-manufacturing standpoint (we will not attempt to include mining, refining, and fabricating stages), we will begin at the point where copper and aluminum are received as large coils of round rod. The diameter of aluminum rod for producing conductors is commonly 3/8 inch in diameter (0.375 inches) while 5/16” diameter is common for copper rod. For larger solid conductors; [i.e., 1/0 AWG or larger (0.325” diameter)], it is common to begin with a larger diameter rod. The larger diameter (often 0.500”) allows for enough diameter draw-down to remove surface imperfections in the rod as received to make a conductor surface without residual surface imperfections.

2.1 Wire Drawing

In wire drawing, the copper or aluminum rod is drawn through a series of successively smaller dies to reduce the rod to a wire of the desired diameter. The quality of the wire surface depends on sufficient drawing and reduction to eliminate surface defects. Thus, there is the need to utilize a rod or intermediate wire having a diameter somewhat larger than the solid wire to be produced. If fine wire is desired, it is common to utilize a coarse wire-drawing machine followed by a fine wire drawing machine. The wires are taken up on spools for later stranding operations or on reels for use as a solid conductor.

2.2 Annealing

Drawing copper or aluminum wires increases the temper of the metal. That is, a rod of a “softer” temper is “hardened” as the wire is drawn down to the required diameter.

Except for the use of full hard temper aluminum stranded conductors for electric utility outside plant secondary and primary cables, it is generally desirable to use a softer temper.

To produce a softer temper, the wire is exposed to elevated temperatures well in excess of emergency operating temperatures of the cable. For many years, this has been accomplished in a large oven. Exposure time using this method is a matter of hours.

It is possible to partially anneal wires “on the fly”. This is generally done on a wire before it is used in a stranding operation. The method is not generally suitable for full annealing to a soft temper nor to conductors after they have been stranded.

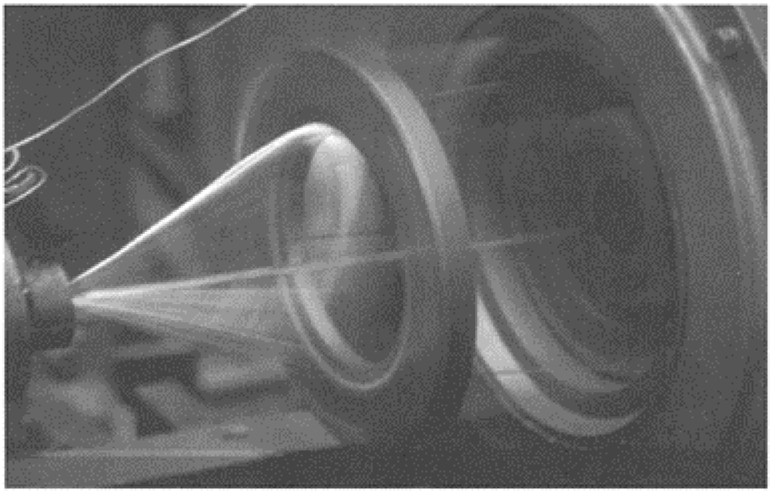
2.3 Drawing to Temper

Another method of arriving at wires of the desired temper is to begin with rod of a softer temper and using the work hardening associated with the wire drawing to arrive at the desired temper.

2.4 Stranding

The simplest conductor is a solid rod/wire. As the cross sectional area of the conductor increases, the conductor becomes increasingly stiff. Stranded conductors use a number of smaller wires the sum of which total the desired conductor cross sectional area. The machines used in stranding range from those that apply successive layers of strands over a central core made up of one or a number of strands, to those producing stranded configurations resembling ropes and for very fine wires, bunches of fine strands. See Figure 10-1 for an example of a seven-wire strander in operation.

Figure 10-1 Photograph of strander in operation.



3.0 EXTRUDED CABLE MANUFACTURING

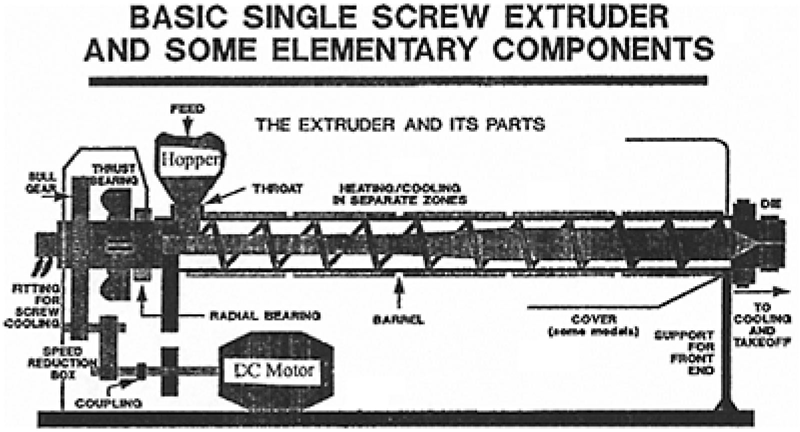
3.1 Insulating and Jacketing Compounds

There are literally thousands of insulating and jacketing compounds used in the cable industry. Many of these compounds are commercially available from compound suppliers. They may also be custom compounded by companies that sell them as finished, “ready-to-extrude” compounds. The cost of “ready-to-extrude” compounds is high enough so there is considerable incentive for the manufacturer to mix many compounds in-house. Low voltage compounds provide special opportunities ranging from the simple addition of one or more ingredients at the extruder to the complete mixing of all the ingredients and production of strips or pellets suitable for extrusion. The complex subject of compounding is beyond the scope of this text. For our purposes, we will assume compounds are complete, “ready-to-extrude”. However, it is necessary to recognize that this all-important compounding step is increasingly becoming a part of the manufacturing process.

3.2 Extrusion

The method of extrusion currently in use to produce polymeric layers comprising the cable are similar regardless of the polymer or layer being extruded.

Figure 10-2 Extruder.



Compound, in the form of pellets or strips, is fed into the back of a screw that rotates in a barrel. The material advances down the screw and is melted during the advance. In general, the barrel is divided into zones that are individually temperature controlled. There are some extrusions where the barrel is heated at the start of the extrusion, but as the extrusion continues, the mechanical shear and friction results in sufficient heat generation that barrel heating is no longer required. In fact, depending on compound and extrusion parameters, barrel cooling and even screw cooling may be required. Properly executed, the compound is all melted and forced through a die-head arrangement that deposits the melt on the core being passed through the head. This core may be a bare wire or cable in some stage of completion. Figure 10-2 shows the common features of an extruder. Figure 10-3 shows a photograph of the physical arrangement of three extruders and the crosshead at a manufacturing facility.

In many cases, the compound is introduced with all of its final ingredients included. However, variations such as the addition of curing peroxides, color concentrates, or other ingredients at, or near the extruder are quite commonly used.

3.3 Curing

This term is somewhat of a carryover from the rubber materials that required curing. The cross-linking process for modern thermosetting compounds, such as cross-linked polyethylene and ethylene propylene rubber, is often referred to as a curing stage. While materials such as polyethylene can be cross-linked by a radiation-induced reaction, the majority of cross-linking for power cables continues to be by the chemical means.

Taking a simple case of polyethylene, the addition of a peroxide agent such as dicumyl peroxide to the polyethylene and supplying heat energy results in a chemical reaction that cross-links the polyethylene—turning it from a thermoplastic material into a thermosetting material. Peroxides are also commonly used for cross-linking EPR compounds. The heating period to effect cross-linking is commonly called curing. It is also referred to as vulcanization (a carry over from the tire industry), hence reference to the CV tube is the “continuous vulcanization” tube.

Curing tubes have three distinct configurations. The most commonly used is a curved tube that is in the shape of a centenary as shown in Figure 10-4. The first portion is the curing section and the lower portion is the cooling section. The shape is designed to prevent touch-down of the cable until the cable has cured. The weight of the cable, line speed, and length of the total tube must be considered in this design. Other forms of curing tubes may be horizontal or vertical. Horizontal tubes are used for very small cables or, for large thick insulation walled cables, in special extruders that employ very long dies. A vertical extruder has the advantage of being able to make very large cables with thick insulation walls, especially transmission cables. They run relatively slowly, but gravity does not work to deform the shape of the cable.

The heat source most commonly used in the past was steam in a tube through which the extruded cable was passed. This continues to be the most popular means for curing secondary cables. When curing relatively heavy walls such as primary cables, the upper limit on temperature that steam can practically impose makes it desirable to use other heat sources. The most popular heat source today for medium and high voltage cables is radiant heating in a nitrogen filled tube. This is one of a number of dry curing methods. This method allows for much higher curing temperatures and therefore faster line speeds and curing. These curing tubes are divided into a number of zones each of which has its individual temperature controls. This allows for optimum temperature profiling to effect cure.

Because of the high temperature involved, care must be taken to avoid thermal damage of the polymer. More common in Europe and gaining in popularity in North America for cables up to 600 volts is silane curing. The system is based on the technology of silicones and “sioplas” as originally developed is a two-part system of cross-linkable graft polymer and a master batch catalyst.

Figure 10-3 Crosshead and extruders at a cable manufacturer's plant.

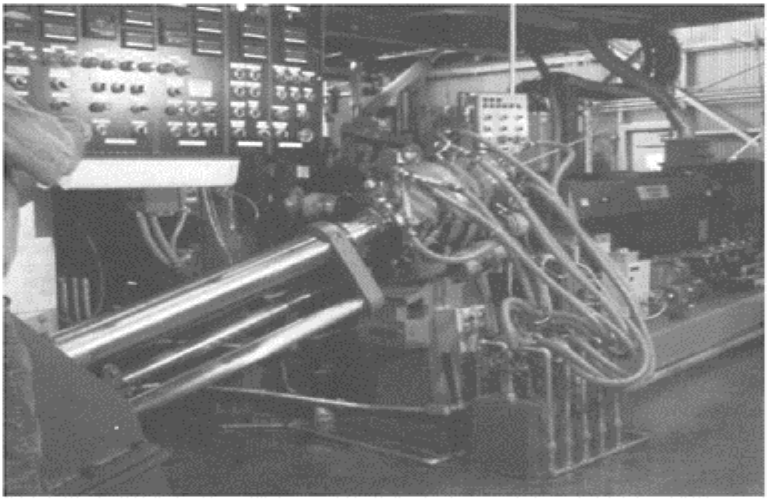
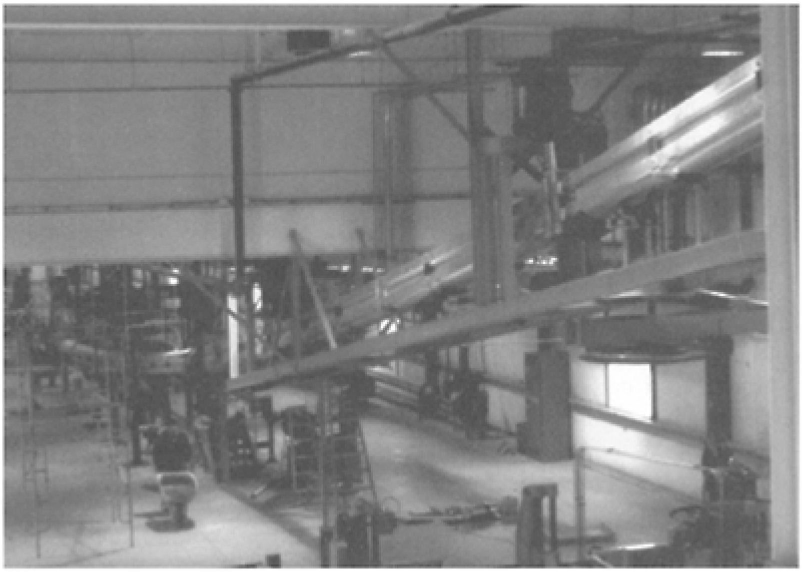


Figure 10-4 Photograph of curing section of a dry cure line.



A further development, "monosil" introduces ingredients at the extruder and thus eliminates the grafting process. Water is the cross-linking agent in these silane systems and cure rates become very thickness dependent. One of the advantages of moisture curing is that a thermoplastic extrusion line (no curing tube as required for peroxide curing) can be used to produce the thermosetting cable.

3.4 Cooling

Thermoplastic materials, such as polyethylene or polyvinyl chloride, do not require curing. Single layers that are relatively thin—such as 600 volt building wire—may be cooled in a water trough following extrusion. In the case of polyethylene, care must be taken to avoid too rapid a quench. This rapid cooling can result in locked-in mechanical stresses that will result in shrink-back of the material on the wire.

Heavier thermoplastic layers, such as encountered on primary cables, require gradient cooling to avoid these stresses in the polyethylene.

Following curing, thermosetting materials must also be cooled. When steam is the curing medium, water cooling is universally employed. Cross-linked polyethylene must not be rapidly quenched to avoid "shrink back" that is caused by locked-in stresses. Cooling zones are used to control the cooling process for water-cooled cables.

With the dry cure process, there is the possibility of using nitrogen as the cooling method. This is not frequently used for cables at this time. Cooling is sufficiently gradual that stresses are not locked-in.

4.0 EXTRUSION LINE CONFIGURATIONS

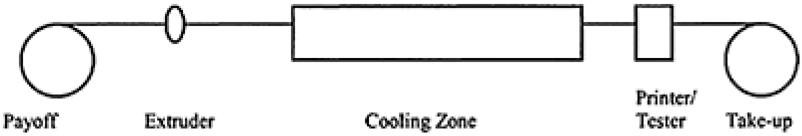
4.1 Single Extruder Line

The simplest configuration for an extrusion line is one that can be used for low voltage thermoplastic cables having a single plastic layer over a conductor. A few examples of cables that are produced this way are:

- line wire
- building wire
- a jacket over other cores.

A curing zone may be added just before the cooling zone if curing is needed.

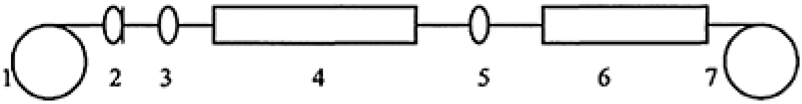
Figure 10-5 Single extrusion.



4.2 "Two Pass" Extrusion

Thermoplastic primary cables have been produced in a similar line configuration, but two separate extruders were used to apply the conductor shield and the insulation. Another "pass" through the third extruder after the first two layers were applied and cooled became knows as “two pass”. The figures that are shown here do not imply that the curing and cooling tubes are straight. The figures are representing all possible configurations.

Figure 10-6 Triple tandem single pass extrusion.



where 1 is payoff, 2 is conductor shield extruder, 3 is insulation extruder, 4 is first cooling zone, 5 is insulation shield extruder, 6 is second cooling zone (for the insulation shield, and 7 is the takeup reel.

If the product was to be cured, a curing zone had to be included. Note that the third extruder, (#5 in Figure 10-5), was placed after the first cooling zone. That made it difficult to impossible to maintain the desired stripability of thermo-setting insulation shields over thermosetting insulations. Thus, it was common to utilize a thermoplastic insulation shield over thermosetting insulation.

4.3 “Single Pass” Extrusion

The development of semiconducting thermosetting shield materials that would be readily strippable from thermosetting insulation even though all three layers were cured at the same time led to the development of lines where all three layers of a primary cable could be extruded over the core prior to any curing or cooling.

Figure 10-7 Single pass with three extruders.

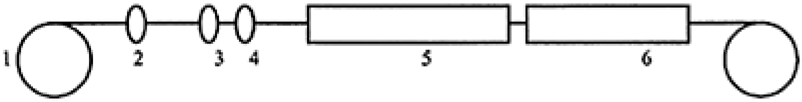
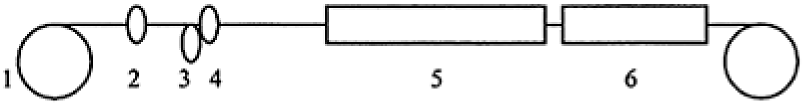


Figure 10-7 shows a single pass extruder where the conductor goes in at one end and the three layers are applied by three different extruders but in one complete operation. Here 1 is the payoff reel, 2 is the conductor shield extruder, 3 is the insulation extruder, 4 is the insulation shield extruder, 5 is the curing zone, 6 is the cooling zone, and 7 is the take-up reel.

This was the first time the “triple extrusion” term was applied. While this arrangement was preferable to all previous methods because of minimal exposure of the insulation to possible contamination or abuse, further developments were desired. Dual extrusion of the two layers at positions 3 and 4 above would make for a smoother interface. Thus, the next improvement was single extrusion of the conductor shield and then, a few feet away, the dual extrusion of the insulation and the insulation shield. This was also called “triple extrusion"! About this time, dry curing lines were growing in popularity and many lines of this type were installed.

Figure 10-8 Single pass with one dual extruder.



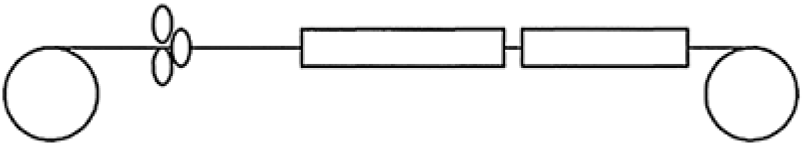
where the equipment is the same as in Figure 10-3 except that extruders 3 and 4 are now in one "crosshead".

Unfortunately this method continued to allow the conductor shield to be vulnerable to scraping in the next extrusion head, continued to allow build-up on the extruder die face (die drool), and exposed the conductor shield to the environment.

4.4 "True Triple" Extrusion

The method now used for the majority of medium voltage cables utilizes a single crosshead where all three layers are applied simultaneously. This is referred to as "true triple" extrusion.

Figure 10-9 True triple extrusion.



All three extruders feed into a single head for "true triple" extrusion. There are numerous lines now in service in North America, and the world in general, that make use of these triple heads.

4.5 Extrusion Heads

Extrusion heads are designed to "channel" the extrudate to and on the wire or cable passing through the head. Dual and triple heads channel the flow of 2 and 3 extruders in a single head. Figure 10-10 gives a cut away view of a dual crosshead and Figure 10-11 a triple head.

Figure 10-10 Dual style crosshead.

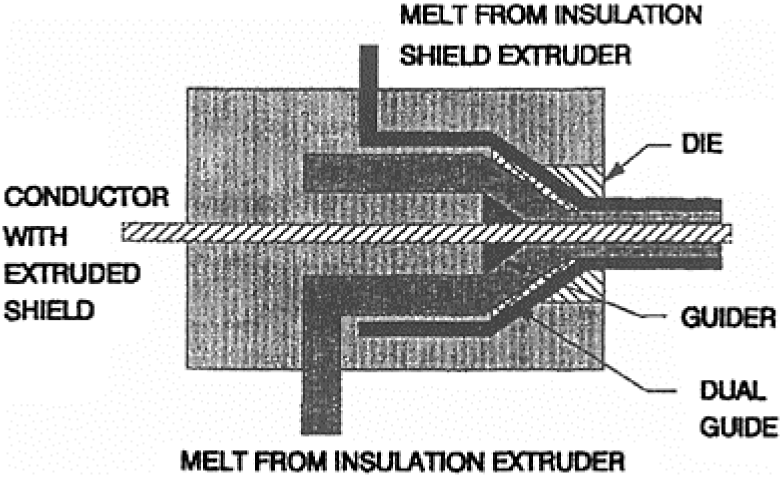
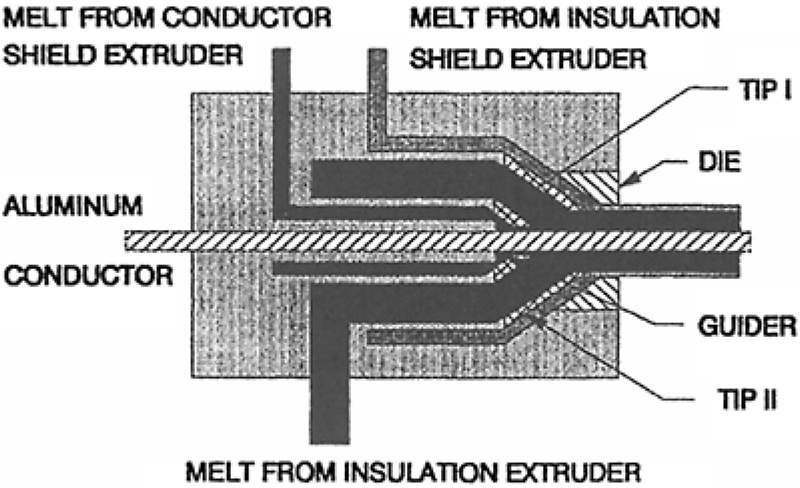


Figure 10-11 Triple style crosshead.



4.6 Finishing

Finishing operations generally include the addition of wires, tapes, or braids (in medium-voltage cables, the addition of metallic shields) prior to jacketing.

4.7 Assembly

In cases of covered overhead service cables and similar constructions, a number of single cables may be assembled as a group. This is done on cablers or twisters. The equipment has some similarity to the equipment discussed under stranding. For assemblies to later be jacketed and serve as multi-conductor cables, it is common to add fillers to “round out” the assembly as well as using taping heads to apply binder and jacketing tapes in the same operation.

5.0 PAPER INSULATED CABLES

5.1 Paper Insulation

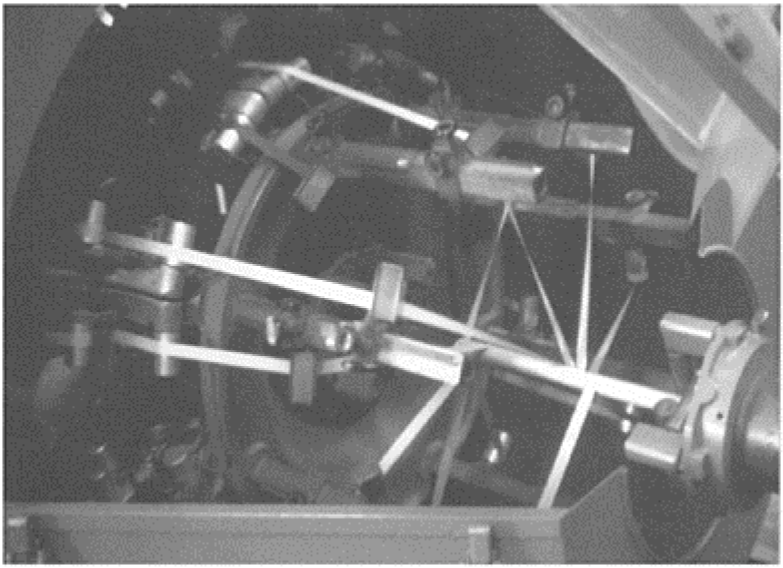
It has been found that up to a certain point, the mechanical strength of paper increases with its moisture content. Accordingly, prior to their use in the taping machine, pads (rolls) of paper are conditioned for a definite period in a room in which the temperature and humidity are controlled. This procedure assures that all the paper is in the same condition as it is being applied over the conductor and results in more uniformity in the taped insulation. When the paper is dried prior to impregnation, the paper shrinks uniformly. This allows for cables with sector conductors to be cabled without wrinkling.

5.2 Paper Taping

The importance of controlled tension in the taping process is realized when one is reminded that to have an optimum of electrical strength, paper insulation must be tightly applied, free from wrinkles, and other mechanical defects that non uniformly applied layers of tapes would have. Close, automatic control must be accomplished.

In one method, the tape from the pad passes around a pulley that is geared to a small motor armature whose direction or rotation is opposite to the direction of tape feed. As the tapes feeds along, the armature is revolved opposite to the direction it would take if turning freely and against the motor field torque. The pulley, therefore, exerts a back pull on the tape at all times and with a constant value. Torque must be regulated to the tension that is required. See Figure 10-12 for an example of a paper taping machine.

Figure 10-12 Photograph of paper taping machine.



5.3 Cabling

A large cabling machine is used for assembling individually insulated conductors into two, three, or four-conductor cables. The cradles may be operated rigidly or in a planetary motion to accommodate the large diameter cabling bobbins. This reduces the bending stresses to which the paper is subjected. Facilities are provided for mounting smaller bobbins between cradles that may be used for fillers, smaller cables such as fiber optic, or tubes. Small packages of fillers may also be carried on the spindles. Guides and bushings are used for placing sector-shaped conductors in their proper position without undue strain on the insulation. Behind the assembly bushings, heads are mounted for applying paper tapes on non-shielded type cables, or in the case of shielded cables, intercalated binder tapes.

Metal binder tapes are spot-welded when a new pad of tape is inserted in a taping head. The cable is drawn through the machine by a large capstan to a take-up reel. The large diameters of the capstan and impregnating reels reduce the bending stresses in the insulation.

5.4 Impregnating Compounds

Paper cables have been impregnated with numerous compounds over the years. A few that have been used include:

Type A. Unblended naphthenic-base mineral oil.
Type B. Naphthenic-base mineral oil blended with purified rosin.

Type C. Naphthenic-base mineral oil blended with a high-molecular-weight polymer.
Type D. Petrolatum blended with purified rosin.
Type E. Polybutene

When paper-insulated cable is impregnated with a dielectric fluid, the combination is better than either part and results in valuable characteristics:

1. High initial electrical resistivity.
2. Low rate of deterioration from high temperatures.
3. Low power factor.
4. Very flat power factor vs. temperature curve.
5. Low ionization factor.

Investigation had shown that the unblended mineral oil was the most stable oil from a chemical and electrical standpoint. Natural inhibitors in the petroleum afforded high oxidation stability.

These inhibitors are complex resins occurring naturally in crude petroleum. For the most part, they are eliminated in the refining process and necessarily so because they represent impurities. If the petroleum is over-refined, all these inhibitors are removed, resulting in a clear oil of high electrical characteristics but having unstable qualities. These resins act as anti-oxidants by taking up oxygen themselves from the oil and thus inhibiting oxidation deterioration. In the refining process used for this oil, a good balance is obtained between electrical characteristics and high thermal stability. Most of the oil impregnated, medium voltage cables were made with Type A compound. Types B, C, and D were more viscous than Type A and were suitable for long vertical runs or slopes with Type C being the most frequently used compound.

The predominant compound used since 1980 has been the synthetic material polybutene. Since this is not an oil, it is proper to refer to these as fluid-filled cables.

5.5 Drying and Impregnating

Assuming that the proper materials have been selected and good mechanical construction employed, the electrical characteristics of the completed cable depend primarily upon the drying and impregnating process.

It has been established by many laboratory investigations that oil, under heat and exposure to air, rapidly loses its desirable insulating properties. Also, the presence of residual air and moisture are harmful to impregnated paper insulation. Thus, paper insulated cables are dried and impregnated in a closed system.

The functional principles of this closed system are:

1. Transfer of hot impregnating fluid from a vacuum tank to another tank under vacuum without exposure to air.
2. Use of relatively high fluid pressure (85 to 200 pounds per square inch) during impregnation.
3. Complete degassing and dehydration of the fluid.
4. Use of extremely high vacuum (1 mm or less).

If there is more than one impregnating compound used in a plant, it is desirable to have separately assigned tanks for each material.

Prior to transfer to the impregnating tank, the fluid to be used is heated in its steam-jacketed storage tank where it is kept under vacuum. During this heating period, the fluid is agitated in order to maintain a uniform temperature.

In the center of each of the steam-jacketed vacuum and pressure impregnating tanks is a steam-jacketed cylinder of slightly smaller diameter than the hollow drum of the impregnating tanks. This reduces the amount of fluid subjected to heat during each impregnating cycle. Over the top of this cylinder, a large, circular baffle plate is mounted. When the fluid is admitted into the tank, it strikes this baffle where it forms a thin film. This affords an opportunity to subject the fluid to a second degassing treatment.

The impregnating of the paper can be considered to take place in two steps. First the fluid travels back and forth between the tapes from the outside of the insulation towards the conductor. This is best accomplished by applying vacuum. Second, the fluid penetrates into the fibers of the individual paper tapes. This is accomplished by using pressure.

5.6 Conditioning the Impregnating Fluid

When the fluid is subjected repeatedly to the temperatures used in impregnating, it gradually loses many of its desirable properties. A plant to condition the fluid is frequently installed at the factory to ensure uniform quality fluid. Each of the vacuum operations is performed under a vacuum of a precise absolute pressure. Automatically controlled electric heaters maintain the proper temperatures for each operation. By the use of this equipment, the fluid is maintained at all times at a quality equal to that of the new fluid. This, together with the impregnating control, results in cables of uniform quality.

5.7 Control of Impregnation

In the manufacturing of solid-type paper insulated cables, the general practice is to regulate the drying and impregnating process by setting up standard periods of time for each operation. Slight modifications are made for the particular size and type of cable to be treated.

Due to the inherent variations in materials and manufacturing, dielectric measurements are made on the cable undergoing drying and impregnation. This control consists of periodic readings, giving an accurate measure of temperature and degree of impregnation. This established definite control throughout every step of the impregnating process.

Flexible electrical connections are made between the ends of the cable and the permanent terminals on the tank as the cable is placed in the tank.

The conductor resistance is converted to conductor temperature. Knowing the viscosity-temperature characteristics of the fluid, these combined data effect a control of the impregnating ability of the fluid. Dryness is determined by the constancy of the ac capacitance values. Thorough saturation is determined by the change in ac capacitance. Complete cooling is determined from the conductor temperature measurements.

5.8 Control of the Cooling Cycle

Uniform cooling at a defined rate produces high quality paper insulated cable. To accomplish this, a large refrigeration plant can be installed as part of the impregnating system. This enables the mill to cool the impregnated cables at a prescribed rate independent of the water supply temperature.

The cooling is brought into use after the impregnation cycle is completed. The temperature of the entire tank is reduced under this controlled cycle to room temperature. This is a gradual reduction that is made while the cable is still in the sealed tank. The seal is then broken and the cables, coated with a thick layer of fluid, are transferred to the lead press, or other sheathing process.

The lead presses that were used for most medium voltage cables in the past, could extrude lead under pressures of 3,000 tons. A lead charge of up to 2,000 pounds was placed in a melting kettle located adjacent to each press. The advantage of a large charge was that fewer stops had to be made. This stop could last for several minutes and for all of that time the cable in the die-block was subjected to high temperatures. Continuous extrusion techniques were also developed.

The melting kettle had automatic temperature control to keep the lead at the proper, molten state. An agitator was used to keep the metal stirred so there was no separation in the mix. Means were provided to removing dross (oxidized lead) from the top of the molten mass. Over the lead, an atmosphere of in inert gas, such as carbon dioxide or nitrogen, could be used to reduce the formation of oxides.

The lead sheathing process takes the impregnated cables through a steel die-block attached to the cylinder of the press. The die-block has a core tube having a diameter just large enough to receive the cable core and a die having an outer diameter of the sheath diameter. Pressure is exerted on the lead in its plastic state by a hydraulic ram or piston. The lead is extruded at temperatures of about 375 to 400°F from the cylinder into the die-block and around the outer portion of the core tube. The lead is squeezed down over the cable to form a thick, continuous, homogeneous sheath. Pressure behind the lead tube forces the cable through the die-block.

When the cylinder is charged, it is overflowed and the exposed lead is allowed to congeal. The exposed lead is then skimmed off level with the cylinder by means of a mechanical guillotine or cropping device that removes all traces of oxide. The hydraulic ram, having a rounded nose, is then immediately brought down onto the surface of the skimmed surface of the lead.

The press is started and a quantity of lead pipe is extruded and checked to make sure the crystalline structure, welds, and ductility are satisfactory. After the cable is started through the press, a sample of lead sheathed cable is cut off and concentricity checked. As the cable leaves the die-block, it is water-cooled and either given a jacket or a coating of grease, as required.

The discontinuous type of extrusion presses with vertical rams and containers that had to be filled with liquid lead were largely replaced by continuous extrusion machines. The screw of these machines is vertical and lead is fed from the bottom end from a reservoir of lead. The extrusion temperature is maintained at about 300°C.

6.0 FACTORY TESTING

6.1 Electrical Tests for 100% Inspection

The Insulated Cable Engineers Association (ICEA) recognizes three alternative test methods for electrical testing of secondary cables (up to 1,000 volts phase-to-phase).

6.1.1 ac Spark Test.

The cable conductor is grounded. The covered/insulated cable surface is passed through a close network of metallic bead chains or similar contact electrode. The electrodes are at an ac voltage potential selected on the basis of the type and thickness of the covering. In the event of a pinhole, skip, or other sufficiently weak spot (electrically speaking), a fault to the grounded conductor occurs. The fault triggers an alarm such that the operator can mark the fault for removal or repair.

6.1.2 dc Spark Test.

This is similar to the ac spark test except direct current, higher potential values, and continuous circular electrodes are used.

6.1.3 Alternating Current Water Tank Test.

The entire reel of finished cable is immersed in a water tank with only the cable ends protruding above the water. After a soak period to insure that water has permeated the entire reel of cable, the cable conductors are energized at an ac voltage level that is dependent on material type and thickness. The test voltage is applied for five minutes. The water acts as a ground and during the soak period it is hoped that water infiltrates in to any damage, pinhole, or electrically weak areas.

6.1.4 Insulation Resistance Test.

For most modern insulations, this test is meaningless, but persists in industry standards. In connection with the water tank test above and while still immersed, a bridge is used to read the insulation resistance. For modern insulations, the readings are so high that “apparent” differences, even though possibly huge, are meaningless and dependent on numerous factors unrelated to the insulation resistance.

6.2 Testing Medium Voltage Cables

Except for the insulation resistance test described under Section 6.1.4, Tests described in 6.1 are not generally applicable to medium voltage cables. The electrical 100% inspection tests are generally conducted in a dry environment on finished cables.

6.2.1 ac Voltage Withstand Test.

This test is conducted from the conductor to the insulation shield which acts as the outer electrode precluding the need for water immersion.

6.2.2. Partial Discharge Test.

Unique to medium and higher voltage cables is the partial discharge test. AEIC requires that such cables be subjected to a partial discharge while on the shipping reel.

The cable must be allowed to "rest" after manufacturing to allow any pressures that were developed during manufacturing to escape. It must be performed prior to the ac voltage test. Alternating current voltage is raised to an established level that is approximately four times operating voltage. The voltage is lowered while the partial discharge level in picocolombs is recorded. In the past, the voltage at which the measurable discharge extinguished (extinction voltage) was of particular interest. In modern cables, no measurable discharge is allowed through out the test voltage range and time of application.

Corona testing is extremely sensitive to defects in the cable capable of discharging as well as external electrical interference. Shielded rooms are provided to minimize this external noise.

7.0 REFERENCES

[10-1] Landinger, Carl, Adapted from class notes for "Understanding Power Cable Characteristics and Applications," University of Wisconsin—Madison, 2001.

[10-2] Kelly, Larry, Adapted from class notes for "Power Cable Engineering Clinic," University of Wisconsin—Madison, 1995.

CHAPTER 11
CABLE INSTALLATION

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1.0 INTRODUCTION

Thomas A.Edison installed his earliest cables in New York City in 1882. The cables were placed in iron pipes in the factory and then were spliced together in the field every 20 feet in an egg-shaped splice casing. Other systems, such as by Brooks, Callender, and Crompton, were installed by 1885 where they also used short sections of iron conduit. American Bell Telephone Company installed the first flexible communication cables in 1882 and 1883 where cables were pulled into the conduit in the field. "Pumplogs" were first used for water supply lines, but were used in 1883 in Washington, DC, for telegraph cables. Tree logs were hollowed out, the exterior was trimmed to make them square, and the entire log was treated with creosote. These became the conduits of choice! So began the duct and manhole systems with the need to pull cables.

The *Underground Systems Reference Book* [11-1] of 1931 stated "It is necessary to inquire into the harmful effects of the pulling stress on the cable insulation. The conclusion that has been reached, based on tests and experience, is that satisfactory operation of the cable is assured, provided that it has suffered no mechanical injury." It was recommended that a coefficient of friction between 0.40 and 0.75 should be used and that the total tension should be limited to 10,000 pounds. Little other advice was offered.

Significant advances were made in the understanding of cable pulling calculations with the 1949 paper by Buller [11-2] and the 1953 work of Rifenberg [11-3]. These papers provide the basic data for making cable pulls in all situations encountered in the field. They provide excellent quantitative data when used to calculate pulling tensions.

Even in the 1957 version of the *Underground Systems Reference Book* [11-4], there was little additional guidance given for such an important consideration as sidewall bearing pressure for distribution type cables. It was generally felt that 100 pounds per foot was acceptable. Later this was increased to 300 pounds per foot with no test work to support that value. Experience was still relied upon and 300 pounds met those criteria. A 400-pound per foot value was given for pipe type cables. Since the runs were relatively straight and short, this didn't pose a problem until the 1970s. Nuclear power plants had long pulls, many bends, and large cables. Many pulls exceeded that comfortable level established over the years.

Pipe-type cable systems pointed the way to the importance of accurate tension calculations. Here the avoidance of a splice could impact the cost of the system very significantly. Rifenburg's work [11-3] included all the necessary options, but the allowable sidewall bearing pressure needed to be evaluated since the somewhat arbitrary value of 400 pounds had not actually been tested in a laboratory environment. The understanding of the need for such information led to the project for "Increasing Pipe Cable Section Lengths," EPRI Final Report EL-2847, March 1983 [11-5].

A significant increase in understanding about cable pulls was reached with the completion of EPRI Final Report, EL-3333, "Maximum Safe Pulling Lengths for Solid Dielectric Insulated Cables," February 1984 [11-6]. A discussion of the results of these and other test work will be described below.

2.0 DISCUSSION OF CABLE PULLS

Cable manufacturers have handbooks in print that describe methods of making safe cable pulls and for making the necessary calculations of pulling tensions. Pull programs are available from suppliers of cable pulling compounds. Cable pull programs are available from EPRI [11-7]. There are many cable manufacturers, utilities, architect-engineering firms, and pulling equipment companies that also have programs.

An entirely new group of cable pulling compounds has become available since the EPRI project. They are able to achieve the very low coefficients of friction that their literature suggests—generally these lower values are for the higher sidewall bearing pressures that are found in the field and in the newer test procedures.

2.1 Maximum Allowable Tension on Conductors

The maximum allowable tension on cable conductors that should be used during pulls must be based on experience as well as good engineering. Factors that have an impact on the value include type of metal, temper, and factors of safety. The limits have been set based on only the central conductor of the cable or cables. This quickly establishes one of the safety factors, because all of the components of a cable provide some mechanical strength.

One obvious limit is to consider the mechanical stress level at which the conductor will permanently deform/stretch. Upper limits have generally been set well below the elongation value of the conductor metal. The classic approach has been to use the values shown in Table 11-1, but the spread in values shown below represent present-day data from suppliers. Even higher values have been recommended and published by AEIC [11-7].

Table 11-1 Maximum Allowable Pulling Tension on Conductors

Metal	Temper	Pounds per cmil
Copper	Soft (annealed)	0.008
Aluminum	Hard	0.008
Aluminum	¾ Hard	0.006 to 0.008

Aluminum	½ Hard	0.003 to 0.004
Aluminum	Soft	0.002 to 0.004

2.2 Pulling Tension Calculations

The concept of the significant factors in a cable pull can be appreciated by looking at the equation for pulling a single cable in a straight, horizontal duct. The basic equation is:

$$T=W\times L\times f \tag{11.1}$$

where T=tension in pounds

W=weight of one foot of cable in pounds

L=length of pull in feet

f=coefficient of friction for the particular duct material and outer layer of the cable.

It is obvious that the weight of the cable and the length of the pull can be determined with great accuracy. The one thing that varies tremendously is the value of the coefficient of friction—it can vary from 0.05 to 1.0. In test conditions, values as high as 1.2 have been recorded! Even when the materials used in the duct and jacket are known, the type and amount of lubricant can be an important factor in this variation.

The significance of this is that the accuracy of the calculation can't come out to six decimal places even if you have a calculator or computer with that many places! It is also not wise to argue whether one method of tension calculation can attain an accuracy of one percent better than another when one considers the probable inaccuracy of the coefficient of friction.

2.3 Coefficient of Friction

Since this is a significant variable in all calculations, let's look at this early in the discussion of cable pulling. What do we mean by "coefficient of friction?" Historically the test apparatus for friction determination consisted of a section of duct that was cut longitudinally in half. The open duct was mounted on an inclined plane. A short sample of cable was placed near the top end and the angle of incline was increased until the cable started to move as the result of gravity. Using the angle at which movement began, the static coefficient of friction was calculated. Generally the angle of incline could be decreased and the cable would maintain its slide. Using this second angle, the dynamic coefficient of friction was obtained.

As described above, many of the earlier publications suggested that the coefficient of friction that should be used varied from 0.40 to 1.0. This was, of course, very safe for most situations.

The EPRI project [11-6], demonstrated that there were other important issues that needed to be established in making accurate determinations of the coefficient of friction such as the level of sidewall bearing pressure. This force is duplicated in present day test methods by applying a force that pushes the cable down on the conduit. The interesting fact is that this actually reduces the coefficient of friction in most instances! The quantity and type of lubricant are important. Too much lubricant can increase the friction. A more viscous lubricant should be used with heavier cables, etc.

2.4 Sidewall Bearing Pressure (SWBP)

When one or more cables are pulled around a bend or sheaves, the tension on the cable produces a force that tends to flatten the cable against the surface. This force is expressed in terms of the tension out of the bend in pounds divided by the bend radius in feet.

$$SWBP=T_O/R \tag{11.2}$$

where *SWBP*=force in pounds per foot

To=tension coming out of the bend in pounds

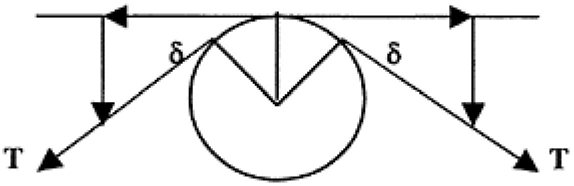
R=radius of the inside of the bend in feet

SWBP is not truly a unit of pressure, but rather a unit of force for a unit of length. In the case of a smooth set of sheaves or bend, the unit is the entire length of contact. However, any irregularity, such as a bump on the surface, or a small radius sheave with limited bearing surface (even though it may be part of a multi-sheave arrangement), reduces the effective bearing surface length. This must be taken into account in the calculation to prevent damage to the cable.

For multiple cables in a duct, the matter is complicated because of the fact that the sidewall bearing pressure is not equally divided among the cables. This situation is taken into account by using the weight correction factor that will be discussed later in this chapter.

Figure 11-1 shows the mathematical derivation for a horizontal bend of one cable—ignoring the weight of the cable. As the angle approaches zero, the force between the cable and the bend approaches unity.

Figure 11-1 Pulling forces in horizontal bend.



The force per unit lenth

$$= \frac{2\,T\,\sin\delta}{2\,R\,\delta} \tag{11.3}$$

where

sin δ=δ for smali angles

and sidewall pressure,

$$T/R = \frac{2\,T\,\sin\delta}{2\,R\,\delta} \tag{11.4}$$

The T/R ratio is independent of the angular change of direction produced by the bend. It depends entirely on the tension out of the bend and the bend radius with the effective bend radius taken as the inside of the bend. Increasing the radius of the bend obviously decreases the SWBP.

Sidewall bearing pressure limits that have been used historically are shown in Table 11-2. As with maximum pulling tension values, AEIC [11-7] has published limits that exceed the values shown in this table.

Table 11-2 Sidewall Bearing Pressure Limits

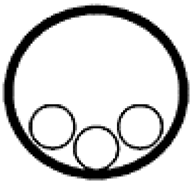
Cable Type	**SWBP in Pounds per Foot**
Instrumentation	100
600 V non-shielded control	300
600 V power	500
5 to 15 kV shielded power	500
25 to 46 kV power	300
Interlocked Armored	300
Pipe-type	1,000

2.5 Pulling Multiple Cables in a Duct or Conduit

2.5.1 Cradled Configuration.

A frequent requirement is to pull three cables into one duct. This brings the relative diameters of the cables into play with the inner diameter of the duct. If the cables are relatively small as compared with the duct diameter, the cables are said to be “cradled.”

Figure 11-2 Cradled cables.



The outer two cables push in on the center cable, making it seem to be heavier than it actually is.

The pulling calculation handles this by using a “weight correction factor” that increases the apparent weight of that center cable.

The sidewall bearing pressure (SWBP) on the center cable in Figure 11-2 is influenced by the other two cables. The effective SWBP for the cradled configuration may be calculated from:

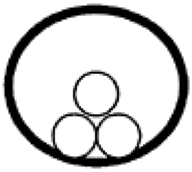
$$SWBP=[(3\,W_C-2)/3]\,T_O/R \tag{11.5}$$

See Equations 11.2 and 11.7 for definitions of terms.

2.5.2 Triangular Configuration.

When the diameter of each of the three cables is closer to one-third that of the inner diameter of the duct, the situation is known as a “triangular” configuration.

Figure 11-3 Triangular arrangement.



In this situation, the top cable is riding on the two lower cables without touching the duct wall.

The effect of this is that the one cable effectively increases the weight of the two lower cables, but does not function as a longitudinal tension member. This means that one must use the cross-sectional area of only two of the cables in the maximum allowable tension determination in this example, not three cables.

The sidewall bearing pressure on the two lower cables in Figure 11-3 is influenced by the upper cable. The effective SWBP for the triangular configuration may be calculated from:

$$SWBP=WcTo/2R \tag{11.6}$$

The units are defined in Equations 11.2 and 11.7.

2.5.3 Weight Correction Factor.

When two or more cables are installed in a duct or conduit, the sum of the forces developed between the cables and the conduit is greater than the sum of the cable weights.

Weight correction factor is therefore defined as:

$$Wc=\sum F/\sum W \tag{11.7}$$

where W_c=weight correction factor (also merely “c”)

ΣF=force between cable and conduit, usually in pounds

ΣW=weight of the cable with same units as above

For the typical case of three cables of equal diameter and weights in a conduit of given size, the weight correction factor is higher for the cradled configuration than the triangular configuration.

The mechanism for this relationship is shown in Figure 11-4 as:

Figure 11-4 Weight correction.

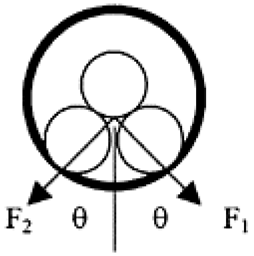


Table 11-3 Weight Correction Factors

Configuration of Three Cables	Weight Correction Factor
Triangular	1.222
Cradled	1.441

It is always safer to anticipate the cradled configuration unless the cables are triplexed or if the clearance is near the 0.5-inch minimum.

The equations for calculating the weight correction factor are:

Cradled: $$W_C = 1 + 4/3\,(d/D-d)^2 \qquad (11.8)$$

Triangular: $$W_C = \frac{1}{1-[(d/D-d)^2]^{1/2}} \qquad (11.9)$$

where D=diameter of inside of conduit

d=diameter of each cable

2.5.4 Jamming of Cables.

When the diameter of each cable is about one-third the inner diameter of the duct, a situation may occur where the cables may jam against the inside of the conduit. This generally occurs when the cables go around a bend or a series of bends. The “center” cable may try to pass between the outer two cables. When the sum of the diameters of the three cables is just slightly larger than the inner diameter of the duct, jamming can occur. Jamming increases the pulling tension many fold and can result in damaging the cable or even pulling cables in two, breaking pull irons in manholes, etc.

Figure 11-5 Cable jamming.

The condition that causes jamming for three cables in a conduit.

The "jam ratio" of the cables in this duct needs to be evaluated. The equation for finding the jam ratio of three cables in a duct may be determined by:

$$\text{Jam Ratio}=1.05\times D_d/D_c \tag{11.10}$$

where D_d=inside diameter of the duct or conduit

D_c=outer diameter of each of the three cables

The factor of 1.05 has been used to account for the probable ovality of the conduit in a bend and to account for the cable having a slightly different diameter at any point. If precise dimensions are known, this 5% factor can be reduced.

Where the jam ratio falls between 2.6 and 3.2, jamming is probable if there are bends in the run and unless other precautions are taken. To avoid any problems with jamming, it is wise to avoid pulls where the ratio is between 2.6 and 3.2.

How can jamming be avoided even though the calculation shows that the ratio indicates a significant probability of jamming? There are several solutions, some of which are obviously possible during the planning stages and some that are possible during the installation stage.

- □ Use a different size of cable or conduit to change the ratio.
- □ Have the cable triplexed (twisted together) at the factory.
- □ Tie the cables together in the field with straps.
- □ Use precautions at the feed point to keep a triangular configuration and allow no crossovers.

The National Electric Code, ANSI C-1, requires that the total fill of a conduit be 40% or less for three cables in a conduit. This means that the cross-sectional area of all three of the cables cannot be more than 40% of the cross-sectional area of the conduit. Unfortunately, for 40% fill, the jam ratio is 2.74, which is in the lower danger ratio. An example of this situation is when three 1.095 inch diameter cables are installed in a conduit with an inside diameter of exactly 3.0 inches. (The actual inside diameter of a nominal 3-inch conduit is 3.068 inches!) If the designer tries to reduce the fill to say 38% to stay safely within the 40% limit, the jam ratio gets worse −2.81.

The NEC generally does not govern utility practices, hence clearance limits are not based on percent fill. Utility practice considers that 0.5 inches of clearance is satisfactory for general pulls. Clearances as small as 0.25 inches have been successfully made when good engineering practices and careful field supervision are employed [11-7].

To complete this discussion of jam ratio, it is important to know that jamming can occur when more than three cables are installed in a conduit. A modification of the equation is necessary as shown:

$$\frac{3D}{n_1 d_1 + n_2 d_2 + n_3 d_3 + n_4 d_4 + \ldots\ldots} \qquad (11.11)$$

where D=conduit inner diameter (ID)

$n1$, n_2, n_3,=number of cables of diameter 1, 2, 3, etc.

$d1$, ${}_2d$, d_3,=diameters of cables in groups 1, 2, 3, etc.

Theoretically any combination of cable diameters that fall in the critical zone can jam. Field experience has shown that the probability of jamming decreases as the number of cables increases.

2.5.5 Clearance.

Another consideration before cables are placed in a conduit is the amount of clearance between the cable or cables and the inside of the conduit. This may be quickly seen in the example of the three cables in a triangular configuration in Figure 11-1. The distance from the top cable to the inside "top" of the conduit is defined as the clearance.

3.0 PULLING CALCULATIONS

The previous sections have presented some of the fundamentals of pulling cables. Now let's see how those factors, plus a few more, come together when we actually calculate the tension on a cable or cables that are to be installed.

3.1 Tension Out of a Horizontal Bend

Bends in cable runs are a fact of life. The important point is that the friction and sidewall bearing pressure around that bend increase the tension coming out of the bend in respect to the tension on the cable coming into the bend.

$$T_O=T_{IN}\,\mathrm{e}^{cfa} \qquad (11.12)$$

where T_O=tension going out of the bend

T_{IN}=tension coming into the bend

c=weight correction factor

f=coefficient of friction

a=angular change of direction in radians

This is a simplified equation that ignores the weight of the cable. It is sufficiently accurate where the incoming tension at the bend is equal to or greater than ten times the product of the cable weight per foot times the bend radius expressed in feet. The practical situation where T_{IN} is less than ten times the product of the weight and radius is where the cable is being fed at low tension into a large radius bend [11-8]. In such a case, the equation becomes:

$$T_O = T_{IN}\left[\frac{e^{cfa} + e^{-cfa}}{2}\right] + \left[(T_{IN})^2 + (wr)^2\right]^{1/2}\left[\frac{e^{cfa} - e^{-cfa}}{2}\right] \tag{11.13}$$

In order to fully appreciate the effect of the impact of the exponent of e, cfa, Table 11-4 shows the multiplier of the tension for various values of the exponent. This also shows the significance of keeping the coefficient of friction down to a low value—especially when you have multiple bends in a run.

Table 11-4 Multiplier of Tension Values for Various Exponents

cfa	45 Degree Bend	90 Degree Bend
0.1	1.08	1.17
0.2	1.17	1.37
0.3	1.27	1.60
0.4	1.48	2.19
0.5	1.60	2.56

It is essential to remember that the exponent of e has three terms: weight correction factor, coefficient of friction, and angle of deflection. Sometimes this exponent is shown only as two factors because of limitations of older computer programs. In order to make that workable when multiple cables are installed, it is necessary to multiply the selected coefficient of friction by the weight correction factor. If you therefore have a situation where three cables will be cradled, for instance, the cfa value (from Table 11-4) is 1.442 times the coefficient of friction. Putting this another way, if you consider the proper coefficient of friction to be 0.2, and the cables will be in a cradled configuration, you must use a cfa value of 0.3. If there is only one cable, this means that you would use the 0.2 value of cfa for that same coefficient of friction since W_C for one cable is unity.

A large number of bends in a run can literally multiply the tension exponentially! This is one of the reasons that many installation practices keep the number of 90° bends to a maximum of three or four.

3.2 Which Direction to Pull?

There are always two possible directions that a cable can be pulled for any run—just as a cable always has two ends. Let us go through the calculations of an example that has one bend so that we can see how the pulling tension can vary.

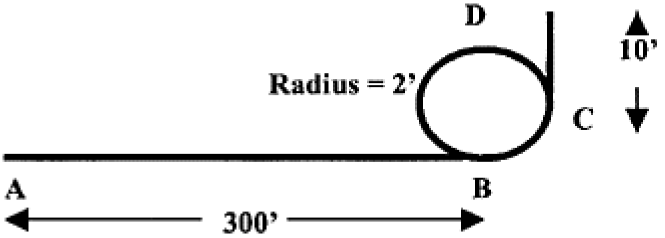


Figure 11-6 Pulling around a bend.

Given: 1×1,000 kcmil copper cable
Weight of cable=6 pounds per foot
Coefficient of friction=0.5
Pulling from A to D:

Tension at A = 0

Tension at B = 300×6×0.5=900pounds

$e^{cfa} = e^{1\times0.5\times1.5708}=2.713^{0.7854}=219$

Tension at C = 900×2.19=1,971 pounds

Tension at D = −10×6×0.5+1,971=30+1,971=2,001

This exceeds the long established 1,000-pound limit for a pulling grip, so this must be pulled with a pulling eye on the conductor. The established limit for a 1,000 kcmil copper conductor is based on the conductor kcmils multiplied by 0.008, or 8,000 pounds.

The maximum allowable tension coming out of the bend at point C results in a sidewall bearing pressure of 1,971/2, or 985.5 pounds per foot which is above the value generally agreed to by the manufacturers.

Pulling from D to A:

Tension at D = 0

Tension at C = 10×6×0.5=30pounds

$e^{cfa} = e^{1\times0.5\times1.5708}=2.713^{0.7854}=2.19$

Tension at B = 2.19×30=65.7pounds

Tension at A = 300×6×0.5+65.7=965.7 pounds

This is satisfactory in all respects. The total tension does not exceed 1,000 pounds and the tension coming out of the bend is well below accepted levels. A cable grip may be used to pull the cable from D to A.

From this example, it can be seen that it is always preferable to set up the reel as close to the bend as possible.

4.0 CABLE INSTALLATION RESEARCH

Pipe type cable pulling was addressed by EPRI in Final Report EL-2847, March 1983, entitled “Increasing Pipe Cable Section Lengths” [11-5]. Sidewall bearing pressures of up to 1,000 pounds per foot were recommended.

The fact that the suggested values for pulling tension and related considerations of extruded distribution cables had developed only from an understanding of past successful pulls made it seem reasonable to look at extruded dielectric cables using laboratory and field generated data. EPRI undertook Research Project 1519 in the late 1970s. The work was published as Final Report EL 3333 [11-6] in March 1983. Additional insight into pulling considerations was accomplished through the publication of AEIC G5–90 [11-7], *Underground Extruded Power Cable Pulling Guide*, in May 1990.

The values of sidewall bearing pressure, allowable maximum tension on the conductors, and maximum allowable tension on a pulling basket, are much less conservative than the level generally accepted by cable manufacturers.

Since there are obvious advantages for a utility to make longer pulls based on this data, a good deal of caution and experience is necessary.

4.1 Research Results

Before reviewing the results, a few words of caution are needed. Field conditions are seldom ideal. The actual installation may not go as smoothly as was planned. For instance, when one believes that the cable may be pulled in one continuous motion, the actual pull may be made in a series of starts and stops. This alters the coefficient of friction because of the unplanned start, with the cable probably already far into the duct. When one anticipates excellent lubrication application, the amount of lubrication may be more or even less than that planned. Therefore,

- **Don’t blindly use these values to their upper limits.**
- **Be conservative.**
- **Follow the cable manufacturer’s recommendations.**

The most dramatic findings of this EPRI research project over previously accepted values were:

- Pulling tension on both copper and aluminum conductors was about 50% greater than older limits.
- Allowable sidewall bearing pressure was as much as 200% greater than previously recommended.
- Coefficient of friction was about 50% lower—with values as low as 0.05.
- Basket grips could be used to pull 10 times (or more) the force previously recommended as long as tension limits on the conductor are not exceeded.

5.0 FIELD EXPERIENCE

While the calculations have been found to be very accurate, field experience has shown that conditions may exist in the field that may greatly affect the success of the cable pull. A new installation can be calculated and results of the cable pull will follow the calculations fairly well. However, older conduits may have been exposed to unknown conditions. The following work practices and field conditions should be considered to make a successful installation without damaging the cable.

- Since buried conduit is not visible verification of the location route should be made before setting up the cable pulling equipment. Conduit maps are helpful and a brief survey of the area to see if there has been new construction, which may affect the pull is often required. Checking the areas where the pulling equipment and reels of cable are to be set up for the pull will often times save a lot of field modifications. Choosing these locations is especially important in a congested area, or narrow streets or alleys.
- Older conduits may be damaged, contain stones and dirt, or have sections that have shifted leaving ridges. It is therefore recommended that the older conduits be inspected for these conditions. This can be done by pulling a mandrel through the conduit and inspecting its condition upon leaving the conduit pull.
- Measurements should be made while the cable is being installed so as to monitor any conditions that could cause possible damage. Equipment is available that contains a dynamometer to indicate pulling tensions. Some equipment contains charting facilities, which will record the pulling tensions as the pull progresses. These measurements are very important when installing transmission cable in a pipe.
- Feeding tubes are flexible metal tubes, which guide the cable toward the conduit or pipe. Their purpose is to supply smooth arc so that the cable is not damaged when entering a manhole. They are often used when installing transmission cable. This flexible metal tube must be sized to match the diameter of the conduit or pipe into which the cable is being installed.
- Lubricating compounds or fluids are used to reduce the coefficient of friction as previously mentioned. These come in a variety of viscosities and contain lubricants that must be compatible with the cable being installed. As an example PILC cable with a bare lead sheath was installed with a lubricant consisting on a hydrocarbon based grease. This lubricant, while reducing the pulling tension, also provided corrosion protection to the lead. Conduits that contain this grease may require cleaning before installing a cable with an outer coating with semi conducting properties. Otherwise the semi conducting properties of the new cable will deteriorate with time. Prelubrication of the conduit will ensure a better distribution of the lubricating material and ultimately reduce the pulling tension for the installation.
- Attachments to the cable for pulling operations vary with the amount of tension expected and the type of cable being installed. A woven basket grip is very useful for short pulls of limited tension. These grips are very popular when pulling three single conductor cables. The basket grip fits around all three conductors and as tension is applied during installation the basket fits more tightly against the three conductors. It is important that each cable of the bundle have a sealed end so that water cannot enter the strands during installation. This precaution is needed as some conduits contain standing water, and that water can be forced into the stranding of the conductor during

the cable installation. PILC cable requires a lead seal to be installed over single conductor and three conductor cables. It is necessary for the conductors to be wiped into the pulling eye for strength.

- Installing cables in a hi-rise building offers some unique situations. Foremost is the place that you are going to setup the pulling equipment as well as the reel of cable being installed. Choice can be made to install the reel of cable in the upper floors or to feed the cable in from the lower floors. Installation of vertical pulls must take into account the type of grips that will be used as well as intermittent grips if required. Methods of holding cable when intermittent grips are used require special attention in order to generate enough slack to get grips to hold their respective weight. Clamping devices used to support vertical cables must be designed so that they do not damage the cable while providing the function of holding the cable.
- Lines used to pull cable vary mostly by the amount of tension they are expecting to see during installation. Hemp and braided plastic ropes may be used on short pulls. Longer pulls, such as those on highpressure fluid filled pipe cable installations will require steel rope. Steel rope is also available with a plastic coating.
- Installation of a cable in a conduit, which already contains cable is not recommended. Called a pull-by, it is very difficult to prevent damage to the existing cable or the cable being installed. Not only is it difficult to keep from damaging cable, it is also difficult to detect the damage incurred. Damage may occur to the jackets, sheaths, and neutral inside the conduit without detection.

6.0 REFERENCES

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[11-2] Buller, F.H., "Pulling Tension During Cable Installation in Ducts or Pipes," General Electric Review, Schenectady, NY; Volume 52, No. 8, August, 1949, pp. 21–33.

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[11-4] *Underground Systems Reference Book,* EEI, 1957.

[11-5] "Increasing Pipe Cable Section Lengths," EPRI Final Report EL-2847, March 1983, EPRI, P.O. Box 10412, Palo Alto, CA, 94303–0813, USA.

[11-6] "Maximum Safe Pulling Lengths for Solid Dielectric Insulated Cables," EPRI Final Report EL-3333, February 1984, EPRI, P.O. Box 10412, Palo Alto, CA, 94303–0813, USA.

[11-7] *Underground Extruded Power Cable Pulling Guide,* AEIC G5–90, May, 1990, Association of Edison Illuminating Companies, P.O. Box 2641, Birmingham, AL 35291–0992, USA.

[11-8] Kommers, T.A., "Electric Cable Installation in Raceways," Pulp and Paper Industry Technical Conference, Portland, Oregon, June 1980.

CHAPTER 12

SPLICING, TERMINATING, AND ACCESSORIES

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1.0 INTRODUCTION

A fundamental concept that needs to be established early in this chapter is that when they are used here a “splice” and “joint” are one and the same! “Cable Splicers” have been around for about 100 years, but officially in IEEE Standards, when you join two cable ends together, you make a joint [12-1,12-2, 12-3].

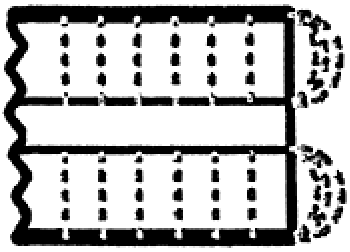
The basic dielectric theory that has been previously described for cable in Chapter 2 also applies to joints and terminations. Some repetition of those concepts may be presented so that this will be a stand-alone treatment and some repetition is constructive.

This chapter will address the design, application, and preparation of cables that are to be terminated or spliced together. The application of this material will cover medium voltage cable systems in particular with higher and lower voltage application being mentioned in particular designs and applications. The field theory described in Chapter 2 lays the foundation for the theory utilized in the design and construction of joints and terminations.

2.0 TERMINATION THEORY

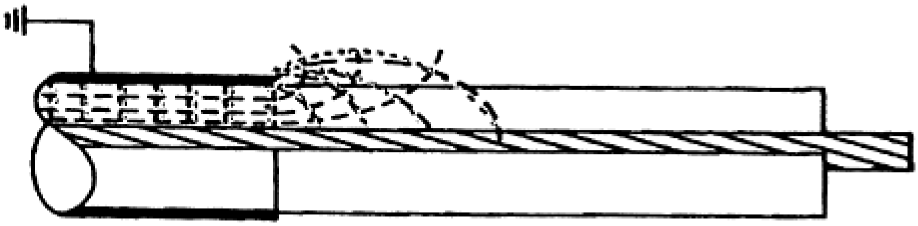
A termination is a way of preparing the end of a cable to provide adequate electrical and mechanical properties. A discussion of the dielectric field at a cable termination serves as an excellent introduction to this subject. Whenever a medium or high voltage cable with an insulation shield is cut, the end of the cable must be terminated so as to withstand the electrical stress concentration that is developed when the geometry of the cable has changed. Previously the electrical stress was described as lines of equal length and spacing between the conductor shield and the insulation shield. As long as the cable maintains the same physical dimensions, the electrical stress will remain consistent. When the cable is cut, the shield ends abruptly and the insulation changes from that in the cable to air. The concentration of electric stress is now in the form of Figure 12-1 with the stress concentrating at the conductor and insulation shield.

Figure 12-1 Electrical stress field with cut end.



In order to reduce the electrical stress at the end of the cable, the insulation shield is removed for a sufficient distance to provide the adequate leakage distance between the conductor and the shield. The distance is dependent on the voltage involved as well as the anticipated environmental conditions. The removal of the shield disrupts the coaxial electrode structure of the cable. In most cases, the resulting stresses are high enough that they cause dielectric degradation of the materials at the edge of the shield unless steps are taken to reduce that stress.

Figure 12-2 Electrical stress field with shield removed.



In this operation, the stress at the conductor is relieved by spreading it over a distance. The stress at the insulation shield remains great since the electrical stress lines converge at the end of the shield as seen in Figure 12-2. The equipotential lines are very closely spaced at the shield edge. If those stresses are not reduced, partial discharge may occur with even the possibility of visible corona. Obviously, some relief is required in most medium voltage applications.

2.1 Termination with Simple Stress Relief

To produce a termination of acceptable quality for long life, it is necessary to relieve voltage stresses at the edge of the cable insulation shield. The conventional method of doing this has been with a stress cone.

A stress cone increases the spacing from the conductor to the end of the shield. This spreads out the electrical lines of stress as well as providing additional insulation at this high stress area. The ground plane gradually moves away from the conductor and spreads out the dielectric field—thus reducing the voltage stress per unit length. The stress relief cone is an extension of the cable insulation. Another way of saying this is the electrostatic flux lines are not concentrated at the shield edge as they are in Figure 12-2. It follows that the equi-potential lines are spaced farther apart.

Terminations that are taped achieve this increase in spacing by taping a conical configuration of tape followed by a conducting layer that is connected electrically to the insulation shield as in Figure 12-3. When stress cones are pre molded at a factory, they achieve the same result with the concept built into the unit.

Figure 12-3 Leakage path.

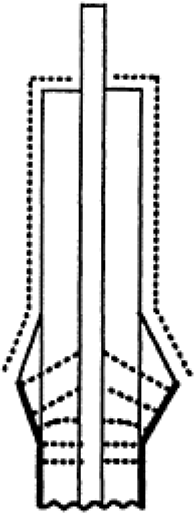
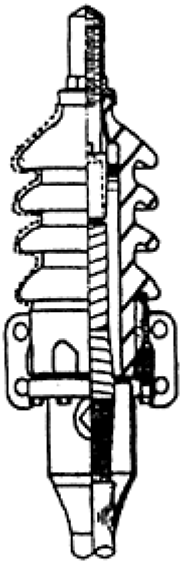


Figure 12-4 Leakage path.

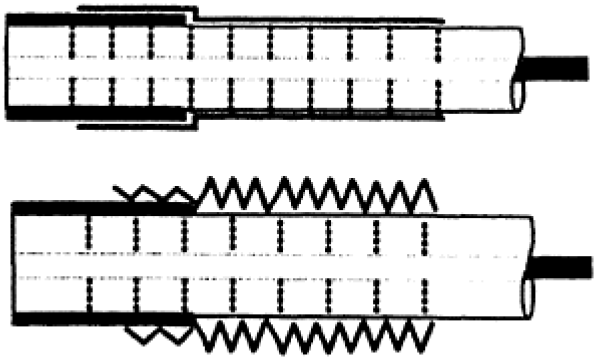


When additional leakage distance over the insulation is required, skirts can be placed between the conductor and insulation shield. These skirts can be built into the termination as shown in Figure 12-4 or added in a separate field assembly operation.

2.2 Voltage Gradient Terminations

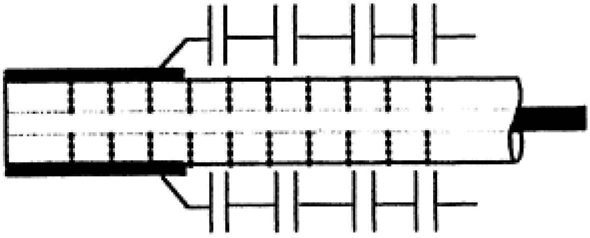
Electrical stress relief may come in different forms. A high permittivity material may be applied over the cable end as shown in Figure 12-5. This material may be represented as a long resistor connected electrically to the insulation shield of the cable. By having this long resistor in cylindrical form extending past the shield system of the cable, the electrical stress is distributed along the length of the tube. Stress relief is thus accomplished by utilizing a material having a controlled resistance or capacitance. Other techniques may be employed, but the basic concept is to utilize a material with say a very high resistance or specific dielectric constant to extend the lines of stress away from the cable shield edge.

Figure 12-5 Stress cones using high dielectric constant and high resistivity materials.



An application of a series of capacitors for stress control is frequently used on high and extra high voltage terminations. These specially formed capacitors are used to provide the stress relief. The capacitors are connected in series, as shown in Figure 12-6, and distribute the voltage in a manner that is similar to the high permittivity material that was discussed previously.

Figure 12-6 Capacitive graded stress cone.



3.0 TERMINATION DESIGN

3.1 Stress Cone Design

The classic approach to the design of a stress relief cone is to have the initial angle of the cone to be nearly zero degrees and take a logarithmic curve throughout its length. This provides the ideal solution, but was not usually needed for the generous dimensions used in medium voltage cables. There is such a very little difference between a straight slope and a logarithmic curve for medium voltage cables that, for hand build-ups, a straight slope is completely adequate.

In actual practice, the departure angle is in the range of 3 to 7 degrees. The diameter of the cone at its greatest dimension has generally been calculated by adding twice the insulation thickness to the diameter of the insulated cable at the edge of the shield.

3.2 Voltage Gradient Design

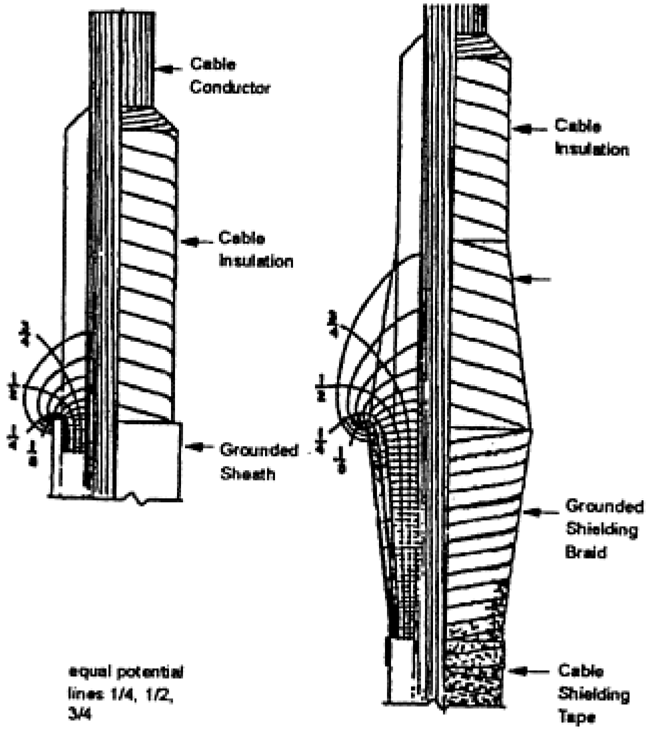
Capacitive graded materials usually contain particles of silicon carbide, aluminum oxide, or iron oxide. Although they are not truly conductive, they become electronic semiconductors when properly compounded. They do not have a linear E=IR relationship, but rather have the unique ability to produce a voltage gradient along their length when potential differences exist across their length. This voltage gradient does not depend on the IR drop, but on an exchange of electrons from particle to particle.

Resistive graded materials contain carbon black, but in proportions that are less than the semiconducting materials used for extruded shields for cable. They also provide a nonlinear voltage gradient along their length. By proper selection of materials and proper compounding, these products can produce almost identical stress relief to that of a stress cone. One of their very useful features is that the diameter is not increased to that of a stress cone. This makes them a very valuable tool for use in confined spaces and inside devices such as porcelain housings.

3.3 Paper Insulated Cable Terminations

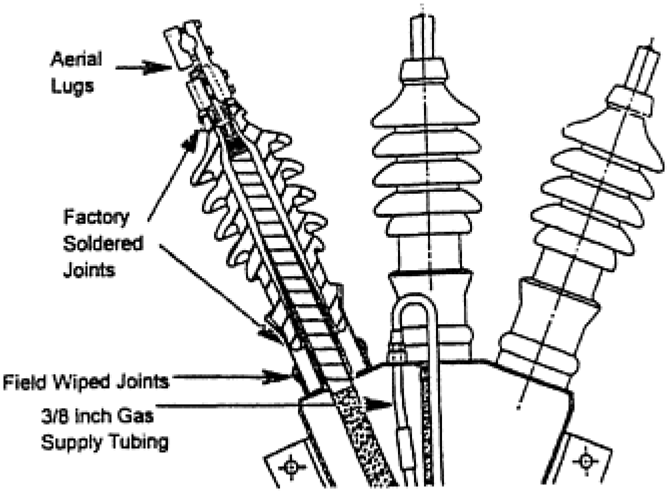
Cables that are insulated with fluid impregnated paper insulation exhibit the same stress conditions as those with extruded insulations. In the build up of the stress cone, insulating tapes are used to make the conical shape and a copper braid is used to extend the insulation shield over the cone, as shown in Figure 12-7. Similar construction is required on each phase of a three-conductor cable as it is terminated.

Figure 12-7 Equal potential lines.



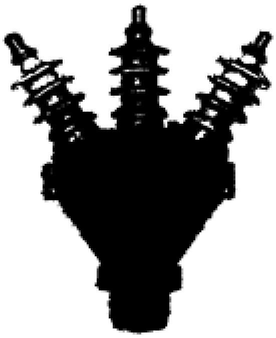
The field application of installing stress relief on individual phases can be seen in Figure 12-8 and 12-9. The type of termination is consistent on all types of PILC cables whether they are enclosed in a porcelain enclosure, a three conductor terminating device, or inside a switch or transformer compartment.

Figure 12-8 Gas filled termination.



A critical part of the design is the material used to fill the space inside the porcelain or other material that surrounds the paper cable. Since the cable is insulated with a dielectric fluid, it is imperative that the filling compound inside the termination be compatible with the cable's dielectric fluid. In gas filled cable designs, the termination is usually filled with the same gas as the cable, but a dielectric fluid may be used in conjunction with a stop gland.

Figure 12-9 PILC cable termination.



3.4 Lugs

The electrical connection that is used to connect the cable in a termination to be connected to another electrical device must be considered. Generally called a "lug", this connector must be able to carry the normal and emergency current of the cable, it must provide good mechanical connection in order to keep from coming loose and create a poor electrical connection, and it must seal out water from the cable. The water seal is accomplished by two forms of seals. Common to all terminations is the need to keep water out of the strands. Many early connectors were made of a flattened section of tubing that had no actual sealing mechanism and water could enter along the pressed seam of the tubing. Sealing can be accomplished by filling the space between the insulation cutoff and lug base with a compatible sealant or by purchasing a sealed lug. The other point that requires sealing is shown in Figure 12-10 that is common to most PILC cable terminations. Here the termination has a seal between the end of the termination and the porcelain body. Another seal that is required is at the end of the termination where the sheath or shield ends. Moisture entering this end could progress along inside of porcelain and result in a failure.

Figure 12-10 Terminal lug.

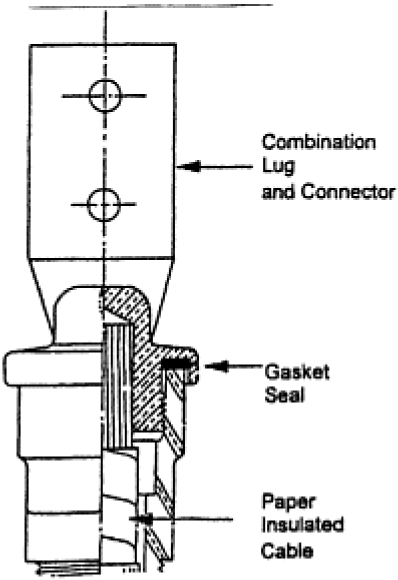
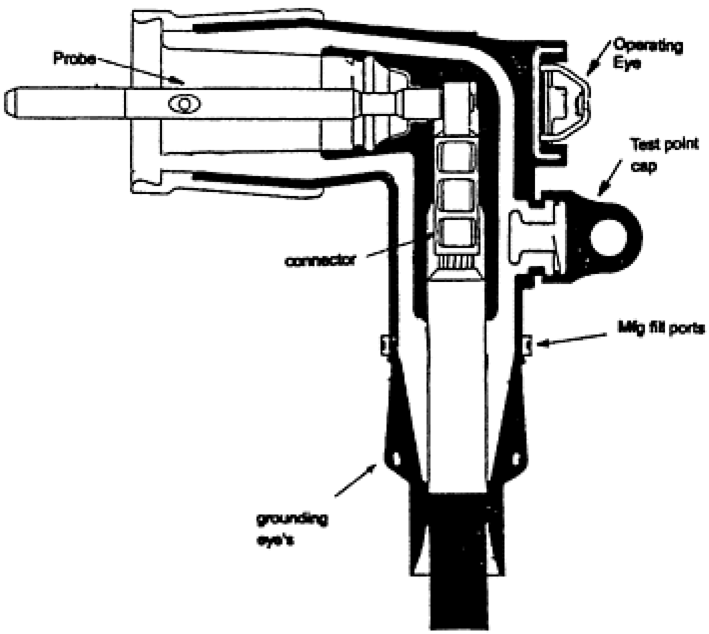


Figure 12-11 Load-break elbow.



3.5 Separable Connectors (Elbows)

One of the most widely used terminations for cables is the “elbow,” as it was originally called, but is more properly called a separable connector. It is unique in that it has a grounded surface covering the electrical connection to the device on which it is used. Used as an equipment termination, it provides the connection between the cable and the electrical compartment of a transformer, switch, or other device. Since the outer surface is at ground potential, this type of termination allows personnel to work in close proximity to the termination.

Another design feature is the ability to operate the termination as a switch. This may be done while the termination is energized and under electrical load. While elbows are available that cannot be operated electrically, this discussion will deal with the operable type shown in Figure 12-11. This figure shows a cut away of a separable connector followed by a brief description of the parts.

The insulating portion of the elbow is made of ethylene propylene diene monomer (EPDM) rubber with an outer covering of similar material that is loaded with carbon black to make it conductive. The inner semiconducting shields are the same material as the outer semiconducting layer.

Probe: The probe consists of a metallic rod with an arc quenching material at the end that enters the mating part, the bushing. The metallic rod makes the connection between the connector and the bushing receptor. Arc quenching material at the tip of the probe quenches the arc that may be encountered when operating the elbow under energized and loaded switching conditions. A hole in the metallic rod is used with a wire wrench to tighten the probe into the end of the cable connector.

Connector: The connector is attached to the conductor of the cable and provides the current path between the conductor and the metallic probe. It is compressed over the conductor to make a good electrical and mechanical connection. The other end has a threaded hole to accept the threaded end of the probe.

Operating Eye: This provides a place for an operating tool to be attached so that the elbow assembly can be placed or removed from the bushing. It is made of metal today and is molded into the conducting outer layer of the elbow.

Locking Ring: This is molded in the inside surface of the elbow and maintains the body of the elbow in the proper position on the bushing. There is a groove at the end of the bushing into which the locking ring of rubber must fit.

Test Point: Elbows may be manufactured with a test point that allows an approved testing device to determine if the circuit is energized. The test point is in the form of a metallic button that is molded into the elbow body and is simply one plate of a capacitor. It is supplied with a conductive rubber cap that serves to shunt the button to ground during normal service. The molded cap must be removed when the energization test is performed. A second use of the test point is a place to attach a faulted circuit indicator—a device made for test points that may be used to localize a faulted section of circuit for the purpose of reducing the time of circuit outage. When in use, the indicator can remain on the elbow during normal service.

Test Point Cap: Covers and grounds the test point when a test point is specified.

Grounding Eye: This is provided on all molded rubber devices for the purpose of ensuring the outer conductive material stays at ground potential.

Operating/Switching: Load-break elbows are designed to function as a switch on energized circuits. They can safely function on cables carrying up to 200 amperes and are capable of being closed into a possible fault of 10,000 amperes. Since this elbow can be operated while energized, devices are required to keep the internal surfaces free of contamination. Good operating practices call for cleaning the mating surfaces of the bushing and the elbow followed by the application of lubricant—while both devices are de-energized! Lubricant is also applied when assembling the elbow on the cable. Some manufacturers supply a different lubricant for the two applications and consequently care should be taken that the correct lubricant is used in each application.

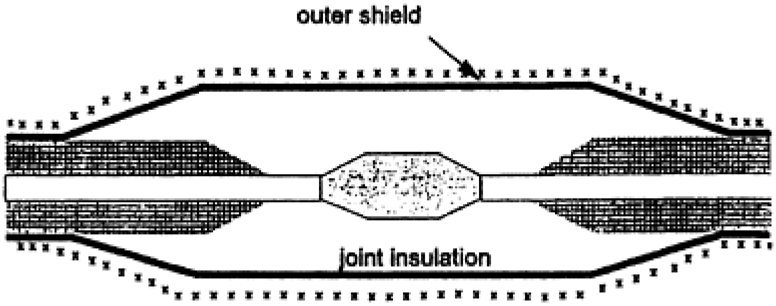
4.0 SPLICING/JOINTING

As was mentioned earlier in this chapter, a termination may be considered to be half of a joint. The same concerns for terminations are therefore doubled when it comes to designing and installing a splice.

4.1 Jointing Theory

The ideal joint achieves a balanced match with the electrical, chemical, thermal, and mechanical characteristics of its associated cable. In actual practice, it is not always economically feasible to obtain a perfect match. A close match is certainly one of the objectives. The splicing or joining of two pieces of cable together can best be visualized as two terminations connected together. The most important deviation, from a theoretical view, between joints and terminations is that joints are more nearly extensions of the cable. The splice simply replaces all of the various components that were made in to a cable at the factory with field components. Both cable ends are prepared in the same manner unless it is a transition joint between say PILC and extruded cables. Instead of two lugs being attached at the center of the splice, a connector is used. At each end of the splice where the cable-shielding component has been stopped, electrical stress relief is required just as it was when terminating. Figure 12-12 shows a taped splice and its components.

Figure 12-12 Taped splice.



Connector: Joins the two conductors together and must be mechanically strong and electrically equal to the cable conductor. In this application, the ends of the connector are tapered. This provides two functions: 1) it provides a sloping surface so that the tape can be properly applied and no voids are created, and 2) sharp edges at the end of the connector are not present to cause electrical stress points.

Penciling: On each cable being joined, you will notice that the cable insulation is “penciled” back. This provides a smooth incline for the tape to be applied evenly and without voids.

Insulation: In this application, rubber tape is used. Tape is applied to form the stress relief cone at each end of the splice. The overlapped tape continues across the connector to the other side. The thickness at the center of the splice is dictated by the voltage rating.

Conducting Layer: Covering the insulation is a layer of conducting rubber tape that is connected to the insulation shield of the cable at both ends of the splice. Metallic Shield: A flexible braid is applied over the conducting rubber tape and connects to the factory metallic portion of the cable on each end. This provides a ground path for any leakage current that may develop in the conducting tape.

While not shown in this figure, there must be a metallic neutral conductor across the splice. This may be in the form of lead, copper concentric strands, copper tapes, or similar materials. It provides the fault current function of the cable’s metallic neutral system.

4.2 Jointing Design and Installation

4.2.1 Cable Preparation.

This is the most important step in the entire operation and is the foundation upon which reliable joints and terminations are built. Improperly prepared cable ends provide inherent initiation of failures.

The acceptable tolerances of cable end preparation are dependent upon the methods and materials used to construct the device. Common requirements include a cable insulation surface that is free of contamination, imperfections, and damage caused by such things as shield removal. Smooth surface for extruded dielectric insulations minimizes contamination and moisture adhering to the surface. If the insulation shield can be removed cleanly, there is no reason to use an abrasive on the surface. If a rough surface remains, it must be made smooth.

One of the most critical areas is the edge where the insulation shield is removed. A cut into the insulation cannot be remedied and must be removed. For premolded devices, the edge of the shield must be “square”—perpendicular to the cable axis. Metallic connections to the metal shield of the cable must not damage the underlying cable components. Cutting into the strands of wire, or even of greater importance, into a solid conductor, can not be tolerated.

The concern about length of the termination is somewhat modified for a joint since the environmental concerns of a termination (external creepage path) are really not a concern for joints. The internal creepage path in a joint is certainly of concern. If you study the literature of the 1950s [11-5], one finds that the internal creepage path for a paper insulated cable operating at 15 kV would be one inch for every 1 kV. When you look at the design of a premolded joint today, you find that the same class of cable has a joint with about one inch of creepage—TOTAL. Both of those values are correct. Why is there such a difference? The paper cable was joined using hand applied tapes, either of paper or varnished cloth. There was an air path between the two insulating layers, so the one inch per kV was correct. Premolded joints fit very solidly over the cable insulation and use its elastic pressure to maintain the seal. Experience has shown that the approximate 7 kV per inch is reliable for such joints.

4.2.2 Connecting the Conductors.

Cable conductors are generally either copper or aluminum. Copper is a very forgiving metal in a splice and many methods of connecting two copper conductors together are possible: compression, welding, heat-fusion, soldering, (even twisting for overhead conductors 75 years ago), etc. Aluminum connections are not as tolerant as copper. Great care must be taken to match the compression tool, die, and connector with each other for aluminum conductors. As conductor sizes approach 1,000 kcmil, these concerns must be addressed more completely. One of the facts involved in the larger size conductors is that, on utility systems especially, they are the feeder cables are more prone to extended periods of high temperature operation as well as emergency overloads. The operation of the connector must be stable throughout load cycling and be capable of carrying the maximum amount of current without causing thermal degradation of the joint.

The connector metal should be the same as the cable where this is possible. There are situations where this can not be done, such as the case where a copper conductor is to be connected to an aluminum conductor. It is acceptable to use an aluminum connector over a copper conductor, but a copper connector must not be used over an aluminum conductor because during load cycles the relative rates of expansion of the two metals causes the aluminum to extrude out and results in a poor connection.

The shape of the connection is always of importance if the connection is not in a shielded area such as exist in all premolded splices. In order to minimize voltage stress at the connection for all of those other conditions, special connectors are required for medium and higher voltage cables. Tapered shoulders and filled indents are hallmarks of these connectors. Semiconducting layers are generally specified over these connectors.

4.2.3 Insulation for Joints.

The material used as the primary insulation in a joint must be completely compatible with the materials in the cable. The wall thickness and its interfaces with the cable insulation must safely withstand the intended electrical stresses. The old rule-of-thumb for paper-insulated cables was that you “doubled” the insulation thickness of the cable. In other words, the designs called for putting a layer equal to twice the factory thickness over the cable insulation. In premolded devices today, the thickness is usually about 150% of the factory insulation. The joint insulation for hand taped joints (called self-amalgamating tapes) are predominately made from ethylene propylene rubber but were originally made of a butyl or polyethylene base as long as the thermal properties matched the cable insulation. Premolded joints almost always made of ethylene rubber compounds. Heat shrink joints are made of polyolefin compounds that have the property of being expanded after being cross-linked using irradiation. The greater diameter remains until heat is applied to the product as it is in place over the connection.

It is not always a good idea to put on too much insulation. Besides being good electrical insulation, these materials are also good heat barriers. Too much insulation can reduce the ability of the joint to carry the same current as the cable without overheating the center of the joint.

4.2.4 Shield Materials.

These materials must be compatible with the rest of the cable as well as having adequate conductance to drain off the electrostatically induced voltages, charging currents, and leakage currents. Electromagnetically induced currents and fault currents must also be safely handled across the joint area.

Joint semiconducting shields, like cable shields, achieve their ability to perform the task of electrical shielding by having a considerable amount of carbon black (about 30%) compounded into the material. These particles do not actually have to touch each other in order to be conductive.

4.2.5 Jackets for Joints.

They must provide physical strength, seal against moisture entry into the splice, and resist chemical and other environmental attacks. It is important to use a jacket over the splice when jacketed cables are spliced together since corrosion of metallic neutrals or shields may concentrate at this point.

4.2.6 Premolded Splices.

The manufactured splice shown in Figure 12-13 has essentially the same components requirements of the taped splice. These devices are designed to cover the range of medium voltage cable sizes. It is essential that the specified cable diameters of the splice be kept within the specified size range of each of the cables. The body of the splice must be slid over one of the cable ends prior to the connector being installed. It is finally repositioned over the center of the joint.

Figure 12-13 Premolded splice.

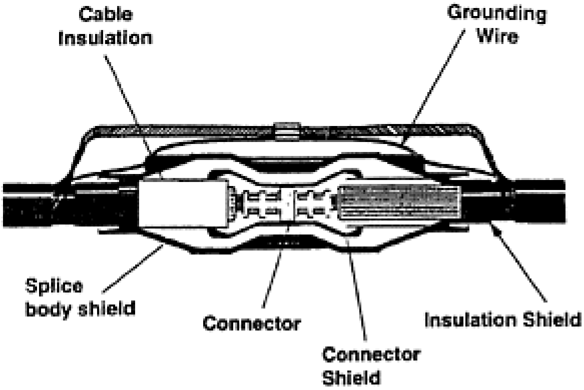
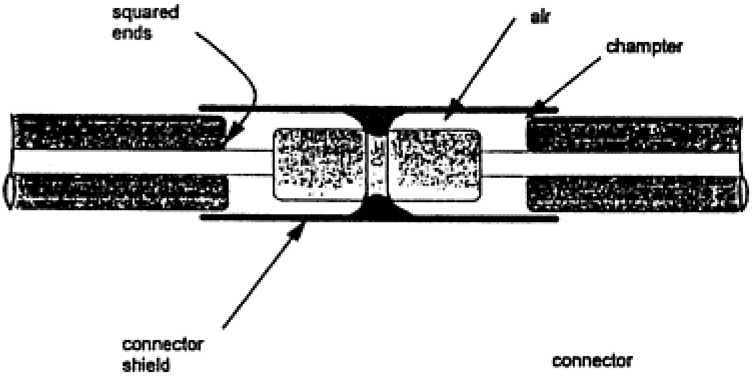


Figure 12-14 Detail of connector area of premolded splice.



The components of this type of splice are listed as follows:

Connector: The connector shown indicates that it was mechanically pressed on the conductors. In addition, the ends of the connector are not tapered, nor is that a requirement when covered by a connector shield.

Cable End Preparation: The insulation of the cable at the connector is now cut at a right angle to the conductor. In the taped splice, a penciled end was required for proper application of tapes. However, in this design, there is no taping required and consequently a pencil is not required. A chamfer is required to remove any sharp edges of the cable to prevent scratching the inner surface of the splice housing and to make it easier to slide the splice body into position.

Connector Shield: This component is not found in this form in a taped splice, but is critical to the performance of a premolded splice. It is composed of conducting rubber material. In order to nullify the sharp edges of the connector and the air that is between the connector and the cable insulation, this connector shielding must make electrical contact with the cable conductor to eliminate any voltage difference to exist. When the connector shield makes contact with the connector and the cable is energized, both the connector and the shield material are at the same potential. With this design, no discharges can occur in the air or at the connector edges. Figure 12-14 gives an expanded view of the connector shield and its application over a connector.

Insulation: The EPDM insulation is injected between the connector shield and the outer conducting shield of the splice body.

Splice Body Shield: This is a thick layer of conducting rubber. It is designed to overlap the cable’s conducting insulation shield on each end of the splice and to provide stress relief at both cable ends.

Grounding Eye: At each end of the splice, a grounding eye is required on all medium voltage premolded devices and they must be connected to the cable neutral. This provides a parallel path for the grounding of the splice body shield.

Neutral Across Splice: This generally consists of concentric strands from the cable that are twisted together and joined at the center of the splice. The wire used to make an electrical connection to the molded eye is shown connected into the neutral connector and to the concentric strands at each end of the splice.

In an actual field application, these strands should spiral around the splice and be in contact with the outer layer of the splice. This facilitates fault locating by providing a reliable metallic ground for the splice shield

Adapters: Some designs of premolded splices incorporate adapters. They extend the range of cables that can be accommodated in a specific housing. They also permit the jointing of two widely different cable sizes and they also may enable the user to minimize inventory of housings. Positioning of the adapter is important so that electrical stress points are not introduced. Adapters are applied before the connector is installed and as in the case of other premolded splices, the body must also be installed prior to the connection and the entire assembly is moved into place.

5.0 ALTERNATE DESIGNS

There are many ways of producing a joint or termination for medium-voltage cables: hand application of tapes, combinations of premolded stress cones and hand applied tapes, premolded, and heat shrink—just to mention some of them. The proper choice of which termination to select for a given application must consider factors such as cost of materials, time of installation, frequency of use, reliability, space requirements, and skill of the installer. Obviously, there is no universal solution to the wide variety of needs and conditions that are encountered in the field. The proper selection of a joint must consider all of these.

Field molded splices are constructed somewhat like a conventional taped splice. The insulating material is an uncured rubber material that may come in the form of tape or pre-formed sections. When the proper amount of material has been applied, the splice body in enclosed in a temperature controlled “oven” that confines the expanding material for the proper temperature and time required to cure the tapes. Stress relief is maintained by utilizing a conductive paint over the connector and the insulation after it is cured. The remainder of the shielding and neutral system is restored in the normal manner.

Heat shrink splices are available as a series of heat shrinkable tubes. Some may be pre-assembled by the manufacturer to reduce the number that must be handled in the field. The tubes must be slipped over the cable prior to connecting the conductors. After positioning each tube over the connected cables, heat is applied to shrink the tube snugly over the underlying surface and soften any mastic material used in the assembly. Stress relief is generally provided by stress control tubes that are also shrunk into place so that ends of the stress control tube overlap both cable insulation shields. The joint is finished in the normal manner.

Cold shrink splices are similar except that a removable liner is pulled out and the tube collapses over the underlying surface. As the name implies, no heat is required. Medium voltage joints contain all the necessary electrical components.

6.0 SELECTION OF JOINTS AND TERMINATIONS

When making a decision as to the best choice of devices to purchase, here are some of the questions and opportunities that should be considered:

- Are the components of the device compatible with the cable being spliced or terminated?
- Did the device pass all the tests that were specified so that it meets the requirements of the electrical system involved?
- Are codes applicable in the decision to use the chosen device?
- Review all safety requirements involved in the construction, application, and installation of the device.
- Will the device meet the mechanical requirements of the installation?
- Can the device be assembled with the tooling that is already available or are special tools required?
- Consider the positioning of the device. Splices are not recommended for installation at bends in the cable. Terminations are normally installed in an upright position. Other positions are possible but require special attention.
- Environmental conditions are of importance to attain expected life of any device. Heat may affect the ampacity of the device. Cold may have an effect on the assembly during installation. Contaminants are critical to the leakage path of a termination.
- Moisture is always the enemy of an underground system and must be controlled in construction and installation.
- Are there any existing work practices or procedures that will conflict with the application of this device?
- Investigate the economics of using different devices such as emergency reserve parts, training new personnel after original installation personnel have gone.
- The cost of the device and the cost of installation.
- Will the device do the job as well or better than what is presently used?

7.0 REFERENCES

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[12-4] L.G.Virsberg and P.H.Ware, “A New Termination for Underground Distribution,” 1967 IEEE Transactions, Vol. PAS-86, PP 1129–35.

[12-5] *Underground Systems Reference Book*, EEI, 1956.

CHAPTER 13
AMPACITY OF CABLES

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1.0 INTRODUCTION

Ampacity is the term that was conceived by William Del Mar in the early 1950s when he became weary of saying “current carrying capacity” too many times. AIEE/IPCEA published the term “ampacity” in 1962 in the “Black Books” of *Power Cable Ampacities* [13-1]. The term is defined as the maximum amount of current a cable can carry under the prevailing conditions of use without sustaining immediate or progressive deterioration. The prevailing conditions of use include environmental and time considerations.

Cables, whether only energized or carrying load current, are a source of heat. This heat energy causes a temperature rise in the cable that must be kept within limits that have been established through years of experience. The various components of a cable can endure some maximum temperature on a sustained basis with no undue level of deterioration.

There are several sources of heat in a cable, such as losses caused by current flow in the conductor, dielectric loss in the insulation, current in the shielding, sheaths, and armor. Sources external to the cable include induced current in a surrounding conduit, adjacent cables, steam mains, etc.

The heat sources result in a temperature rise in the cable that must flow outward through the various materials that have varying resistance to the flow of that heat. These resistances include the cable insulation, sheaths, jackets, air, conduits, concrete, surrounding soil, and finally to ambient earth.

In order to avoid damage, the temperature rise must not exceed those maximum temperatures that the cable components have demonstrated that they can endure. It is the careful balancing of temperature rise to the acceptable levels and the ability to dissipate that heat that determines the cable ampacity.

2.0 SOIL THERMAL RESISTIVITY

The thermal resistivity of the soil, rho, is the least known aspect of the thermal circuit. The distance for the heat to travel is much greater in the soil than the dimensions of the cable or duct bank, so thermal resistivity of the soil is a very significant factor in the calculation. Another aspect that must be considered is the stability of the soil during the long-term heating process. Heat tends to force moisture out of soils increasing their resistivity substantially over the soil in its native, undisturbed environment. This means that measuring the soil resistivity prior to the cable being loaded can result in an optimistically lower value of rho than the will be the situation in service.

The first practical calculation of the temperature rise in the earth portion of a cable circuit was presented by Dr. A.E.Kennelly in 1893 [13-2]. His work was not fully appreciated until Jack Neher and Frank Buller demonstrated the adaptability of Kennelly's method to the practical world.

As early as 1949, Jack Neher described the patterns of isotherms surrounding buried cables and showed that they were eccentric circles offset down from the axis of the cable [13-3]. This was later reported in detail by Balaska, McKean, and Merrell after they ran load tests on simulated pipe cables in a sandy area [13-4]. They reported very high resistivity sand next to the pipes. Schmill reported the same patterns [13-5].

Factors that affect the drying rate include type of soil, grain size and distribution, compaction, depth of burial, duration of heat flow, moisture availability, and the watts of heat that are being released. A lengthy debate has been in progress for over twenty years of the main concern for this drying: the temperature of the cable/earth interface or the watts of heat that is being driven across that soil. An excellent set of six papers was presented at the Insulated Conductors Committee Meeting in November 1984 [13-6].

In situ tests of the native soil can be measured with thermal needles. IEEE Guide 442 outlines this procedure [13-7]. Black and Martin have recorded many of the practical aspects of these measurements in reference [13-8].

3.0 AMPACITY CALCULATIONS

Dr. D.H.Simmons published a series of papers in 1925 with revisions in 1932, "Calculation of the Electrical Problems in Underground Cables," [13-9]. The National Electric Light Association in 1931 published the first ampacity tables in the United States that covered PILC cables in ducts or air. In 1933, EEI published tables that expanded the NELA work to include other load factor conditions.

The major contribution was made by Jack Neher and Martin McGrath in their June 1957 classic paper [13-10]. The AIEE-IPCEA "black books" [13-1] are tables of ampacities that were calculated using the methods that were described in their work. Those books have now been revised and were published in 1995 by IEEE [13-11]. IEEE also sells these tables in an electronic form [13-12].

The fundamental theory of heat transfer in the steady state situation is the same as Ohm's law where the heat flow varies directly as temperature and inversely as thermal resistance:

$$I = \sqrt{\frac{T_C - T_A - \Delta T_d}{R_{el} \; x \; R_{th}}} \; x \; 10^{-3} \qquad (13.1)$$

where I=current in amperes that can be carried (ampacity)

T_C=maximum allowable conductor temperature in °C

T_A=ambient temperature of ambient earth in °C

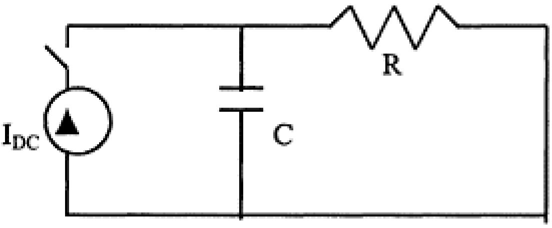
ΔT_d=temperature rise due to dielectric loss in °C

R_{el}=electrical resistance of conductor in ohms/foot at T_C
R_{th}=thermal resistance from conductor to ambient in thermal ohm feet.

3.1 The Heat Transfer Model

Cable materials store as well as conduct heat. When operation begins, heat is generated that is both stored in the cable components and conducted from the region of higher temperature to that of a lower temperature. A simplified thermal circuit for this situation is equivalent to an R-C electrical circuit:

Figure 13-1



At time t=0, the switch is closed and essentially all of the energy is absorbed by the capacitor. However, depending on the relative values of R and C, as time progresses, the capacitor is fully charged and essentially all of the current flows through the resistor. Thus, for cables subjected to large swings in loading for short periods of time, the thermal capacitance must be considered. See Section 4.0 of this chapter.

3.2 Load Factor

The ratio of average load to peak load is known as load factor. This is an important consideration since most loads on a utility system vary with time of day. The effect of this cyclic load on ampacity depends on the amount of thermal capacitance involved in the environment.

Cables in duct banks or directly buried in earth are surrounded by a substantial amount of thermal capacitance. The cable, surrounding ducts, concrete, and earth all take time to heat (and to cool). Thus, heat absorption takes place in those areas as load is increasing and permits a higher ampacity than if the load had been continuous. Of course, cooling takes place during the dropping load portions of the load cycle.

For small cables in air or conduit in air, the thermal lag is small. The cables heat up relatively quickly, i.e., one or two hours. For the usual load cycles, where the peak load exists for periods of two hours or more, load factor is not generally considered in determining ampacity.

3.3 Loss Factor

The loss factor may be calculated from the following formula when the daily load factor is known:

$$LF = 0.3(lf) + 0.7(lf)^2 \tag{13.2}$$

where LF=loss factor

lf=daily load factor per unit

Loss factor becomes significant a specified distance from the center of the cable. This fictitious distance, D_X, derived by Neher and McGrath, is 8.3 inches or 21.1 mm. As the heat flows through the surrounding medium beyond this diameter, the effective rho becomes lower and hence the explanation of the role of the loss factor in that area.

3.4 Conductor Loss

When electric current flows through a material, there is a resistance to that flow. This is an inherent property of every material and the measure of this property is known as resistivity. The reciprocal of this property is conductivity. When selecting materials for use in an electrical conductor, it is desirable to use materials with as low a resistivity as is consistent with cost and ease of use. Copper and aluminum are the ideal choices for use in power cables and are the dominant metals used throughout the world.

Regardless of the metal chosen for a cable, some resistance is encountered. It therefore becomes necessary to determine the electrical resistance of the conductor in order to calculate the ampacity of the cable. See Chapter 3 for details of the conductor loss calculation.

3.4.1 dc Conductor Resistance.

This subject has been introduced in Chapter 3. Some additional insight is presented here that applies directly to the determination of ampacity. The volume resistivity of annealed copper at 20°C is:

$$\rho_{20} = 0.017241 \text{ ohm mm}^2/\text{meter} \tag{13.3}$$

In ohms-circular mil per foot units this becomes:

$$\rho_{20} = 10.371 \text{ ohm-circular mil/foot} \tag{13.4}$$

Table 13-1 Direct-Current Resistivity at 20°C

Metal	**Volume Conductivity Percentage IACS**	**Volume Ohms-cmil/ft**	**Resistivity Ohms-mm^2/m**	**Weight Resistivity Ohms-lb/mile^2**
Soft copper	100.00	10.371	0.01724	875.2
Hard copper	96.16	10.785	0.01793	910.15
Copperweld	39.21	26.45	0.043971	2046.3

1350–H19	61.2	16.946	0.02817	434.81
5005–H19	53.5	19.385	0.03223	497.36
6201 T81	52.5	19.755	0.03284	506.85
Alumoweld	20.33	51.01	0.08401	3191.0
Steel	5.0	129.64	0.21551	9574.0

Conductivity of a conductor material is expressed as a relative quantity, i.e., as a percentage of a standard conductivity. The International Electro-technical Commission in 1913 adopted a resistivity value known as the International Annealed Copper Standard (IACS). The conductivity values for annealed copper were established as 100%.

An aluminum conductor is typically 61.2% as conductive as an annealed copper conductor. Thus a#1/0 AWG solid aluminum conductor of 61.2% conductivity has a volume resistivity of 16.946 ohms-circular mil per foot and a cross-sectional area of 105,600 circular mils. Thus, the dc resistance per 1,000 feet at 20°C is:

$R_{dc(20)}$=16,946×1,000/105,600

$R_{dc(20)}$=0.1605 ohms

To adjust tabulated values of conductor resistance to other temperatures that are commonly encountered, the following formula applies:

$$R_{T2}=R_{T1}[1+\alpha(T_2-T_1)] \qquad (13.5)$$

where R_{T2}=dc resistance of conductor at new temperature

R_{T1}=dc resistance of conductor at “base” temperature

α=temperature coefficient of resistance

Temperature coefficients for various copper and aluminum conductors at several base temperatures are as follow:

Table 13-2 Temperature Coefficients for Conductor Metals

Metal at:	**0°c**	**20°C**	**25°C**	**30°C**
61.2% Al.	0.00440	0.00404	0.00396	0.00389
100.0% Cu.	0.00427	0.00393	0.00385	0.00378
98.0% Cu.	0.00417	0.00385	0.00378	0.00371
96.0% Cu.	0.00408	0.00377	0.00370	0.00364

3.4.2 ac Conductor Resistance.

This subject was covered in Chapter 3, Section 7.2. When the term “ac resistance of a conductor” is used, it means the dc resistance of that conductor plus an increment that reflects the increased apparent resistance in the conductor caused by the skin-effect inequality of current density. Skin effect results in a decrease of current density toward the center of a conductor. A longitudinal element of the conductor near the center is surrounded by more magnetic lines of force than is an element near the rim. Thus, the counter electromotive force (emf) is greater in the center of the element. The net driving emf at the center element is thus reduced with consequent reduction of current density.

Methods for calculating this increased resistance have been extensively treated in technical papers and bulletins [13-10, for instance].

3.4.3 Proximity Effect.

The flux linking a conductor due to near-by current flow distorts the cross-sectional current distribution in the conductor in the same way as the flux from the current in the conductor itself. This is called proximity effect. Skin effect and proximity effect are seldom separable and the combined effects are not directly cumulative. If the distance apart of the conductors exceeds ten times the diameter of a conductor, the extra I^2R loss is negligible.

3.4.4 Hysteresis and Eddy Current Effects.

Hysteresis and eddy current losses in conductors and adjacent metallic parts add to the effective ac resistance. To supply these losses, more power is required from the cable. They can be very significant in large ampacity conductors when magnetic material is closely adjacent to the conductors. Currents greater than 200 amperes should be considered to be large for these effects.

3.5 Calculation of Dielectric Loss

As has been seen in Chapter 4, dielectric losses may have an important effect on ampacity. For a single-conductor, shielded and for a multi-conductor cable having shields over the individual conductors, the following formula applies:

$$W_d = 2\pi f C n E^2 F_p \times 10^{-6} \tag{13.6}$$

and

$$C = 7.354\, \varepsilon / \mathrm{Log}_{10} (D_O/D_I) \tag{13.7}$$

where f=operating frequency in hertz

n=number of shielded conductors in cable

C=capacitance of individual shielded conductors in μμF/ft

E=operating voltage to ground in kV

F_p=power factor of insulation

ε=dielectric constant of the insulation

D_O=diameter over the insulation

D_I=diameter under the insulation

3.6 Metallic Shield Losses

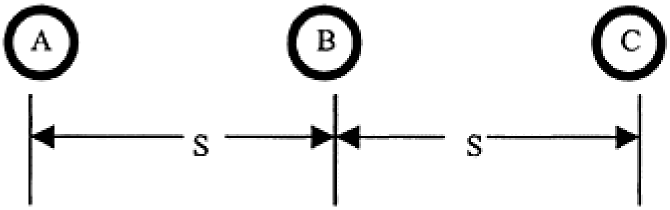
When current flows in a conductor, there is a magnetic field associated with that current flow. If the current varies in magnitude with time, such as with 60 hertz alternating current, the field expands and contracts with the current magnitude. In the event that a second conductor is within the magnetic field of the current carrying conductor, a voltage, which varies with the field, will be introduced in that conductor.

If that conductor is part of a circuit, the induced voltage will result in current flow. This situation occurs during operation of metallic shielded conductors. Current flow in the phase conductors induces a voltage in the metallic shields of all cables within the magnetic field. If the shields have two or more points that are grounded or otherwise complete a circuit, current will flow in the metallic shield conductor.

The current flowing in the metallic shields generates losses. The magnitude of the losses depends on the shield resistance and the current magnitude. This loss appears as heat. These losses not only represent an economic loss, but they have a negative effect on ampacity and voltage drop. The heat generated in the shields must be dissipated along with the phase conductor losses and any dielectric loss. Recognizing that the amount of heat that can be dissipated is fixed for a given set of thermal conditions, the heat generated by the shields reduces the amount of heat that can be assigned to the phase conductor. This has the effect of reducing the permissible phase conductor current. In other words, shield losses reduce the allowable phase conductor ampacity.

In multi-phase circuits, the voltage induced in any shield is the result of the vectoral addition and subtraction of all fluxes linking the shield. Since the net current in a balanced multi-phase circuit is equal to zero when the shield wires are equidistant from all three phases, the net voltage is zero. This is usually not the case, so in the practical world there is some “net” flux that will induce a shield voltage/current flow. In a multi-phase of shielded, single-conductor cables, as the spacing between conductors increases, the cancellation of flux from the other phases is reduced. The shield on each cable approaches the total flux linkage created by the phase conductor of that cable.

Figure 13-2 Effect of spacing between phases of a single circuit.



As the spacing, S, increases, the effect of Phases B and C is reduced and the metallic shield losses in the A phase are almost entirely dependent on the A phase magnetic flux.

There are two general ways that the amount of shield losses can be minimized:

☐ Single point grounding (open circuit shield)
☐ Reduce the quantity of metal in the shield

The open circuit shield presents other problems. The voltage continues to be induced and hence the voltage increases from zero at the point of grounding to a maximum at the open end that is remote from the ground. The magnitude of voltage is primarily dependent on the amount of current in the phase conductor. It follows that there are two current levels that must be considered: maximum normal current and maximum fault current in designing such a system. The amount of voltage that can be tolerated depends on safety concerns and jacket designs.

Another approach is to reduce the amount of metal in the shield. Since the circuit is basically a one-to-one transformer, an increase in resistance of the shield gives a reduction in the amount of current that will be generated in the shield. As an example, a 1,000 kcmil aluminum conductor, three 15 kV cables with multi-ground neutrals that are installed in a flat configuration with 7.5 inch spacing. A cable with one-third conductivity neutral will have four times as much current in the shields as a one-twelfth neutral cable. If the phases conductors are carrying a balanced 600 amperes, this means that the outside, lagging phase cable will have 400 amperes in the shield. A similar cable configuration with one-twelfth neutral will have only 100 amperes. The total current is reduced from 1,000 amperes to 700 amperes. This translates to an increase of ampacity of roughly 25% for the reduced neutral cables.

In order to take shield losses into account when calculating ampacity, it is necessary to multiply all thermal resistances in the thermal circuit beyond the shield by 1 plus the ratio of the shield loss to the conductor loss. This incremental thermal resistance reflects the effect of the shield losses.

The shield loss calculations for cables in other configurations are rather complex, but very important. Halperin and Miller developed a method for closely approximating the losses and voltages for single conductor cables in several common configurations. This table is shown in reference [13-13,14-6].

4.0 TYPICAL THERMAL CIRCUITS

4.1 The Internal Thermal Circuit For A Shielded Cable With Jacket

Thermal circuits will be shown in increasing complexity of the number of components. The symbols used throughout will be:

$\bar{R}$=thermal resistance (pronounced R bar) in thermal ohm-feet
Q=heat source in watts per foot
$\bar{C}$=thermal capacitance

The subscripts throughout are:

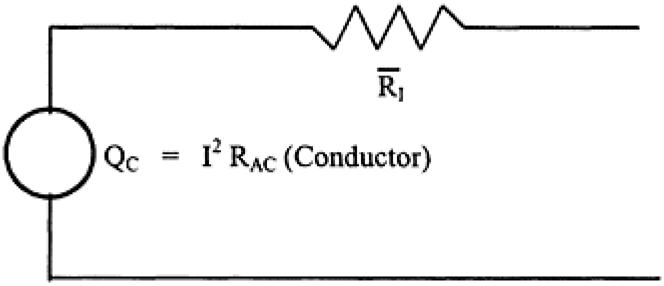
C=conductor
I=insulation
S=shield
J=jacket

D=duct
SD=distance between cable and duct
E=earth

4.2 Single Layer of Insulation, Continuous Load

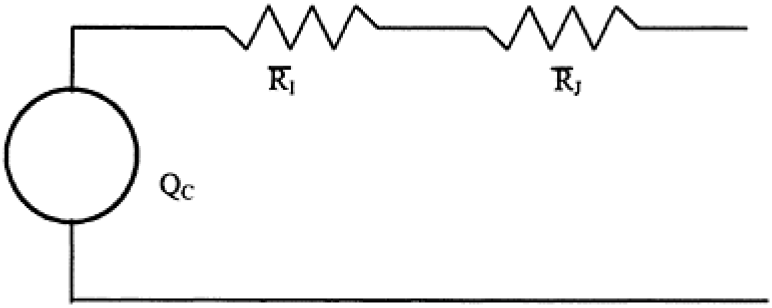
The internal thermal circuit is shown in Figure 13-3 for a cable with continuous load. The conductor heat source passes through only one thermal resistance. This may be an insulation, covering, or a combination as long as they have similar thermal resistances. Note that these circuits stop at the surface of the cable. The remainder of the thermal circuit will be added in examples that follow.

Figure 13-3 This diagram shows a continuous load flowing through one layer of insulation. The heat does not travel beyond the surface of the cable in this example.



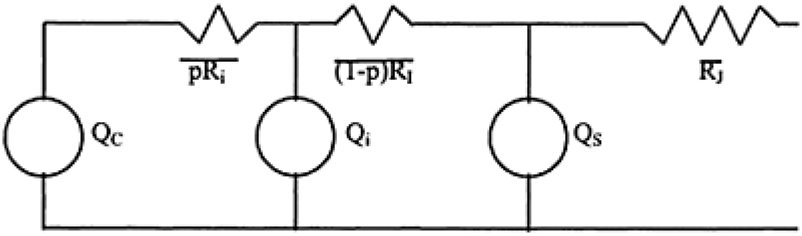
4.3 Cable Internal Thermal Circuit Covered By Two Dissimilar Materials, Continuous Load

Figure 13-4 In this example, the continuous load flows through two dissimilar materials, but the heat still stays at the surface of the last layer of insulation.



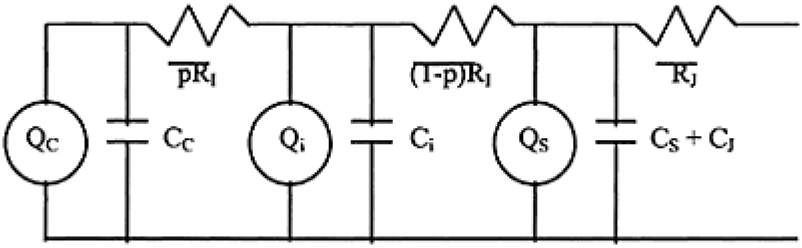
4.4 Cable Thermal Circuit for Primary Cable with Metallic Shield and Jacket, Continuous Load

Figure 13-5 This thermal diagram shows a primary cable with its several heat sources and thermal resistances still with a constant load where p and (1-p) divide the thermal resistance to reflect Q_i.



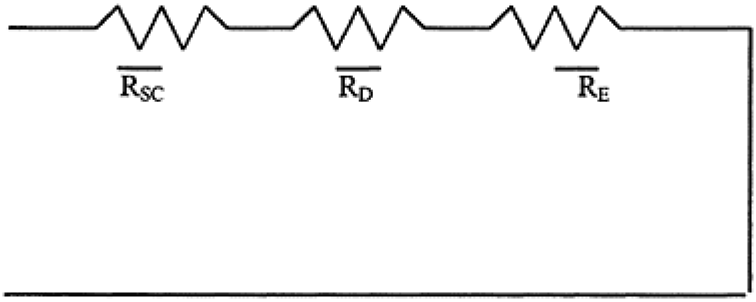
4.5 Same Cable as Example 3, but with Cyclic Load

Figure 13-6 This diagram shows the same cable as in Figure 13-5, but the cyclic load is accounted for with the capacitors that are parallel to the three heat sources.



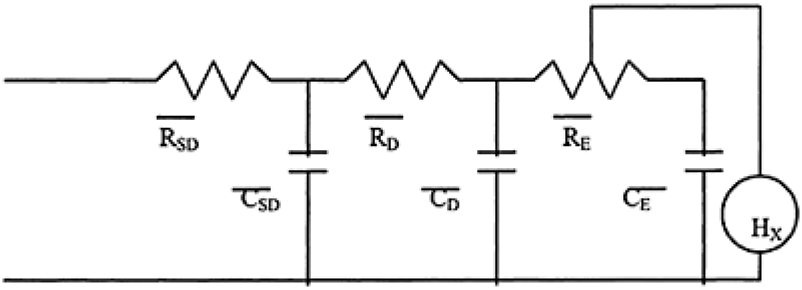
4.6 External Thermal Circuit, Cable in Duct, Continuous Load

Figure 13-7 In this diagram, the resistances that are external to the cable are shown.



4.7 External Thermal Circuit, Cable in Duct, Time Varying Load, External Heat Source

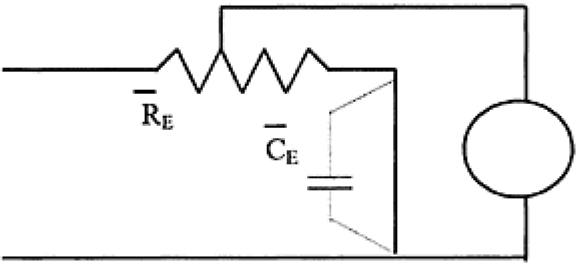
Figure 13-8



where H_X=external Heat Source

4.8 External Thermal Circuit, Cable Buried in Earth, Load May Be Cyclic, External Heat Source May Be Present

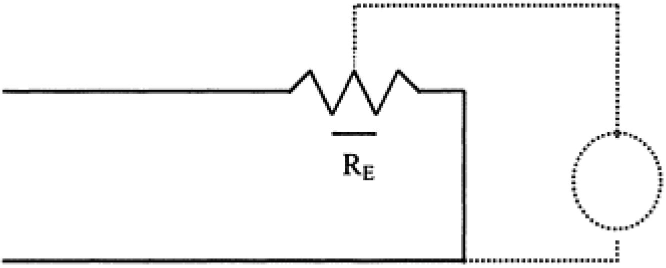
Figure 13-9



The depiction of possible cyclic load and external heat source are shown by dotted lines.

4.9 External Thermal Circuit, Cable in Air, Possible External Heat Source

Figure 13-10



The external thermal circuit is shown with the possible external heat source shown by dotted lines.

5.0 SAMPLE AMPACITY CALCULATION

5.1 General

Methods to calculate the ampacity of operating cables continue to be a popular subject for technical papers. Fortunately, the portion of the work that had been done by slide-rule and copious quantities of notepaper has been replaced with computers. Manipulations were handled by assuming intermediate values of the various parameters prior to the advent of the computer. The hand calculations were laborious, but the user did achieve a feel for the concept. The availability of tables and computer programs could lead to quick, but possibly incorrect, answers. The Neher-McGrath paper [13-10] is the best reference to use before a hand calculation is attempted. As a matter of fact, you should read that paper even if you have decided to use any available tables or programs!

The following simple example of a calculation is presented with the intent of giving insight into the process:

The general equation that has been previously given:

$$I = \sqrt{\frac{T_C - T_A - \Delta T_d}{R_{el} \ x \ R_{th}}} \ x \ 10^{-3} \qquad (13.7)$$

where I=current in amperes that can be carried (ampacity)

T_C=maximum allowable conductor temperature in °C

T_A=ambient temperature of ambient earth in °C

ΔT_d=temperature rise due to dielectric loss in °C

R_{el}=electrical resistance of conductor in ohms/foot at T_C

R_{th}=thermal resistance from conductor to ambient in thermal ohm feet, assuming no other heat sources.

Another form of this equation recognizes the other possible heat sources that have been indicated in the thermal circuit diagrams. Equation 13.1 expands to:

$$I = \sqrt{\frac{T_C - (T_A + T_D)}{R_{AC} \ (R_i + R_{TH})}} \qquad (13.8)$$

where T_D=temperature rise due to dielectric loss in °C

$\overline{R_i}$ =to account for thermal resistance of insulation and/or coverings between the conductor and the first heat source beyond the insulation.

$\overline{R_{TH}}$ =is the thermal resistance to ambient adjusted to account for additional heat sources such as shield loss, armor loss, steam lines, etc.

6.0 AMPACITY TABLES AND COMPUTER PROGRAMS

6.1 Tables

The *IEEE Standard Power Cable Ampacity Tables*, [13-11,13-12], IEEE Std. 835–1994, is a book (or electronic version) that contains over 3,000 tables in 3,086 pages. Voltages range from 5 kV to 138 kV. Although there are situations that are not covered by these tables, this is an excellent beginning point for anyone interested in cable ampacities.

Manufacturers have also published catalogues that cover the more common situations [13-13,13-14].

6.2 Computer Programs

Most of the large cable manufacturers and architect/engineering firms have their own computer programs for ampacity determination. This is an excellent source of information when you are engineering a new cable system. These programs generally are not for sale.

There are commercially available programs throughout North America. These are especially useful when you need to determine the precise ampacity of a cable, for instance, that is in a duct bank with other cables that are not fully loaded. The general cost of one of these programs is about $5,000 in US dollars.

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CHAPTER 14
THERMAL RESISTIVITY OF CONCRETE

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1.0 INTRODUCTION

The backfill material that surrounds a buried cable system is an extremely critical element in achieving optimum heat dissipation of the system. When soils are used for backfill for power cables, moisture migration can change a soil from about 60 rho (thermal resistivity in °C-cm/watt) to 300–400 rho as the moisture content is reduced from 10% to 3%. [14-1]

Analysis of the thermal resistivity of soils by Fink [14-2], Sinclair [14-3], Adams and Baljet [14-4], Black and Martin [14-5], and others have clearly shown that migration of moisture from the backfill soil is a critical element in the ampacity of cable systems.

Concrete has been used as backfill around buried cables in Europe for many years. The possibility of using concrete instead of soil was considered but initially rejected when it was seen that the previous Ampacity Tables [14-6] used a value of 85 for the thermal resistivity of concrete. This was contradicted in reports of the construction of concrete dams in the United States [14-7]. It should be noted that the value used in the present IEEE Ampacity Tables is a rho 90 for concrete in duct banks [14-8].

2.0 EARLY FIELD EXPEREINCE

A search for a local source of an ideally graded, natural soil often proves fruitless. Native soils frequently have a rather uniform size and hence dry out very quickly when a heat source is applied. A typical silica sand has 88% of the sand passing through a number 40 sieve (0.42 mm or smaller) and with 0.6% silt. Dry densities of only about 100 pounds per cubic foot, mostly made of quartz crystals that have a thermal resistivity of about 11, are attainable with normal construction techniques. The thermal resistivity of these sands in their native state is about 60 to 80 rho as long as they have about 3% by weight moisture.

Typically, a load of about 30 watts per foot from a cable or duct bank are sufficient to dry such sand to near zero percent moisture where the rho can rise to 350 to 400.

Thermal runaway conditions of native soils have been experienced by many utilities involving transmission cables as well as single-circuit, direct buried distribution feeder cables. In one situation, the sand had less than one-half percent moisture adjacent to a direct buried feeder cable exiting a substation even though lawn irrigation sprinklers were only two feet above. With four hours of watering every night, the sand could not retain enough moisture to prevent thermal runaway of one buried three conductor 500 kcmil copper feeder cable. The pattern of eccentric circles of dry sand was found to be in complete agreement with the paper of Balaska, Merrell, and McKean [14-9] that described a simulated transmission cable in a sand hill in New York.

In another example, the native soil around a pipe cable was found to be baked completely dry and adhering to the pipe's outer surface even though the cable was 30 feet under the surface of a bay. The material in this situation had a clay-like composition (marl) with a high amount of organic fillers.

Similar reports have been given regarding high thermal resistivity of soils around cables under waterways in Denmark, England [14-10] and the deepest water in Lake Champlain [14-11].

In the situation described in Denmark, it was stated that "Cooling conditions for a submarine cable are normally assumed to be very good and the ampacity is based on a low value of thermal resistivity of the seabed." Since the land section had a thermal resistivity of 43 to 54°C-cm/watt, it was assumed that the value in the seabed was equally as low. After two joints failed in service, it was discovered in laboratory investigations that the seabed material contained high organic levels and that the thermal resistivity was 105°C-cm/watt. Needle probes into the seabed discovered a rho of 94°C-cm/watt.

In the London investigation [14-10], they found the silt in the bottom of canals to be as high as 118°C-cm/watt and that even higher values could be reached in the presence of heated cables.

The Lake Champlain 115 kV cables [14-11] were installed in 1958 and failed in 1969 at a depth of about 300 feet. A sample of the soil near the failure was sent to a laboratory for analysis. They found the silt to have an average value of rho of 90 to 100 even though the silt "was not tested in the condition that it was in the lake bottom…" The new cable rating was based on the lakebed silt to have a rho of 140°C-cm/watt.

The lessons to be learned here is that moisture can migrate from soils even in deep waterways. To maintain a low thermal resistivity soil in a seabed, water must be free to move through a porous or granular environment and have a limited level of organic material. It should also be pointed out that readings taken with thermal probes along a proposed route may give optimistically low values of thermal resistivity if the heat source is not left on long enough to detect moisture migration in that soil.

3.0 CONCRETE FOR CABLE BACKFILL

Cement bound sand (weak concrete) has been used as a backfill material around direct buried cables in Europe for many years. A typical material in use there is a 12:1 sand/cement mix. Although this provides for some cable movement and relative ease for removal, these mixes do attain a rather high thermal resistivity when a load is applied for many months. A resistivity of about 105°C-cm/watt is typical. Lower values of rho may be attained by decreasing the amount of sand. In other words, by making the concrete more structurally sound.

Greebler and Barnett [14-12] reported that concrete around a laboratory installed duct bank had a rho of 85. This paper was the source of the 85 rho that may be found in the original “black books” of AIEE-IPCEA ampacity tables [14-6]. This concrete was poured above the floor in a wooden trough and was in an air conditioned building. This resulted in a poor structural cure and poor thermal resistivity. Brookes and Starr [14-13] found that concrete around a buried pipe in New Jersey exhibited an initial rho of 92 and after six months it steadied down to about 50 where it stayed until the test was stopped after 24 months.

Nagley and Neese [14-14] found that the thermal resistivity of concrete around duct banks in the Chicago area varied from 38 to 53. An interesting discovery of their study was that a very thin envelope of concrete around heavily loaded duct banks (about 1.25 inches rather than the more frequently used 2.5 inches) allowed the soil around the duct bank to dry out. The thermal resistivity of the surrounding earth soon reached unacceptably high levels.

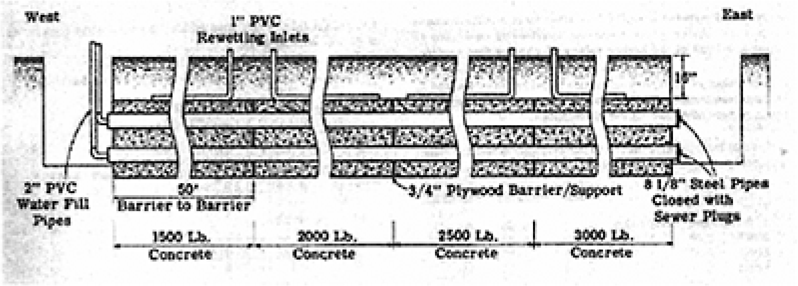
The publication by the US Bureau of Reclamation in 1940, “Thermal Properties of Concrete,” [14-7] showed that the thermal resistivity of concrete used in the Boulder (now Hoover) Dam varied from 28.5 to 42.5.

4.0 FLORIDA TEST INSTALLATION

To determine the actual resistivity of locally available structural concrete, Florida Power & Light installed a test facility near Miami in May of 1969. Two 8 1/8 inch steel pipes, covered with 0.5 inches of Somastic, were placed one above the other in a trench with 12 inches of separation. This configuration was chosen since it would permit evaluation of the effects of burial depth as well as more information on a configuration that might be required in a restricted area.

Thermocouples were installed on the pipe in each section, on the Somastic, three and six inches from the Somastic, and in the earth six inches from the outer surface of the concrete envelope. Figure 14-1 shows the test arrangement.

Figure 14-1 General arrangement of test envelope.



Four 50-foot sections were poured with various grades of commercially available structural grade concrete as a six inch envelope as shown in Figure 14-1. The compressive strengths of these four mixes were 1500, 2000, 2500 and 3000 pounds/in^2.

All sections were allowed to cure for 40 days prior to any application of heat to simulate normal cure in the earth.

4.1 Test Results

Heat runs were begun during early June of 1969 with 15 watts per foot applied to each pipe. The heat was increased to a high of 31 watts per foot in each pipe and continuing that load until the temperatures stabilized.

Values of thermal resistivity were calculated for each pipe and its surrounding material separately by using Bauer's version [14-15] of the Kennelly formula [14-16].

See Tables 2, 3, 4, and 5 for details of the thermal resistivity of the concrete. These values varied throughout the test period, but the general trend was a slight decrease in resistivity for the three higher strength mixes. The section that had the 1500 pound/in^2 concrete was eliminated from the test after three months. It was decided not to replace heater wires because they had burned out and the rho was increasing in that section.

The 31 watts per foot level was chosen as the maximum because this resulted in an interface temperature that was considered at the time to be the maximum permissible value of 50°C. See Section 4.3 and the Minutes of the Insulated Conductors Committee of November 1984 for a six paper review of this thermal resistivity and interface issue and the effects of large heat levels (watts per foot of flux density) [14-17].

Table 14-1 Thermal Resistivity of Concrete Envelope

Concrete Strength	Top Pipe °C-cm/watt	Bottom Pipe °C-cm/watt	Average °C-cm/watt
3000 pound	37.9	44.4	41.2
2500 Pound	41.1	40.4	40.8
2000 Pound	36.2	38.7	37.5
1500 Pound	48.9	51.2	50.1

The wetting system shown in Figures 14-1 was never utilized since the three higher grades of concrete kept a low and stable thermal resistivity.

4.2 Equivalent Cable Ampacity

Application of constant power to such a test site made it much easier to observe stability and to then calculate thermal resistivity in those years before computers. Power systems, unfortunately, do not have steady demands, but we now have computers.

The power input to the test installation was chosen to represent the equivalent losses generated when a 1970s double circuit, 2000 kcmil copper conductor, 230 kV, high pressure pipe cable circuit was at 85°C conductor temperature and a 75% load factor. The ampacity at these conditions is 1170 amperes and at 100% load factor would be 925 amperes. Since the average watts generated in such a circuit are:

$$
\begin{aligned}
W_T &= 3\left[\,W_D + LF\,x\,I^2\ \mathrm{x}\ R_{ac}\ \mathrm{x}\ q_e\,\right] \\
&= 3\left[\,1.531 + 7.52\ \mathrm{x}\ 1.368\ \mathrm{x}\ I^2\,\right] \\
&= 4.593 + 30.861\,I^2
\end{aligned}
$$

where q_e is the ratio of the sum of the losses in the conductors, sheath, and pipe to the losses in the conductors.

$$\text{then}\quad I = \sqrt{\frac{W_T - 4.59}{30.86}}\qquad \text{in kA at 100\% LF}$$

when W_T=31 watts,

$$I = \sqrt{\frac{26.41}{30.86}} = 0.925\ \text{kA or 925 amperes}$$

4.3 Earth Interface Temperature

Over the past 40 years, one of the dominant questions for thermal stability of the surrounding soil has been the earth interface temperature. The original Ampacity Tables were printed with both 50 and 60°C columns so that the user could decide which value to use. The theory is that many soils will attain a balance between heat flow, moisture migration, and capillary action that will allow moisture to flow back into the soil near the heat source. Caution is advised on using an interface temperature in this manner without tests that confirm the stability of the soil involved.

Heat flux is considered to be the main reason that moisture migrates away from a heat source. Heat flux is a function of the heat flowing out from the source (in watts/foot) and the cable surface diameter (in inches). The method usually used to determine stability is to place a thermal probe using the maximum heat anticipated from the circuit (e.g., 30 watts/foot) and measure the thermal resistance of the soil as a function of time. The time at which the slope changes gives a good estimate of the time to dry out as well as the thermal resistivity of the dry soil.

$$t_c=t_p(D_c/D_p)^2 \tag{14.1}$$

where

t_c=time for soil near cable to dry, in minutes

t_p=time for soil near probe to dry, in minutes

D_c=diameter of cable or earth interface, in inches

D_p=diameter of probe, in inches

At the time of the described test, a maximum interface temperature of 50°C was chosen to be on the safe side. No adverse effects were noted on the surrounding soil for the loading simulated in the test.

If the same 50°C level had been chosen for a directly buried Somastic coated pipe, only 21W/ft would have been allowed. This would correspond to a reduction in ampacity of 1030 to 920 amperes, or over an 11% decrease in ampacity.

4.4 Installation of Commercial Circuits

The test data from this project, demonstrated that ready-mix, structural concrete would have a low and stable thermal resistivity. Excellent mechanical protection would also be afforded by such construction techniques.

The requirement for a double circuit, 40,000 foot long 230 kV cable in Miami became the economic proving ground for this concept. The established procedure for digging down to the permanent water table would have required the trench to be as much as 17 feet deep. Even there, problems with heat dissipation and the lingering question of thermal instability would leave exist.

The lines were installed with 12 inches of concrete encasement (instead of the 6 inches in the test) with 12 inches of separation between the dual 10¾ inch pipes. A savings of 15% in labor and material costs were realized.

Table 14-2 Section with 3000 Pound Concrete

	W/ft	Rho-Top	Concrete Bottom	Max. Somastic	°C Earth
6–16–69	20.3	42.5	44.4	45.9	41.7
6–23–69	30.2	41.8	46.2	50.5	44.8
7–03–69	31.0	40.9	50.2	54.6	48.1
7–09–69	31.0	44.8	46.3	55.9	50.0
7–14–69	29.8	39.4	48.2	57.0	51.0
7–21–69	25.0	34.5	47.9	54.3	49.3
7–25–69	25.0	41.2	47.9	53.8	48.8
9–04–69	20.0	43.1	50.3	48.2	44.0
9–26–69	20.0	37.1	50.3	48.0	43.8
4–27–70	21.0	44.4	44.4	46.9	43.0
5–11–70	21.0	41.0	47.9	49.0	44.8
5–27–70	21.0	39.9	44.4	48.6	44.7
6–29–70	22.0	40.2	43.5	47.0	43.4
7–13–70	22.0	35.9	41.3	47.5	43.7
8–03–70	23.0	40.6	43.7	44.8	40.9
8–17–70	23.0	38.5	41.6	49.0	45.0

9–01–70	23.0	33.3	40.6	49.5	45.6
9–08–70	23.0	34.3	42.7	50.0	45.9
9–29–70	23.0	31.2	36.4	47.3	43.8
10–13–70	23.0	33.3	39.5	46.6	42.8
10–27–70	23.0	33.3	37.5	46.2	42.6
11–16–70	23.0	34.3	47.9	46.5	41.9
12–01–70	23.0	36.4	44.0	47.1	42.5
12–21–70	24.0	32.9	41.7	46.5	42.3
1–05–71	24.0	37.9	45.9	47.3	37.9
1–18–71	24.0	34.9	40.9	47.9	43.8
Average		37.9	44.4	49.0	44.4

Table 14-3 Section with 2500 Pound Concrete

	W/ft	Rho-Top	Concrete Bottom	Max Somastic	°C Earth
6–16–69	20.3	43.9	43.5	45.6	42.0
6–23–69	30.2	42.6	42.2	50.5	45.3
7–03–69	31.0	43.2	39.4	54.2	49.1
7–09–69	31.0	38.6	40.1	56.1	50.9
7–14–69	29.8	41.0	43.4	57.3	51.9
7–21–69	25.0	45.9	44.0	54.5	49.9
7–25–69	25.0	38.3	42.1	54.1	49.7
9–04–69	20.0	44.3	43.1	48.5	44.9
9–26–69	20.0	47.9	45.5	48.0	44.2
4–27–70	21.0	42.2	42.2	47.5	43.8
5–11–70	21.0	41.0	41.0	49.3	45.7
5–27–70	21.0	52.4	46.7	48.4	44.3
6–29–70	22.0	39.2	37.0	47.0	43.2
7–13–70	22.0	35.9	35.9	47.8	44.5
8–03–70	23.0	39.5	37.5	45.3	41.7
8–17–70	23.0	35.4	42.7	49.6	45.5
9–01–70	23.0	40.6	42.0	50.0	45.0
9–08–70	23.0	40.6	37.5	50.3	46.7
9–29–70	23.0	41.6	35.4	47.4	44.0

10–13–70	23.0	39.5	34.3	46.9	43.6
10–27–70	23.0	40.6	37.5	46.7	43.1
11–16–70	23.0	38.5	34.3	45.9	42.6
12–01–70	23.0	40.2	41.2	47.2	42.9
12–21–70	24.0	37.9	37.9	46.8	43.0
1–05–71	24.0	37.9	36.9	47.4	43.7
1–18–71	24.0	40.9	38.9	48.1	44.2
Average		41.1	40.4	49.2	45.6

Table 14-4 Section with 2000 Pound Concrete

	W/ft	Rho Top	Concrete Bottom	Max. Somastic	°C Earth
6–16–69	20.3	33.5	25.4	44.4	42.3
6–23–69	30.2	40.3	41.4	50.9	45.8
7–03–69	31.0	41.7	41.7	54.9	49.5
7–09–69	31.0	39.4	40.9	56.7	51.4
7–14–69	29.8	38.5	42.6	57.9	52.6
7–21–69	25.0	41.2	45.9	54.9	50.1
7–25–69	25.0	38.3	44.0	54.6	50.0
9–04–69	20.0	39.5	45.5	48.8	45.0
9–26–69	20.0	39.5	40.7	48.2	44.8
4–27–70	21.0	36.5	45.6	47.9	44.0
5–11–70	21.0	34.2	45.6	49.8	46.0
5–27–70	21.0	50.1	45.6	48.6	44.6
6–29–70	22.0	34.8	35.9	47.2	43.4
7–13–70	22.0	33.7	34.8	48.0	44.8
8–03–70	23.0	37.5	38.5	45.6	41.7
8–17–70	23.0	38.5	39.5	49.9	46.1
9–01–70	23.0	32.3	35.4	50.0	46.6
9–08–70	23.0	30.2	39.5	50.8	47.0
9–29–70	23.0	41.6	37.5	47.6	44.0
10–13–70	23.0	30.2	33.3	47.3	40.0
10–27–70	23.0	29.1	31.2	46.9	43.9
11–16–70	23.0	29.1	28.1	46.0	43.3

12–01–70	23.0	35.4	37.3	47.3	43.4
12–21–70	24.0	31.9	37.9	46.9	43.1
1–05–71	24.0	32.9	33.9	47.6	44.2
1–18–71	24.0	32.9	33–9.9	48.3	44.3
Average		36.2	38.7	49.4	45.4

Table 14-5 Section with 1500 Pound Concrete

	W/ft	Rho Top	Concrete Bottom	Max Somastic	°C Earth
6–16–69	20.3	48.5	47.6	46.0	42.4
6–23–69	30.2	51.1	50.3	51.8	45.7
7–03–69	31.0	48.6	50.2	56.0	49.5
7–09–69	31.0	51.0	47.1	57.0	50.9
7–14–69	29.8	52.2	46.6	57.5	51.7
7–21–69	25.0	47.9	52.7	58.3	52.8
7–25–69	25.0	45.9	49.8	56.1	50.9
9–04–69	20.0	41.9	55.0	50.8	46.2
9–26–69	20.0	53.8	62.2	50.5	45.3
Average		48.9	51.2	53.7	48.3

5.0 CONCLUSIONS

The thermal resistivity of structural grade ready-mix concrete is stable in the vicinity of 35 to 45°C-cm/watt because the water is chemically bound in the concrete.

Concrete encasement of a duct bank should be sized to minimize dry out of the soil surrounding the concrete and will provide a stable thermal environment.

Concrete encasement provides mechanical protection to the pipe and improves the long-term stability of the pipe coating.

Concrete may be a cost effective alternative to native backfills in situations where heavy loaded circuits are involved.

“Weak” concretes may have thermal resistivities of 100°C-cm/watt or higher because the moisture is not bound into the concrete.

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CHAPTER 15
SHEATH BONDING AND GROUNDING

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1.0 GENERAL

This discussion provides an overview of the reasons and methods for reducing sheath losses in large cables. While calculations are shown, all of the details are not covered as completely as are in the IEEE Guide 575 [15-1]. A very complete set of references is included in that standard. The reader is urged to obtain a copy of the latest revision of that document before designing a "single-point" grounding scheme.

The terms sheath and shield will be used interchangeably since they have the same function, problems, and solutions for the purpose of this chapter.

- □ Sheath refers to a water impervious, tubular metallic component of a cable that is applied over the insulation. Examples are a lead sheath and a corrugated copper or aluminum sheath. A semiconducting layer may be used under the metal to form a very smooth interface.
- □ Shield refers to the conducting component of a cable that must be grounded to confine the dielectric field to the inside of the cable. Shields are generally composed of a metallic portion and a conducting (or semiconducting) extruded layer. The metallic portion can be either tape, wires, or a tube.

The cable systems that should be considered for single-point grounding are systems with cables of 1,000 kcmils and larger and with anticipated loads of over 500 amperes. Fifty years ago, those cables were the paper insulated transmission circuits that always had lead sheaths. Technical papers of that era had titles such as "Reduction of Sheath Losses in Single-Conductor Cables" [15-2] and "Sheath Bonding Transformers" [15-3], hence the term "sheath" is the preferred word rather than "shield" for this discussion.

2.0 CABLE IS A TRANSFORMER

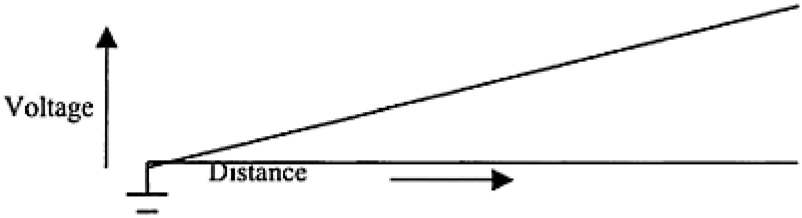
Chapter 2 described how a cable is a capacitor. That is true. Now you must think about the fact that a cable may also be a transformer.

When current flows in the "central" conductor of a cable, that current produces electromagnetic flux in the metallic shield, if present, or in any parallel conductor. This becomes a "one-turn" transformer when the shield is grounded two or more times since a circuit is formed and current flows.

We first will consider a single, shielded cable:

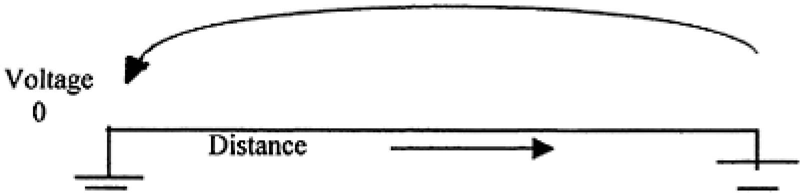
□ If the shield is only grounded one time and a circuit is not completed, the magnetic flux produces a voltage in the shield. The amount of voltage is proportional to the current in the conductor and increases as the distance from the ground increases. See Figure 15-1.

Figure 15-1 Single-point grounding.



□ If the shield is grounded two or more times or otherwise completes a circuit, the magnetic flux produces a current flow in the shield. The amount of current in the shield is inversely proportional to the resistance of the shield. (Another way of saying this is the current in the shield increases as the amount of metal in the shield increases.) The voltage stays at zero. See Figure 15-2.

Figure 15-2 Two or more grounds.



One other important concept regarding multiple grounds is that the distance between the grounds has no effect on the magnitude of the current. If the grounds are one foot apart or 1,000 feet apart, the current is the same—depending on the current in the central conductor and the resistance of the shield. In the case of multiple cables, the spatial relationship of the cables is also a factor.

3.0 AMPACITY

3.1 Ampacity

In Chapter 13, there is a complete description of ampacity and the many sources of heat in a cable such as conductor, insulation, shields, etc. This heat must be carried through conduits, air, concrete, surrounding soil, and finally to ambient earth. If the heat generation in any segment is decreased, such as in the sheath, then the entire cable will have a greater ability to carry useful current.

The heat source from the shield system is the one that we will concentrate on in this discussion as we try to reduce or eliminate it.

3.2 Shield Losses

When an ac current flows in the conductor of a single-conductor cable, a magnetic field is produced. If a second conductor is within that magnetic field, a voltage that varies with the field will be introduced in that second conductor—in our case, the sheath. See Chapter 13 for a more complete discussion of this condition.

If that second conductor is part of a circuit (connected to ground in two or more places), the induced voltage will cause a current to flow. That current generates losses that appear as heat. The heat must be dissipated the same as the other losses. Only so much heat can be dissipated for a given set of conditions, so these shield losses reduce the amount of heat that can be assigned to the phase conductor.

Let us assume that we are going to ground the shield at least two times in a run of cable. What is the effect of the amount of metal in the shield?

The following curves present an interesting picture of the shield losses for varying amounts of metal in the shield. These curves are taken from ICEA document P 53–426 [15-5]. As you can see, they were concerned about underground residential distribution (URD) cables where the ratio of conductivity of the shield was given as a ratio of the conductivity of the main conductor; thus, one-third reutral, etc. In the situation where 2000 kcmil aluminum conductors are triangularly spaced 7.5 inches apart, the shield loss for a one-third neutral is 1.8 times the conductor loss!

For single-conductor transmission cables having robust shields, losses such as these are likely to be encountered in multi-point grounding situations and generally are not acceptable.

3.3 Shield Capacity

The shield, or sheath, of a cable must have sufficient conductivity in metal to carry the available fault current that may be imposed on the cable. Single conductor cables should have enough metal in its shield to clear a phase-to-ground fault and with the type of fusing or reclosing scheme that will be used. It is not wise to depend on the shield of the other two phases since they may be some inches away. You need to determine:

☐ What is the fault current that will flow along the shield?
☐ What is the time involved for the back-up device to operate?
☐ Will the circuit be reclosed and how many times?

Too much metal in the shield of a cable section with two or more grounds is not a good idea. It costs additional money to buy such a cable and the losses not only reduce the ampacity of the cable but cause undue economic losses from the heat produced.

One way that you can test your concept of a sufficient amount of shield is to look at the performance of the cables that you have in service. Even if the present cable has a lead sheath, you can translate that amount of lead to copper equivalent. You will also need to consider what the fault current may be in the future. EPRI has developed a program that does the laborious part of the calculations [15-6].

We can “convert” metals used in sheaths or shields to copper equivalent by measuring the area of the shield metal and then translate that area to copper equivalent using the ratio of their electrical resistivities.

Table 15-1 Electrical Resistivity of Metals

Metal	**Electrical Resistivity in Ohm-mm$^{2/}$m$\times 10^{-8}$, 20°C**
Copper, annealed	1.724
Aluminum	2.83
Bronze	4.66
Lead	22.0
Iron, hard steel	24.0

As an example, we have a 138 kV LPOF cable that has a diameter of 3.00 inches over the lead and the lead is 100 mils thick.

The area of a 3.00 inch circle is: =7.0686 in.^{2}

The area of a circle that is under the lead is:

Diameter=3.00−0.100−0.100 =2.80 in.

Area=1.4×1.4×π =6.1575 in.^{2}

Area of the lead is 7.0686−6.1575 =0.9111 in.^{2}

The ratio of resistivities is 1.724/22.0 =0.0784

The copper equivalent is 0.9111 in$^2\times$0.0784 =0.07139 in.^{2}

To convert to cmils, multiply in^2 by $4/\pi\times 10^6$ =90,884 cmils

This lead sheath is between a #1/0 AWG (105, 600 cmils) and a #1 AWG (83,690 cmils).

If the sheath increases to 140 mils and the core stays the same, we have:

The area of the sheath is =7.4506 in^2.

The area of lead is 7.4506−6.1575 =1.2931 in^2.

Multiply by the same ratio of 0.0784 =0.1014

To convert to cmils, multiply by $4/\pi\times 10^6$ =129,106 cmils

This is almost a #2/0 AWG (133, 100 cmil) copper conductor.

Using the same concept, one can change from aluminum to copper, etc.

The allowable short-circuit currents for insulated copper conductors may be determined by the following formula:

$$[I/A]^2 t = 0.0297 \log_{10}[T_2+234/T_1+234] \tag{15.1}$$

where I=short circuit current in amperes
A=conductor area in circular mils
t=time of short circuit in seconds
T_1=operating temperature, 90°C
T_2=maximum short circuit temperature, 250°C

A well-established plot of current versus time is included in [13-13]. It is important to be aware that these results are somewhat pessimistic since the heat sink of coverings is ignored and has not been addressed in equation (15.1). On the other hand, the answers given are very safe values.

3.4 Jumper Capacity

You must make a good connection between the bonding jumper and the cable sheath to have enough capacity to take the fault current to ground or to the adjacent section—no matter how well you designed the cable sheath. This is frequently a weak point in the total design.

The bonding jumper should always be of greater size than the equivalent sheath area and should be as short and straight as possible to reduce the impedance of that portion of the circuit. In all cases, the bonding jumper should be covered, such as with a 600 volt cable.

4.0 MULTIPLE-POINT GROUNDING

4.1 Advantages

☺ No sheath isolation joints
☺ No voltage on the shield
☺ No periodic testing is needed
☺ No concerns when testing or looking for faults

4.2 Disadvantages

☹ Lower ampacity
☹Higher losses

4.3 Discussion

Although you may have already decided to drop this concept, you should be aware of the consequences of a second ground or connection appearing on a run of cable that had not been planned. Such a second ground can complete a circuit and result in very high sheath currents that could lead to a failure of all of the cable that has been subjected to those currents. The higher the calculated voltage on the sheath, the greater the current flow may be in the event of the second ground. Periodic maintenance of single-point grounded circuits should be considered. If this is will be done, a graphite layer over the jacket will enable the electrical testing of the integrity of the jacket.

5.0 SINGLE-POINT AND CROSS-BONDING

To be precise, single-point grounding means only one ground per phase, as will be explained later. Cross-bonding also limits sheath voltages and demonstrates the same advantages and disadvantages as single-point grounding.

5.1 Advantages

☺ Higher ampacity
☺ Lower losses

5.2 Disadvantages

☹Sheath isolation joints are required
☹Voltage on sheath/safety concerns

5.3 Background

The term that were used to describe single-point grounding during the 1920s to 1950s time period was <u>open-circuit sheath</u>. The concern was to limit the <u>induced sheath voltage</u> on the cable shield. A 1950 handbook said that "The safe value of sheath voltage above ground is generally taken at 12 volts ac to eliminate or reduce electrolysis and corrosion troubles." The vast majority of the cables in those days did not have any jacket—just bare lead sheaths. Corrosion was obviously a valid concern. (Some US cable manufacturers still recommend 25 volts as the maximum for most situations.) The vastly superior jacketing materials that are available today have helped change the presently accepted value of "standing voltage" to 100 to 400 volts for normal load conditions. Since the fault currents are much higher than the load currents, it is usually considered that the shield voltage during fault conditions be kept to a few thousand volts. This is controlled by using sheath voltage limiters—a type of surge arrester.

5.4 Single-Point Bonding Methods

There are numerous methods of managing the voltage on the shields of cables with single-point grounding. All have one thing in common: the need for a sheath or shield isolation joint.

Five general methods will be explored:

♦ Single-Point Grounding
♦ Cross-Bonding
♦ Continuous Cross-Bonding
♦Auxiliary Bonding

♦ Series Impedance or Transformer Bonding

Diagrams of each method of connection, with a profile of the voltages that would be encountered under normal operation, are shown below.

Figure 15-3 Single-point grounding.

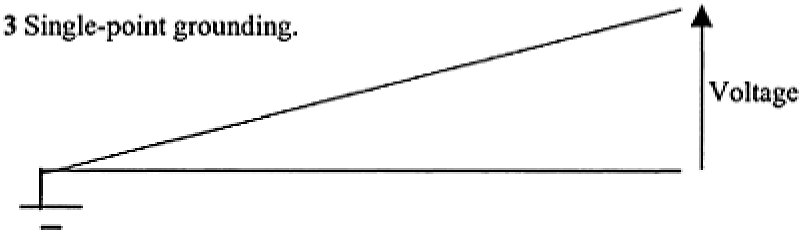


Figure 15-4 Single-point grounding near center of cable run.

In this situation, only half of the previous voltage appears on the sheath.

Figure 15-5 Cross-bonding connections.

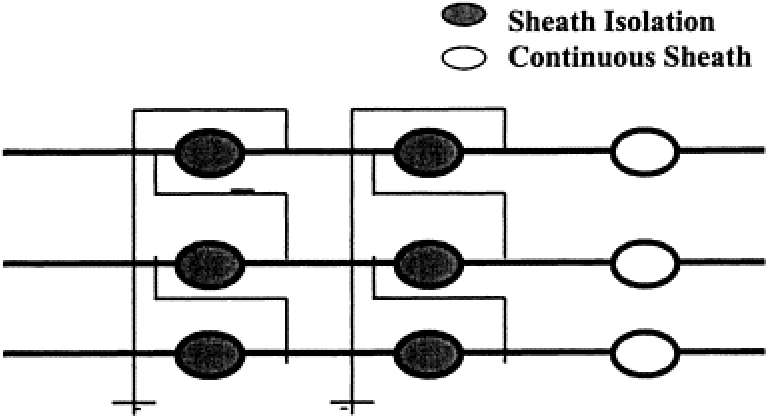


Figure 15-6 Continuous cross-bonding connections.

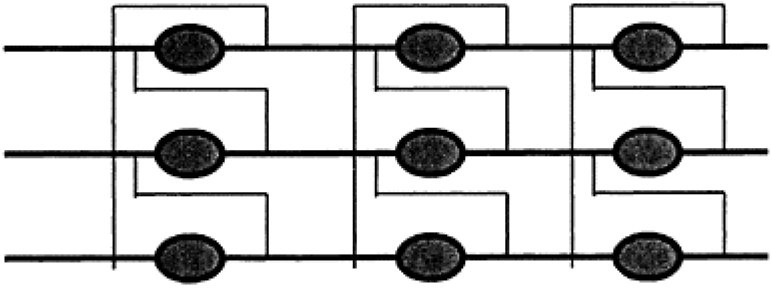
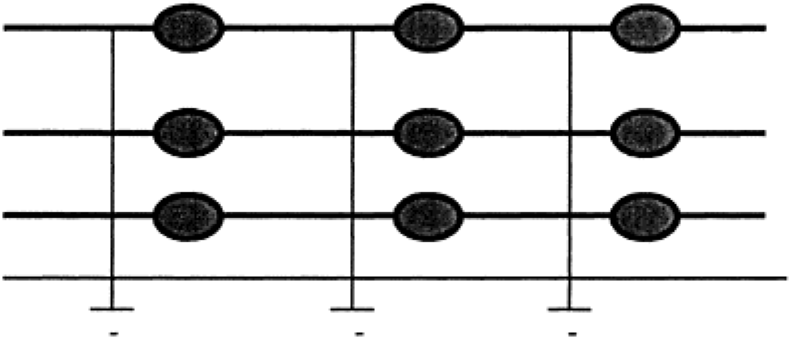


Figure 15-7 Auxiliary cable bonding.



There are other types of grounding schemes that are possible and are in service. Generally they make use of special transformers or impedances in the ground leads that reduce the current because of the additional impedance in those leads. These were very necessary years ago when the jackets of the cables did not have the high electrical resistance and stability that are available today.

5.5 Induced Sheath Voltage Levels

Formulas for calculating shield voltages and current and losses for single conductor cables were originally developed by K.W.Miller in the 1920s [15-2]. The same general equations are also given in several handbooks. The table from reference [15-6] is included as Figure 15-7. The difference in these equations is the use of the "j" term—to denote phase relationship—so only the magnitude of the voltage (or current) is determined. Each case that follows will include the formulas from that reference [15-6].

The induced voltage in the sheath of one cable or for all cables in a circuit where the cables are installed as an equilateral triangle is given by:

$$V_{sh}=I\times X_m \qquad (15.2)$$

where V_{sh}=sheath voltage in microvolts per foot of cable

I=current in a phase conductor in amperes

X_m=mutual inductance between conductor and sheath

The mutual inductance for a 60 hertz circuit may be determined from the formula:

$$X_m = 52.92 \log_{10} S/r_m \tag{15.3}$$

where X_m=mutual inductance in micro-ohms per foot

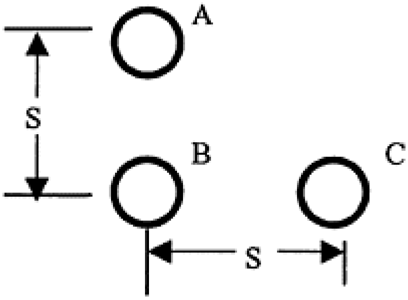
S=cable spacing in inches

r_m=mean radius of the shield in inches. This is the distance from the center of the conductor to the mid-point of the sheath or shield

For the more commonly encountered cable arrangements such as a three-phase circuit, other factors must be brought into the equations. Also, A and C phases have one voltage while B phase has a different voltage. This assumes equal current in all phases and a phase rotation of A, B, and C.

Right-angle or “rectangular” spacing is a probable configuration for large, single-conductor cables in a duct bank. One arrangement is:

Figure 15-8 Right angle arrangement.



The induced shield voltages in A and C phases are:

$$V_{sh} = I/2\sqrt{3\,Y^2 + (X_m - A/2)^2} \times 10^{-6} \tag{15.4}$$

where V_{sh}=sheath voltage on A and C phases in volts to neutral per foot

I=current in phases conductor in amperes

$Y = X_m + A/2$

$X_m = 52.92 \log_{10} S/r_m$ for 60 hertz operation

S=spacing in inches

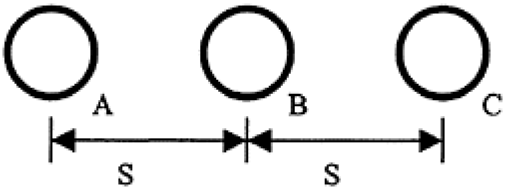
A=15.93 micro-ohms per foot for 60 hertz operation

The induced shield voltage in B phase is:

$$V_{sh} = I \times X_m \times 10^{-6} \tag{15.5}$$

A flat configuration is commonly used for cables in a trench, but this could be a duct bank arrangement as well.

Figure 15-9 Flat arrangement.



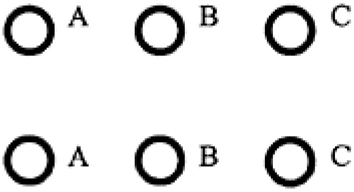
The induced shield voltages in A and C phases are:

$$V_{sh} = I/2\sqrt{3\,Y^2 + (X_m - A)^2}\ \text{x}\ 10^{-6} \tag{15.6}$$

where V_{sh}=sheath voltage on A and C phases in volts to neutral per foot
I=current in phases conductor in amperes
Y=X_m+A {This factor has changed from 14.4)!!!}
X_m=52.92 $\log_{10}$ S/r_m for 60 hertz operation
S=spacing in inches
A=15.93 micro-ohms per foot for 60 hertz operation
The induced shield voltage in B phase is the same as equation 15.5:

$$V_{sh=I\times Xm\times 10}^{-6} \tag{15.7}$$

Figure 15-10 Two circuits, flat configuration.



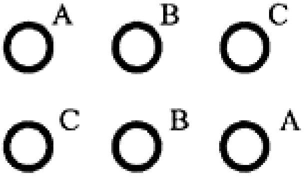
The induced shield voltages in phases A and C are:

$$V_{sh} = \text{I}/2\sqrt{3\,Y^2 + (X_m - \text{B}/2)^2}\ \text{x}\ 10^{-6} \tag{15.8}$$

where V_{sh}=sheath voltage on A and C phases in volts to neutral per foot
I=current in phase conductors in amperes
Y=X_m+A+B/2 {This factor has changed again!}
X_m=52.92 $\log_{10}$ S/r_m for 60 hertz operation
S=spacing in inches
A=15.93 micro-ohms per foot for 60 hertz operation
B=36.99 micro-ohms per foot for 60 hertz operation
The induced shield voltage for B phase is:

$$V_{sh}=I(X_m+A/2)\times10^{-6} \tag{15.9}$$

Figure 15-11 Two circuits, flat configuration, phases opposite.



The induced shield voltages in phases A and C are similar to equation (15.7), but Y changes:

$$V_{sh} = I/2\sqrt{3\,Y^2+(X_m-B/2)^2}\ \times 10^{-6} \tag{15.10}$$

where V_{sh}=sheath voltage on A and C phases in volts to neutral per foot

I=current in phases conductor in amperes

$Y=X_m+A-B/2$ {Now a minus, not +}

$X_m=52.92\log_{10} S/r_m$ for 60 hertz operation

S=spacing in inches

A=15.93 micro-ohms per foot for 60 hertz operation

B=36.99 micro-ohms per foot for 60 hertz operation

The induced voltage on B phase uses the same equation as (15.9):

$$V_{sh}=I(X_m+A/2)\times10^{-6} \tag{15.11}$$

5.6 Discussion of Bonding Methods

5.6.1 Cross-Bonding.

The goal of any shield isolation system is to reduce induced shield currents to the point that they will not seriously affect ampacity of the circuit and to limit the voltage to a safe value.

The most commonly used is cross bonding where the cable circuit is divided into three equal sections (or six, or nine, etc.). The shield is solidly grounded at the beginning of the first section and at the end of the third section. The second section is isolated by means of shield “breaks” from the first and third sections and has its sheath bonded to other phases. See Figure 15-5.

The induced shield voltage from A phase is “cross-bonded” to B phase, etc. This phase change reduces the resultant sheath voltage, and so on, for all sections of the circuit.

Bonding conductors must have sufficient capacity to carry the fault current that will be imposed and voltage resistance to keep the bonding jumper from being inadvertently grounded.

This method has the disadvantage of needing the joints evenly spaced through each triple section. When the joints are not evenly spaced, the voltage from one phase does not completely cancel out the other phase. This may not be critical, but it does mean that somewhat higher voltage levels will result.

5.6.2 Continuous Cross-Bonding.

This is basically the same as the cross bonding of Figure 15-5 except that all of the joints have shield isolation provisions. Such a scheme is useful in situations where the triple sections are not practical from a field standpoint, such as for four sets of joints—where the matched sets of three are not attainable.

The sheath voltages are approximately the same as for cross-bonded circuits. A disadvantage of this system is that there are no solid grounds except at the terminations.

5.6.3 Auxiliary Cable Bonding.

This system is similar to the continuous cross-bonding method since all the joints must have shield isolation and all shields are bonded at each splice. The unique part of this arrangement is that the shields are connected to each other and to a separate neutral cable that runs the length of the circuit.

This permits the through fault current to be transmitted both on the shield as well as the parallel neutral cable. A reduction in the amount of shield materials is thus possible. A cable fault must still be cleared by having the fault current of that phase taken to ground at a remote point. This means that you must still put on a sufficient amount of shield metal to permit the breaker, or other back-up device, to “see” the fault.

5.6.4 Continuous Cross-Bonding, Star Ground.

This system and other impedance type systems have been included in this discussion since they have been employed over the years. The basic need for these systems was to keep the sheath voltage down to that very low value of 12 volts. Now that 100+ volts is considered safe and reliable, the complications of these systems does not seem to be worthwhile. The equipment needed to accomplish these hookups are not very easy to find, have not been too reliable, and take up room in a manhole that is at a premium. Another concern is that these devices require additional maintenance time to be certain that they remain operational.

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CHAPTER 16
UNDERGROUND SYSTEM FAULT LOCATING

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1.0
INTRODUCTION

Underground systems originally established for concentrated areas such as cities or towns consisted of cable installed in conduit systems, and terminated in manholes. The manholes provided a space to join sections of cables and in some cases a place to install transformers and switches. Cable construction used in these systems consisted of paper insulation, impregnated with an insulating fluid, and covered with a lead sheath. When failures occurred on this type of system, the procedure for finding the failure was, to locate the manhole where smoke or flame was coming out of the manhole cover. In the event smoke was not seen, the procedure called for re-energizing the faulted circuit, to produce the detectable smoke location. If this did not work, or if there were other operating problems, a device such as a high voltage transformer could be used to breakdown the failure and generate sufficient smoke for the purpose of detecting which manhole contained the failure. If the fault was found in a manhole or if the fault had occurred in a cable between manholes, no further locating procedures were required. This was because the entire section of cable between adjacent manholes had to be replaced.

When cables were installed directly in the earth, location of the faults became more exacting and difficult to find. The location of a failure on a direct buried cable system requires a great deal of accuracy. That is because a small hole as practical is excavated so that repairs can be made to the cable. On the other hand the hole must be large enough for the repairperson to complete repairs. Instruments were developed to aid in this exact location, but with these new instruments requirements were that the operators become better trained and proficient in their use. This chapter will introduce the state of the art in fault location and some of the equipment, which is or can be used to find underground failures. There have been modifications made by users so as to better suit their various applications. While major strides in fault locating have been achieved through technology and field experience, no one instrument has been able to find the approximate location of the field and an exact location for repairs. It should also be considered that training and experience are a major factor in locating underground failures. Without continual use of the equipment or re-training session’s accuracy of finding the failures and extended time requirements will affect the finding of faults.

2.0 CONDUIT AND MANHOLE SYSTEMS

With the increase of electrical loads and more reliable demands of customers connected to the conduit and manhole systems, the requirement for quicker and safer methods of finding electrical failures became a goal in many companies. As system voltage increased, the use of a high voltage transformer to jump the gap of a fault, and a high current supply to burn the failure into a detectable condition became the approach that many companies utilized. When the failure is reduced to a low value of resistance, a bridge circuit can be used to give an approximate location of the failure. The bridge circuit most widely used is the Murray Loop. This instrument requires a good conductor to complete the circuit and an accurate length of the circuit being tested. Accurate circuit lengths are normal in a conduit system. Since the cables in a conduit system usually have three phases, a return conductor is available most of the time to utilize the bridge instrument.

The Murray Loop bridge instrument provided an approximate location within the capability of the fault locator or accuracy of the instrument used. When the location found gives a questionable location such as a location near a manhole, the locations opens three possibilities. The failure may be in the manhole, or in one of two sections of cable being spliced in the manhole. A way of verifying the correct failure location has been developed and used in the field with success. The instrument used for this purpose consists of a high voltage capacitor that is charged with a direct current supply. The charged capacitor is then connected to the faulted cable for the purpose of discharging at the failure producing a loud noise. The noise may either be detected at the conduit opening at either end of the manhole, or in the manhole itself. Visual detection of the discharge may also occur to aid in the location of the defective cable or splice.

3.0 UNDERGROUND RESIDENTIAL DISTRIBUTION

In the United States around 1950, direct buried cable installations were used to a great extent in new residential areas. This type of installation was both economical and faster to install. After several years, failures occurred on these installations. Cables were found to have inherent problems because of the various applications and field environments to which they were exposed. Consequently the need for accurate fault locating equipment became a prime requirement. Since the cables were direct buried, the ability to removing a section of cable was eliminated. It was now necessary to find the failures within the area that a crew could dig and find the failure. This was not as easy as it sounds. Not only was the equipment needed, but also men must be trained and operated the instruments and accurately locate failures. The process was compounded since there were different designs of both secondary and medium voltage cables. Secondary cables were usually without an insulation shield while the medium voltage cables were of a shielded design. Both of these cable designs required different approaches and techniques to adequately locate the precise area to dig for the failure.

The use of the Murray Loop became impractical mainly because the majority of the residential circuits were single phase. In addition accurate lengths of cable are required with a bridge circuit and these were not available in the residential direct buried cable systems. The capacitor discharge system became very useful in accurately locating buried failures. In fact their use became one of the most widely used instrument by many companies. Many of the engineers that had served in the war and were responsible for fault locating used their experience with military equipment and applied it to failure locating. The equipment they modified was the radar system. Modified to connect to a cable or overhead line, these sets were the first attempts to utilize the theory. They were not accurate and were very complicated to the point where an engineer was needed to properly adjust the various settings.

4.0 METHODS OF LOCATING FAILURES

The following methods of finding failures on underground cable systems. The success of some of these methods is often dependant on the type of system on which it is used, or the skill of an individual operator. You may find the name used to refer to these methods may change from company to company, so it is necessary to refer to the basic concepts when investigating new equipment.

4.1 Cable Locating

Location of the cable route is the most important part of fault finding on a direct buried system. Once the faulted cable has been identified the next step is to verify the route. Unlike a conduit system where accurate locations are maintained for conduit runs, manholes and terminations, the direct buried system does not have a specific route. Installation problems in the field may cause the construction crew to vary the route. These changes are very seldom noted in the original installation drawings. Splices may be installed as part of the initial installation or added when repairs are made on a previous failure. In some cases extra cable may be buried with the intent of extending the circuit for future loads to be added, or situations occur where the cable route is changed to go around unknown objects buried in the ground.

4.2 Cut and Test

This method of isolating the failure was originally used when no other instrument was available. Now seldom used, it has an application where cable length exceeds the capability of available instruments. Long, buried cables can be cut in the center of that length then tested both ways to see which half has the failure. The resulting length of cable to be tested is now reduced by 50%. This can be method can be repeated until a short section of cable is known to contain the failure and is within the capability of the instruments available.

It is advisable to repair the cut sections of the cable with a device that allows the convenient sectionalizing of the cable in the event that a failure occurs again on this cable run.

Figure 16-1 Capacitor discharge unit for field application. (Photograph courtesy of Von Corporation.)

4.3 Capacitor Discharge (Thumper) Set

The capacitor discharge instrument has been nick named “Thumper” because of the audible sound it makes when the energy of the capacitor discharge occurs at the failure in the ground. It is this thumping sound that has made it one of the most useful devices for exactly locating the failure in direct buried systems. The capacitor discharge consists of three basic components. A High Voltage direct current power supply, a high voltage capacitor, and a timing device to control the times the charged capacitor is connected to the faulted cable. The timing device may be an adjustable spark gap, or a set of contacts that are controlled by a timing device. This instrument is requires the discharge from the capacitor occurs between the phase conductor and a shield or near by ground. Therefore it is mostly suited for shielded cable designs. While it can be used on nonshielded cables, special connections are normally required. A simplified block diagram of a capacitor discharge is as follows:

Figure 16-1 shows a fault-locating instrument suitable for field application. The instrument consists of two testing features. The instrument contains a highvoltage direct current circuit used to test cable prior to fault locating, and a capacitor discharge circuit, which can be used to thump the faulted cable. The capacitor circuit contains an adjustable air gap to adjust the thumping voltage and frequency of thump. As you can see in Figure 16-1, the fault locating instrument is self-contained in a metallic case that when connected properly is at ground potential. An operator is then not exposed to any direct high voltage exposure during fault locating.

Figure 16-2 Capacitor discharge setup using non-shielded test equipment. (Photograph courtesy of Von Corporation.)

Figure 16-2 shows a field setup for non-shielded test equipment. It provides the same functions as that in Figure 16-1. The photograph shows the fault locating equipment connected to a URD transformer. Directly in front of the transformer is the thumping capacitor with an adjustable spark gap mounted. In the center is the direct current high voltage power unit and on the right is the control box for the operator to adjust the output of the power supply.

4.4 Murray Loop Bridge

A bridge circuit that has its best application on three phase circuits consisting of three-conductor paper insulated cable in a lead sheath. The reason for this is because it is a bridge circuit that requires a good conductor of the same length and size as the faulted conductor. In these types of circuits the most common failure is on one of the phase conductors. Since the fault itself is part of the bridge circuit, an operator knows if it is going to work by noting the ability to pass a small current through the fault itself. One technique is to reduce the resistance of the failure to the shield or ground by passing a higher current through the fault prior to using the Murray loop bridge circuit. The bridge circuit normally can be used with a low voltage direct current source, however, if the lower voltage is insufficient to pass current through the fault, a higher level of voltage can be applied. This assumes that the bridges, as well as the connections, are capable of withstanding the higher voltage. The Murray loop can be used to find approximate locations on cables that are of shielded or non-shielded design. Accurate records are a must for conductor length and size—if known, this method can give very accurate results.

Figure 16-3 Murray loop diagram. The arrow at upper right points to the fault resistance.

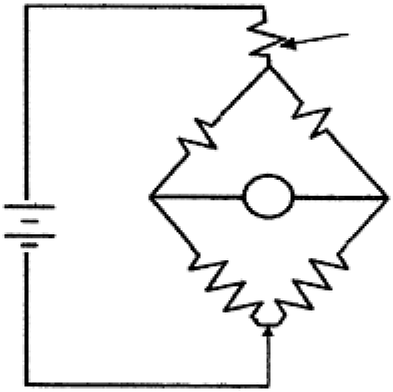
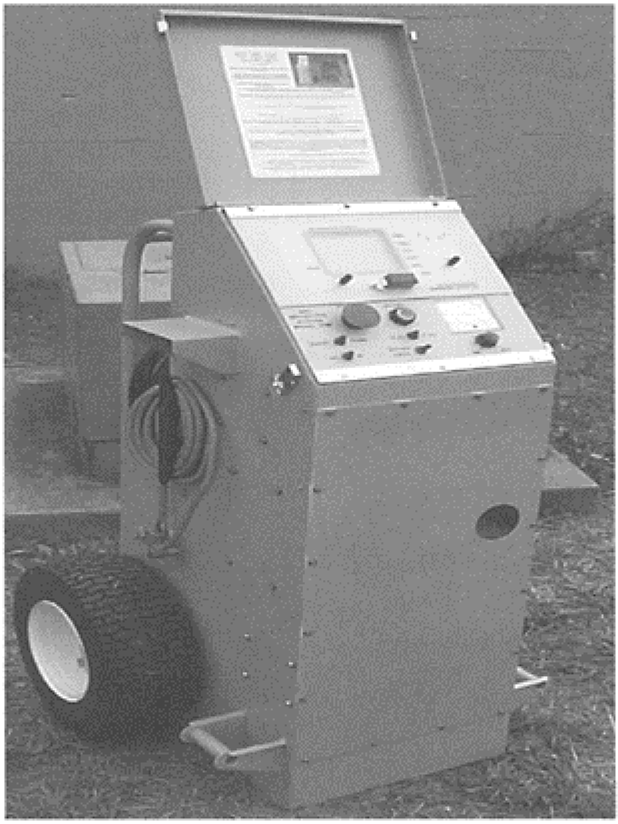


Figure 16-4 Portable TDR (radar) test set. (Photograph courtesty of Von Corporation.)



4.5 Radar or Time Domain Reflectometer

Shortly after World War II, radar or time domain reflectometry (TDR) sets, became available on the surplus market. People who had used the radar sets during the war used their experience to modify these sets for use by underground personnel to find failures on underground cables. At first these sets were cumbersome to use and fairly complicated to adjustments. Like many new instruments, improvements have been made through the years. For the people that do the fault locating radar is becoming the instrument of choice. Radar sets send out a pulse of relative low voltage that is reflected back to the set itself when it encounters a change of impedance. The extremes of the change of impedance are the open end of a cable and a short between the conductor and the ground shield. The trace on a screen is a measure of time for the pulse to travel to the failure and back. It is necessary to know the length of the cable being evaluated as this length is the length of the trace on the radar instrument. Application of this equipment is restricted to a shielded cable design in which the characteristic impedance is fairly constant throughout the length.

Figure 16-4 shows a mobile TDR unit. Wheels allow it to be moved to remote locations by one person. This unit contains the complete radar sensing equipment, a high voltage unit for the purpose of creating a discharge at the fault, and a capacitor, which can be used for limited thumping. Here are a few of the major improvements that have been made through the years:

- Controls have become simplified so as to become user friendly.
- Screen traces have become more visible in bright light.
- Comparative traces are available for the purpose of comparing a good circuit with a faulted circuit.
- Velocity of propagation has been narrowed so as to make fewer choices for various cable constructions. It is still necessary to have an idea what it should be as it affects the accurate distance to the failure.
- Introduction of an electrical discharge at the failure will show the fault location by breaking down the failure and capturing it on the viewing screen.

Figure 16-5 TDR unit in a substation. (Photograph courtesy of Von Corporation.)

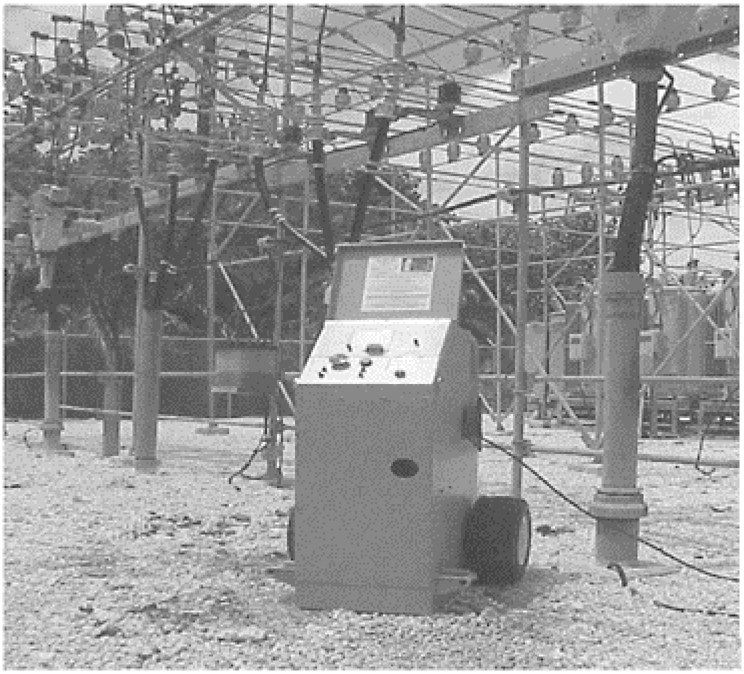


Figure 16-5 shows the TDR unit in operation in a substation where cable terminations are accessible. No additional source of power is required for this particular unit as there is a rechargeable battery in use.

74.6 Earth Gradient

The earth gradient instruments are used on non-shielded cables by applying a signal to the phase conductor of the faulted cable and a return path to a ground connection. The signal travels through the ground returning to the ground connection at the transmitting instrument. The returning signal can be detected above the ground in the close proximity of the buried cable with a sensitive meter.

Transmitters normally consist of a direct current signal of sufficient voltage to supply a detectable signal with probes on the surface of the ground. Direct current signal is preferred where there is a chance of stray alternating currents in the vicinity of the faulted cable.

Detectors used with the direct current transmitter consist of: micro ammeters with a zero center feature, a control for the sensitivity, and a set of probes which either can be frame mounted or used separately.

Used mostly on direct buried non-shielded cable normally used for secondary main and service cables, this method has an excellent record for finding failures on aluminum conductor cables where the aluminum conductor has corroded. During the corrosion process at the failure the aluminum powder expands causing the insulation to break (if it not already broken) and make a connection to ground. This is where the earth gradient starts.

4.7 Capacitance Measurements

This method of fault location can best be used on cables where the failure consists of an open circuit of the phase conductor.

A shielded cable has fairly uniform capacitance between the phase conductor and the insulation shield. By knowing the capacitance per foot of the cable an approximate location of an open type failure can be calculated. If the capacitance per foot is not known, an alternate method consists of measuring capacitance from both ends of the faulted cable. A ratio of the two readings will provide an approximate location. Keeping in mind that the cable is uniform through the run under test. No changes in physical size (175 or 220 mils of insulation) or no changes in insulation type (PE or EPR).

4.8 Additional Instruments Not Normally Used in USA

The following names are methods of fault locating on underground systems that have been used by some fault locating personnel. They are listed here only for reference and are not as a recommendation of widely used practices in the US today. Some of the methods listed here are similar if not identical to others in the list, but have been given different names by users depending on which reference material you are using as a guide.

- Murray—Fisher loop
- Varley loop
- Hilborn loop
- Insulation resistance
- Pulse decay

- Differential decay method
- Standing wave
- Charging current
- Impulse current differential method

5.0 FAULTED CIRCUIT INDICATORS

Faulted circuit indicators (normally referred to as “fault indicators”) do not provide a location of the fault on a circuit, but do reduce the area in which the fault locating equipment can be applied. This is extremely important when locating failures on long lengths of cable. It is also a valuable tool when locating faults, which are installed in areas in where there is limited access to the personnel doing the fault locating.

Fault indicators of the type addressed here can be obtained to cover a range of currents depending on the type of circuit to which they are attached. It is important to know what the normal current is in the circuit and in addition intermittent increases in current, which may occur on the circuit. By knowing these two factors, it will minimize the occurrence of a false tripping of the device. The effect of the exact fault current using minimizes range-faulted indicators, which will automatically reset when the circuit is energized.

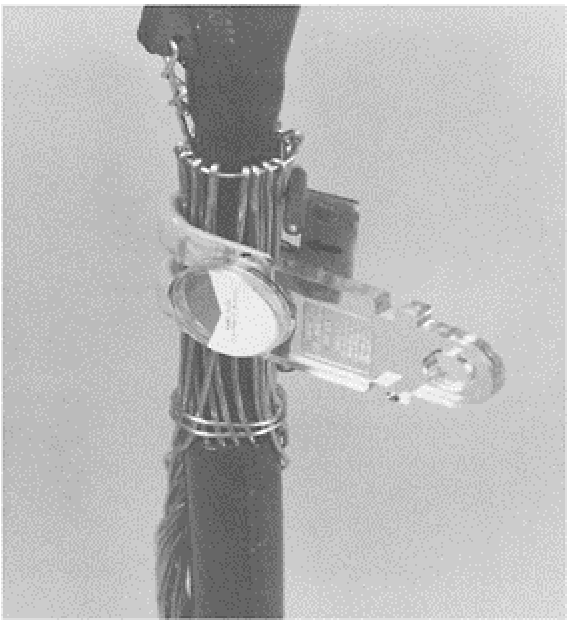
Early applications had limited success in many areas. Due to the following reasons:

(1) Initial fault indicators were of the manual reset type (see Figure 16-6) that requires the operating departments return to the previously faulted cable circuit, access each location where they were installed, and manually reset the device. An external tool is required to reset this indicator.

(2) Information on the correct placement of the fault indicators was often not available to the installer. Consequently they were installed on the cable in such a location where they did not work properly. When properly installed and reset after every failure on the circuit, these devices provided a valuable service to the people locating faults.

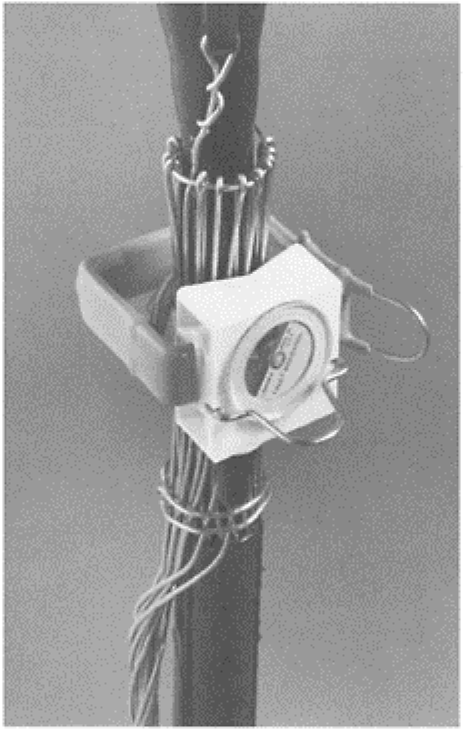
Fault indicators are designed so that they detect a given level of current passing through the cable to which they are connected. On alternating current circuits, the indicators do not show which direction the fault current is flowing—only that the current has exceeded the rated current of the indicating device. It is necessary for the user to inspect the fault indicators starting at the source of the current into the circuit. This continues until the user finds one indicator, which had not experienced the fault current. The user then knows that the circuit failure is between the fault indicator, which showed excessive current, and the one that did not show excessive current (no target).

Figure 16-6 Manual reset fault indicator. (Photograph courtesy of E.O. Schweitzer Mfg. Co.)



Magnetic fault indicators are placed over a conductor and detect the magnetic field caused by electric current flowing in the conductor. When the current exceeds the rating of the fault indicator an warning will appear on the device, either a target, light, or noise showing that current much greater than normal (fault current) has passed through the fault indicator.

Figure 16-7 Fault indicator designed with a reset button. (Photograph courtesy of E.O.Schweitzer Mfg. Co.)



An improvement over the manual reset fault indicator consisted of an operating button, which eliminates the need of a separate tool to reset the indicator. It also eliminates the requirement of removing the fault indicator from the circuit as is required in Figure 16-8.

The automatic reset feature shown in Figure 16-8 is one of the most important features to the utility operating department. It was no longer necessary to return to the circuit that had been faulted and repaired, access every fault indicator, and reset the device manually. These indicators are designed so as to take a sampling of current from the repaired and energized line and use that to reset the fault indicator. In other words all fault indicators return to a no fault indication.

Figure 16-8 Fault indicator with automatic reset. (Photograph courtesy of E.O. Schweitzer Mfg. Co.)

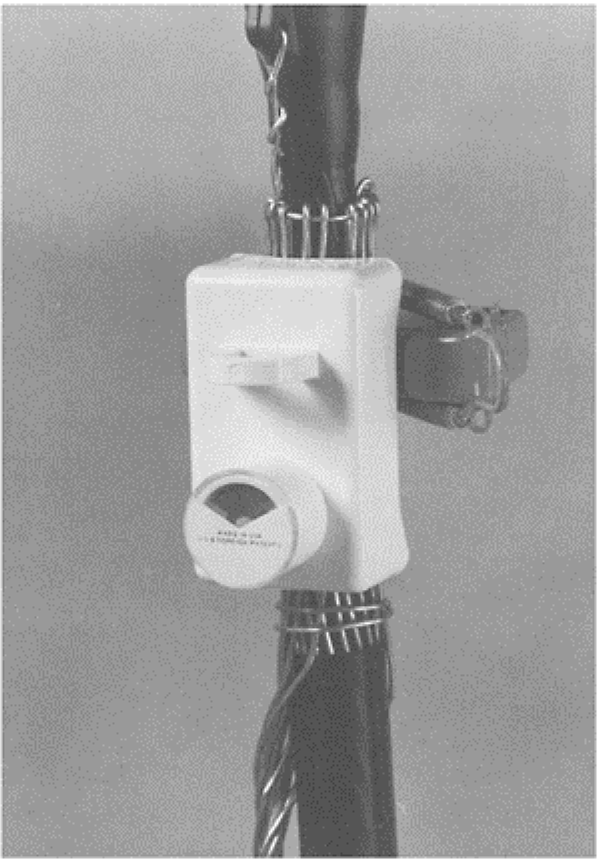
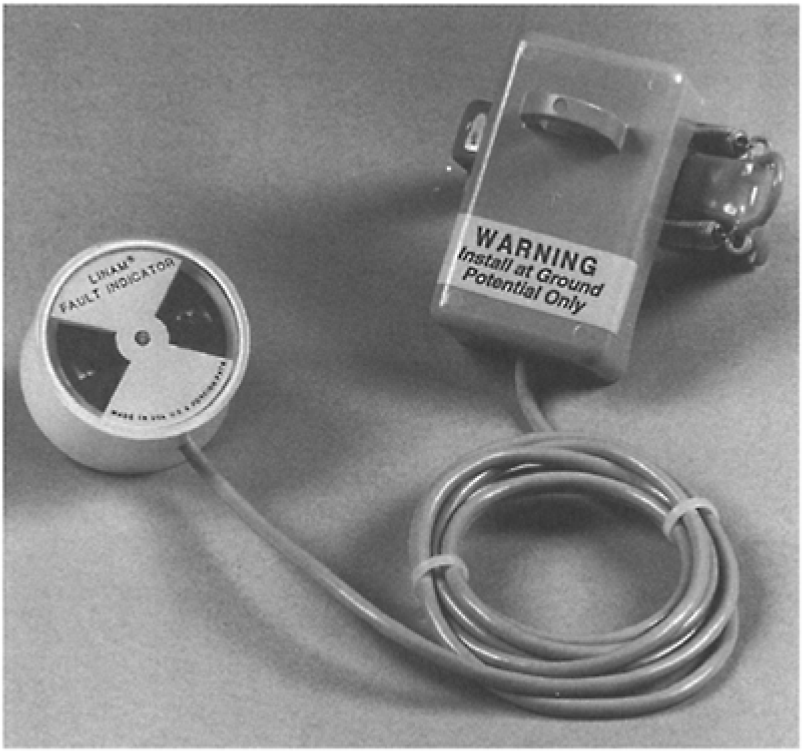


Figure 16-9 shows a fault indicator with a remote target attachment. This allows operating personnel access to the indicator with out entering the transformer or switchgear. It is sometimes used in substations on outgoing circuit for a quick evaluation of which phase is in trouble. One of these must be attached to each phase.

Figure 16-10 shows a fault indicator mounted on the voltage test point on a separable connector. The voltage test point was initially developed for the purpose on testing the line or energization without removing the elbow. However now adapting the fault indicator to the test point has expanded its usefulness.

Figure 16-9 Fault indicator with remote target. (Photograph courtesy of E.O. Schweitzer Mfg. Co.)



The voltage test point is available on purchase for those customers, which choose to use it. If you have or plan to buy this feature when purchasing separable connectors, and if you desire to use the type of fault indicator, you will need to specify this at time of purchase. At the present time, there is not a standard for the physical size of the voltage test point. Therefore when using this feature make sure the fault indicator fits the voltage test point for which it intended. The separable connector fault indicator uses the energy from the energized circuit through the voltage test point to reset the indicator after the circuit is returned to service. Previous indicators used current, or the mechanical push button, to reset the indicator. This fault indicator has the advantage of not being installed incorrectly as it can only be used with a voltage test point.

Figure 16-10 Separable connector with fault indicator mounted on test point. (Photograph courtesy of E.O.Schweitzer Mfg. Co.)

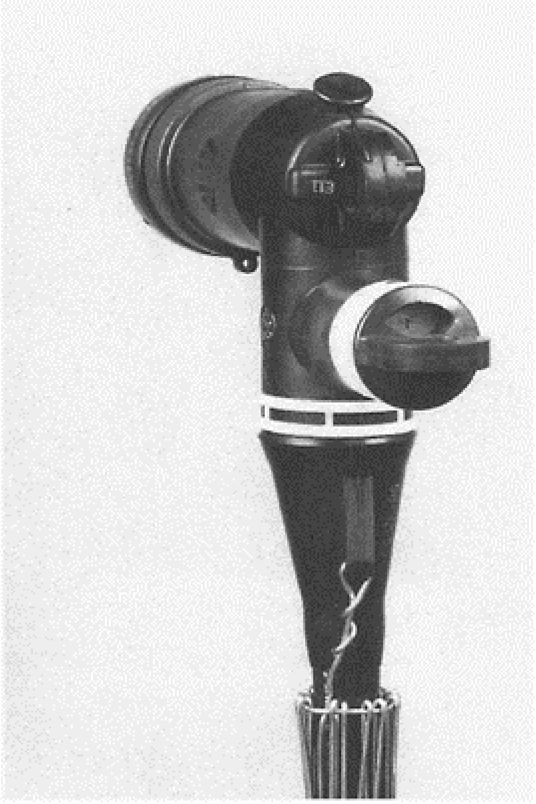
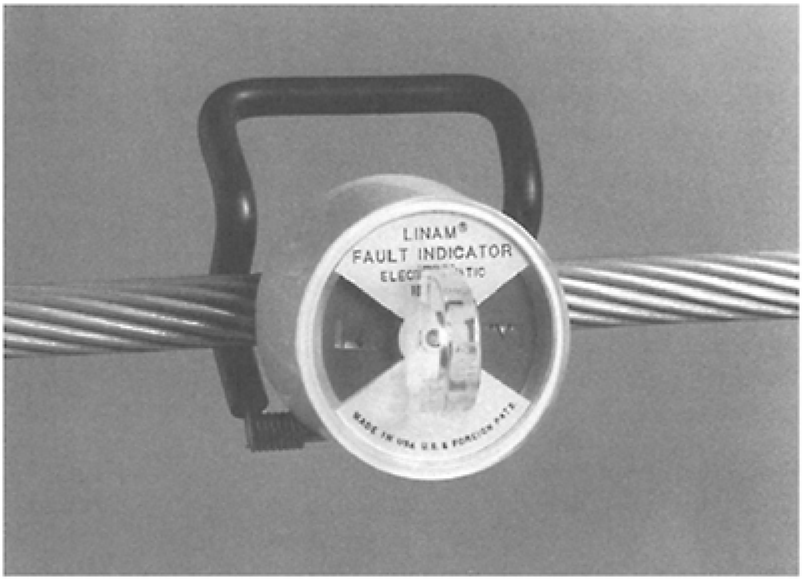


Figure 16-11 shows an application for a fault indicator on overhead circuits. This one utilizes the energy from the voltage in the conductor to reset the target. While the reset feature is of advantage for underground applications, one major advantage of the manual reset fault indicator on overhead applications is the fact that the indicator does not reset.

This means that a circuit that experiences intermittent faults would normally be difficult to find. However, since the manual fault indicator does not reset, operating personnel can return to the to the previously faulted circuit and examine the fault indicators to locate the previous intermittent failure.

Figure 16-11 Fault indicator for overhead appliation. (Photograph courtesy of E.O.Schweitzer Mfg. Co.)



CHAPTER 17
FIELD ASSESSMENT OF POWER CABLES

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1.0 INTRODUCTION

This chapter provides an overview of methods for performing electrical tests in the field on shielded power cable systems. It is intended to help the reader select a test that is appropriate for a specific situation of interest. Field tests can be broadly divided into the following categories:

(1) Withstand tests which are intended to detect defects in the insulation of a cable system in order to improve the service reliability after the defective part is removed and appropriate repairs performed. These are also referred to as "go/no go" or "pass/fail" tests.
(2) Condition assessment tests which are intended to provide indications that the insulation system has deteriorated. Some of these tests will show the overall condition of a cable system and others will indicate the locations of discrete defects that may cause the sites of future service failures. A major goal of these tests are to estimate the future performance of the cable system being tested—hence the term "diagnostic test" is used.

The various field test methods that are presently available for testing shielded, insulated power cable systems rated 5 kV through 500 kV are discussed. A brief listing of "advantages" and "disadvantages" is included, but the users should avail themselves of the technical papers that are referenced, the material listed in the references, manufacturers' literature, and recent research results to make decisions on whether to perform a test and which test method (or methods) to use. In making such decisions, consideration should be given to the performance of the entire cable system, including joints, terminations, and associated equipment.

2.0 FUNDAMENTALS

Test equipment for field use must obviously be reasonably small so that it may be conveniently transported to the location. The source of excitation energy can be the normal line equipment (on-line) or a separate source that is generally capable of applying moderately elevated voltages (off-line).

2.1 Elements of Testing

There are three building blocks of ALL test sets [17-1]:

- **Voltage**
- **Current**
- **Time/Frequency**

2.2 Excitation Voltage

- Direct voltage (dc)
- Low frequency (about 0.1 Hz)
- Power frequency (50/60 Hz)
- High frequency (100 to 500 Hz)
- Oscillating or decay voltages

2.3 Options For Property Measured

- Amperes
- Partial discharge (pC)
- Dissipation factor (tan δ)
- Decay voltage or current
- Inception/extinction voltages

2.4 Time Considerations

The time involved in the reading varies considerably. One of the factors that must be considered here is the frequency of the applied source because it is necessary to average several readings—hence the term “repetition” comes into use. This means that if the frequency is 0.1 Hz and three readings are to be averaged, the source must be applied for at least 30 seconds. If the frequency is 60 Hz, this time can be shortened to just 2 or 3 seconds.

Another consideration for the time of application involves the philosophy of the test. If the goal of the test is to have the failure occur while the circuit is out of service, then an extended time is usually specified (up to 1 hour). If the goal is to only evaluate the circuit, then the time is generally kept very short (a few seconds). Experience also is given consideration in the time decision.

2.4 Global Evaluation Versus Pinpointing Defects

A broad distinction exists between the test methods in their ability to pinpoint a defect as opposed to looking at the “average” of the total circuit—often referred to as a global evaluation. As will be seen later in this chapter, the partial discharge measurement leads to the location of one or more defects while dissipation factor gives an average of the circuit under test and hence does not locate a particular site.

The location of the defect site frequently makes use of a measurement of the time it takes for a signal to travel in the specific cable being tested. Time domain reflectometry (TDR) can measure the time for the signal to go from the test set to the defect and then return (a round trip) or just from the defect to the test set (one way).

2.6 Need for Testing

While medium and high voltage power cables are carefully tested by the manufacturer before shipment with alternating or direct voltage to ensure conformance with published specifications and industry standards. During transport, installation, accessory installation, cables are vulnerable to external damage. Therefore, cables may be tested prior to placing them in service to locate any external mechanical damage and to ensure that jointing and terminating work has been satisfactory. Periodic testing of service-aged cables may also be performed with the desire to determine system degradation and to reduce or eliminate service failures.

Additionally, many users find that, with time, these cable systems degrade and service failures become troublesome. The desire to reduce or eliminate those failures may lead cable users to perform periodic or maintenance tests after some time in service. Cable users also need special diagnostic tests as an aid in determining the economic replacement interval or priority for replacement of deteriorated cables.

Research work has shown that certain types of field testing may lead to premature service failures of XLPE cables that exhibit water treeing [17-3]. This substantiates some field observations that led to the concern about field test methods and levels of voltage.

Experience with paper insulated, lead covered cable systems that have been tested in the field with dc for over 60 years has shown that testing with the recommended dc voltage does not deteriorate sound insulation or only at such a very slow rate that it has not been detected.

The decision to employ maintenance testing must be evaluated by the individual user taking into account the costs of a service failure, including intangibles, the cost of testing, and the possibility of damage to the system. As proven non-destructive diagnostic test methods become available, the users may want to consider replacing withstand type voltage tests with one or more of these assessment methods.

3.0 OVERVIEW

3.1 On-line Versus Off-line Testing

Off-line testing has been the usual way of testing cable systems in the field. As the name implies, the circuit to be tested is de-energized and taken out of service. This is necessary with any method that requires higher than normal test voltages or frequencies other than for normal operations. A disadvantage is that there are times when it is not practical to take a circuit out of service in order to test. Switching may also be time consuming and hence expensive.

Methods are now available that allow diagnostic measurements to be made while the circuit is in normal operation. This method is applicable to all system voltages (5 through 500 kV) and all types of cable construction and insulations (paper, XLPE, EPR, etc.). A disadvantage of this method is that sensors must be placed around the cable or equipment at frequent intervals such as at each joint and termination.

3.2 Direct Voltage Testing

Testing with dc [17-2] has been accepted for many years as the standard field method for performing high voltage tests on the cable insulation systems that were found on utility systems—paper insulated cables. One of the most important uses of testing PILC cable systems prior to placing them in normal service (proof test) was to confirm that the circuit was safe for the workers to energize. This was accomplished very satisfactorily by dc. Testing with dc is still useful in finding gross problems with paper-insulated cable systems either as a proof test or if it is done on a periodic basis (maintenance test). The important consideration is “Are other types of insulation—such as XLPE—in cables on that circuit?”

As systems were added that had extruded insulations, dc was used in the same manner as with paper-insulated systems. Unfortunately, this extrapolation was not based on experience nor research.

Recent research has shown that dc testing tends to be blind to certain types of defects and that it can aggravate the deteriorated condition of some aged XLPE-insulated cables that have water trees. Whenever dc testing is performed, full consideration should be given to the fact that steady-state direct voltage creates within the insulation system an electrical field determined by the conductance of the insulation, whereas under service conditions, alternating voltage creates an electric field determined chiefly by the dielectric constant (or capacitance) of the insulation. Under ideal, homogeneously uniform insulation conditions, the mathematical formulas governing the steady-state stress distribution within the cable insulation are of the same form for dc and for ac, resulting in comparable relative values. However, should the insulation contain defects where either the conductivity or the dielectric constant assume values significantly different from those in the bulk of the insulation, the electric stress distribution obtained with direct voltage will no longer correspond to that obtained with alternating voltage. As conductivity is generally influenced by temperature to a greater extent than dielectric constant, the comparative electric stress distribution under dc and ac voltage application will be affected differently by changes in temperature or temperature distribution within the insulation. Furthermore, the failure mechanisms triggered by insulation defects vary from one type of defect to another. These failure mechanisms respond differently to the type of test voltage utilized, for instance, if the defect is a void where the mechanism of failure under service ac conditions is most likely to be triggered by partial discharge, application of direct voltage would not produce the high partial discharge repetition rate which exists with alternating voltage. Under these conditions, dc testing would not be useful. However, if the defect triggers failure by a thermal mechanism, dc testing may prove to be effective. For example, dc can detect presence of contaminants along a creepage interface.

Testing of extruded dielectric, service aged cables with dc at the presently recommended dc voltage levels can cause the cables to fail after they are returned to service [17-3]. The failures would not have occurred at that point in time if the cables had remained in service and not been tested with dc [17-4]. Furthermore, from the work of Bach [17-5], we know that even massive insulation defects in solid dielectric insulation cannot be detected with dc at the recommended voltage levels.

After engineering evaluation of the effectiveness of a test voltage and the risks to the cable system, high direct voltage may be considered appropriate for a particular application. If so, dc testing has the considerable advantage of being the simplest and most convenient to use. The value of the test for diagnostic purposes is limited when applied to extruded installations, but has been proven to yield excellent results on laminated insulation systems.

3.3 Alternative Test Methods

Renewed interest in alternative tests has appeared that stress the insulation as is done in actual operation and may be used in the factory for testing and evaluation purposes.

A serious disadvantage of power frequency ac tests at elevated voltage levels was the requirement for heavy, bulky and expensive test transformers that may not be readily transportable to a field site. This problem has been mitigated through use of resonant (both series and parallel) test sets and compensated (gapped core) test transformers. They are designed to resonate with a cable at power frequency, the range of resonance being adjustable to a range of cable lengths through a moderate change of the excitation voltage frequency, or a pulse resonant system. Power frequency ac tests are ideally suited for partial discharge location and dissipation factor (tan δ) evaluation.

Some of the practical disadvantages of power frequency tests are reduced while retaining the basic advantages by the use of very low frequency (VLF, or about 0.1 Hz) voltage or by the use of other time-varying voltages such as oscillating waves (OSW).

4.0 DIRECT VOLTAGE TESTING

4.1 Introduction

The use of direct voltage has a historical precedent in the testing of laminated dielectric cable systems. Its application for testing extruded dielectric cable systems at high voltage is a matter of concern and debate. Reference [17-3] contains information relevant to these concerns.

This section presents the rationale for using dc testing, including the advantages and disadvantages and a brief description of the various dc field tests which can be conducted. These are generally divided into two broad categories, delineated by the test voltage level: low voltage dc testing (LVDC) covering voltages up to 5 kV and high voltage dc testing (HVDC) covering voltage levels above 5 kV.

Testing with a dc voltage source requires that only the dc conduction current be supplied rather than the capacitive charging current. This may greatly reduce the size and weight of the test equipment.

4.2 Performing LVDC Tests

Equipment for producing these voltages is typified by commercially available insulation resistance testers. Some have multi-voltage range capability.

Cable phases not under test should have their conductors grounded. Ends, both at test location and remote, should be protected from accidental contact by personnel, energized equipment and grounds.

Apply the prescribed test voltage for specified period of time. It may be advantageous to conduct the test with more than one voltage level and record readings of more than one time period.

Such test equipment provides measurements of the insulation resistance of the cable system as a function of time. Interpretation of the results, covered in greater detail in [17-2], IEEE 400, usually makes use of the change in resistance as testing progresses. A value of polarization index can be obtained by taking the ratio of the resistance after 10 minutes to the resistance after 1 minute.

ICEA provides minimum values of insulation resistance in its applicable publications.

4.3 Performing HVDC Tests

Equipment for producing these voltages is typified by rectification of an ac power supply. Output voltage is variable by adjusting the ac input voltage. Output current, i.e., current into the cable system under test, may be measured on the HVDC side or ratio transformation of the ac input. For the latter case, the test equipment leakage may mask the test current and the interpretation of results.

Apply the prescribed test voltage for the specified period of time. Reference [17-2] provides guidance for the selection of test voltage and time.

The following three general types of test can be conducted with this equipment:

4.3.1 DC Withstand Test.

A voltage at a prescribed level is applied for a prescribed duration. The cable system is deemed to be acceptable if no breakdown occurs.

4.3.2 Leakage Current—Time Tests.

Total apparent leakage output current is recorded as a function of time at a prescribed voltage level. The variations of leakage current with time (rather than its absolute value) provide diagnostic information on the cable system.

4.3.3 Step-Voltage Test or Leakage Current Tip-up Tests.

The voltage is increased in small steps while the steady-state leakage current is recorded, until the maximum test voltage is reached or a pronounced nonlinear relationship between current and voltage is displayed. Such departures from linearity may denote a defective insulation system.

4.4 Advantages And Disadvantages

Some of the advantages and disadvantages of dc testing are listed below:

4.4.1 Advantages

- □ Relatively simple and light test equipment, in comparison to ac, facilitates portability
- □ Input power supply requirements readily available
- □ Extensive history of successful testing of laminated dielectric cable systems and well established database
- □ Effective when the failure mechanism is triggered by conduction or by thermal consideration
- □ Purchase cost generally lower than that of non-dc test equipment for comparable kV output

4.4.2 Disadvantages

- ■ Blind to certain types of defects, such as clean voids and cuts
- ■ May not replicate the stress distribution existing with power frequency ac voltages
- ■ The stress distribution is sensitive to temperature and temperature distribution
- ■ May cause undesirable space charge accumulation, especially in water-treed cable and at accessory/cable insulation interfaces
- ■ May adversely affect future performance of water-tree-affected extruded dielectric cables
- ■ Relatively high voltages have been used and they may damage the cable system

5.0 ON-LINE POWER FREQUENCY TESTING

5.1 Introduction

An on-line condition assessment service is available that utilizes the measurement of a form of partial discharge. The sensitivity is in the order of 0.5 pC. The circuits are energized by their normal source of supply voltage. High frequency inductive sensors are moved to accessible portions of a cable circuit such as cables in manholes, terminations, etc. Novel techniques are used to filter noise in order to obtain these low sensitivity levels. Rather than using the picocoloumb unit for the partial discharge level, the measurements are in millivolts.

5.2 Measurements

Sensors are placed at convenient locations along the cable route, such as near a splice, and noise level readings are taken over a frequency spectrum. Frequencies that produce high noise levels are avoided during actual data collection.

Data is collected and analyzed at the service provider’s office. Sites are located and ranked as to the severity of their findings—at condition levels of 1 through 5. Level 1 means that no action is required, level 2 means to consider testing again in 2 years, level 3 means a low level of the probability of a service failure within 2 years, level 4 indicates a medium probability of failure in 2 years, and level 5 indicates a high probability of failure and that replacement should be considered.

5.3 Advantages

□ The circuit may be left in service during the assessment
□ All types of cable may be analyzed: paper, HMWPE, XLPE, TRXLPE, etc.
□ All voltage levels of cable, joints, and terminations may be analyzed
□ Transformers up to 40 kV may be analyzed

5.4 Disadvantages

■ Attenuation of these small signals that are being recorded is so large that readings should be taken in every to every other manhole
■ Wet manholes may require pumping
■ Analysis of data requires highly trained engineers

6.0 OFF-LINE POWER FREQUENCY TESTING

6.1 Introduction

These methods have the advantage, unique among the off-line test methods described in this chapter, of stressing the insulation exactly the same as normal operating conditions. It also replicates the most common method of factory test on new cables and accessories.

There is a practical disadvantage in that the cable system represents a large capacitive load, and in the past a bulky and expensive test generator was required if the cable system was to be stressed above normal operating levels. This size and bulk can be offset by the use of resonant and pulsed resonant test sources, which are described later.

A further advantage of power frequency testing is that it allows partial discharge and dissipation factor (tan delta) testing for diagnostic purposes. Some other test sources also permit these measurements, but give rise to some uncertainty in interpretation, since the measurements are then made at a frequency other than the normal operating frequency.

It may seem logical that field tests use the same type of test voltage as when the circuit is in normal operation. However, a conventional power frequency transformer required even for full reel tests in the factory is a large and expensive device. Since a power cable may be made up of multiple reels of cable spliced together in the field, an even larger test transformer would be required to supply the heavy reactive current drawn by the geometric capacitance of the cable system.

The size of the transformer can be substantially reduced by using the principle of resonance. If the effective capacitance of the cable is resonated with an inductor, the multiplying effect of the resonant circuit (its Q factor) will allow the design of a smaller test transformer.

In the ideal case of a perfect resonance, the test transformer will only be required to supply energy to balance the true resistive loss in the inductor and cable system. A further and significant reduction in size and weight of the test voltage generator can be achieved by use of the pulsed resonant circuit.

6.2 Test Apparatus Requirements

The following requirements are common to all three types of line frequency, resonant testing systems:

1. The apparatus is provided with an output voltmeter that responds to the crest of the test waveform. For convenience, this may be calibrated in terms of the rms voltage of the output (i.e., as 0.707 times the crest voltage.)
2. The output waveform is sinusoidal and contains a minimum of line frequency harmonics and noise. This is of particular importance when diagnostic measurements (partial discharge, power factor, etc.) are being performed.

Suggested maximum values for total harmonic and noise are:

- For withstand tests ±5% of the output voltage crest.
- For diagnostic tests ±1% of the output voltage crest.

It should be noted that certain types of voltage regulators using inductive methods for regulation tend to produce large amounts of harmonic distortion. Line filters to minimize noise introduced from the power line are recommended for diagnostic measurements.

For withstand tests, the detection and indication of breakdown of the point at which breakdown occurs is defined by the over-current protective device of the test system. For this reason it is desirable that a high speed and repeatable electronic circuit be used to operate the system circuit breaker and that the circuit breaker be as fast operating as practical.

6.3 Characteristics of Test Systems

The operating characteristics of a conventional test set are similar to a power transformer, although there are significant differences in the design of the source equipment.

Resonant systems operate differently than conventional transformers in that they have a specific tuning range for the capacitance of the cable under test. Capacitance outside this range cannot be energized. The minimum that can be energized can be reduced to zero, in the series resonant system, by using an auxiliary capacitor of appropriate rating in parallel with the test sample. The parallel resonant test system can be energized with no connected capacitance. The maximum value is independent of the current or thermal rating of the test system and cannot be exceeded. A typical tuning range is of the order of 20:1, maximum to minimum capacitance.

Both conventional and resonant test transformers provide an output that stresses the cable system under test identically to that under normal operations.

The output of a pulsed resonant test system consists of a power line frequency modulated at a low frequency, such as one Hz. The stress distribution in the cable system under test is therefore identical to that under normal operation. The only difference is that the magnitude of the stress varies periodically. The duration of the test must therefore be extended so that the cable under test is subjected to the same volt-time exposure as with a constant amplitude line frequency test.

6.4 Test Procedures

6.4.1 Testing with System Voltage (Medium Voltage).

It has been a utility practice for field crews to reclose an overhead circuit after a visual patrol is made of the circuit. The visual patrol is important in order to verify that any damaged equipment has been removed, downed lines have been restored, and feeds from alternate circuits have been disconnected. Fusing used in these operations are normally the size and type that was originally found in the switch.

This practice has been carried over to the underground residential distribution (URD) circuits by the same operating crews that switched the overhead system. URD circuits have been re-energized either by the overhead fuse connection or by the use of a separable connector (elbow). In some cases continual re-closing and sectionalizing have been used to isolate a failure. This practice should be used sparingly since it may be damaging to the underground system. Reclosing in this manner may cause high voltage transients to be generated, and hence subject the circuit to excessive current surges. Both of those conditions may reduce the life and reliability of the underground circuit.

Devices have been developed to eliminate the need to re-energize a faulted underground circuit. With the use of a standard operating tester, a high voltage rectifier, the correct adapters, and an ac system source, a test can be applied to the underground circuit that will indicate whether a circuit is suitable for reenergization. A voltmeter phasing tester, in common use for overhead testing, can be modified to test underground circuits with the application of a high voltage rectifier and proper adapters. The voltmeter indicates the amount of charging current that is on the circuit being tested. Since the underground cable is a good capacitor, an un-faulted circuit would give a high reading when the tester is first connected to the circuit. As the capacitance charges, the reading on the voltmeter will decrease. If the reading fails to decrease, a faulted circuit is indicated.

When any of the above tests is complete, all parts of the circuit should be grounded for four times the time it was being tested and the system made secure. The recommended rate-of-rise and rate-of-decrease of the test voltage is approximately 1 kV per second.

The duration of an acceptance test on a new cable system is normally 15 minutes at specified voltage. Maintenance tests may be 5 to 15 minutes. Any diagnostic tests (such as partial discharge) may be performed during this period. The voltage should be maintained at the specified value to within ±1%

7.0 PARTIAL DISCHARGE TESTING

7.1 Introduction

Partial discharge (PD) measurement is an important method of assessing the quality of the insulation of power cable systems, particularly for extruded insulation materials. A significant advantage of PD is that the site of discharge can be located with considerable accuracy by the use of TDR technology.

This chapter considers partial discharge from two points of view: the measurement of all partial discharges occurring within the cable system and the location of individual partial discharge sites. Keep in mind that partial discharges are high frequency events and are attenuated by changes in impedance in the cable system.

7.2 Measurement of Partial Discharge

Perhaps the most significant factory test made on the insulation of full reels of extruded cable is the partial discharge test. This is usually done at power frequency, but can also be carried out at very low frequency and at some voltage significantly higher than normal working voltage to ground. Experience has shown that this test is a very sensitive method of detecting small imperfections in the insulation such as voids or skips in the insulation shield layer.

It would therefore seem logical to repeat this test on installed cables to detect any damage done during the shipping or laying or any problems created by jointing and terminating the cable. In the past, this has been a difficult measurement to perform in the field due to the presence of other partial discharge signals.

Once the necessary steps are taken to reduce the noise level below the partial discharge level to be measured, the test can provide a great deal of useful diagnostic data. By observing the magnitude and phase of the partial discharge signals and how they vary with increasing and then decreasing test voltage, results will disclose information on the type and position of the defects and their probable effect on cable life.

Noise reduction methods necessary for field tests of partial discharge usually include the use of an independent test voltage source such as a motor-generator, power line and high voltage filters, shielding and sometimes the use of bridge detection circuits.

Partial discharges can also be detected at system voltage with special sensors connected to the splice or termination, using the frequency spectrum of the discharges.

In summary, if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition.

7.3 Test Equipment

Excitation voltages for partial discharge test sets that are commercially available include both 0.1 Hz and line frequencies. Resonant transformers are used for operating frequencies such as 50 and 60 Hz. Both resonant sets and 0.1 Hz sets are relatively small so that they can fit in a van or trailer. A TDR measurement is first applied to determine the length of the circuit, the location of splices, and the condition of the neutral.

7.4 Advantages

- Locates partial discharge sites
- Measures both inception and extinction voltages of discharge

- Voltage application (dwell) time is about 2 seconds after about a 10 second ramp time
- Partial discharges at 1.3 to 2.0 times operating voltage are indicative of a near-term service failure in XLPE or TR-XLPE cables

7.5 Disadvantages

- Partial discharge magnitudes in joints and terminations are much higher than acceptable levels for extruded dielectric cables and have not been correlated with remaining life of accessories
- Cable length limited to about 1 to 2 miles due to attenuation
- Joints limit length of cable that may be tested because of their added attenuation of the signal
- Voltages above $2V_0$ may cause damage to extruded insulations

8.0 DISSIPATION FACTOR TESTING

8.1 Introduction

Periodic testing of service-aged cables is practiced with the desire to determine system degradation and to reduce or eliminate service failures. Dissipation factor testing describes a diagnostic testing technique for field testing of serviceaged shielded cable systems.

8.2 Dielectric Loss

Service-aged, shielded cable can be described by an equivalent circuit as shown in Fig. 17-1. The cable capacitance per unit length, C, is

$$C = 7.354\, \varepsilon / \log_{10}(d_i/d_c) \tag{17.1}$$

where ε=dielectric constant of the insulation

di=the diameter over the insulation

d_c=the diameter under the insulation (over the conductor shield)

If the space between the coaxial conductors is filled with a conventional insulating material, the cable conductance per unit length, G, is

$$G = 2\pi k e_v f C \tan\delta \tag{17.2}$$

The quantity tan δ is used to designate the lossyness of the insulating dielectric in an ac electric field. This is called loss factor or the tangent of the loss angle δ of the material. Typical values of e_v and tan δ are shown in Table 17-1.

For an applied voltage, V, the current through the loss-free dielectric is I_C and the current due to the lossyness of the material is IG, see Fig. 17.2. The angle formed by the current, $I=I_C+I_G$ and the current $I_{C'}$ is δ. The angle formed by the current, $I=I_C+I_G$ and the voltage, V, is q and cos q is the power factor. I, I_C, I_G are phasor quantities.

8.3 Method

The tan δ test is a diagnostic test that allows an evaluation of the cable insulation at operating voltage levels. The test is conducted at operating frequency or at the VLF frequency of 0.1 Hz. When the tan δ measurement exceeds a historically established value for the particular insulation type, the cable is declared defective and will have to be scheduled for replacement. If the tan δ measurements are below an historically established value for a particular insulation type, additional tests have to be performed to determine whether the cable insulation is defective.

Tests conducted on 1,500 miles of XLPE insulated cables have established a figure of merit for XLPE, tan $\delta=4\times10^{-3}$. If the cable's measured tan $\delta>4\times 10^{-3}$, the cable insulation is contaminated by moisture (water trees). The cable may be returned to service, but should be scheduled for replacement as soon as possible. If the cable's measured tan $\delta<10^{-3}$, it is not possible to predict the integrity of the cable insulation. The cable insulation could have many small defects, in which case the cable may operate satisfactorily for many more years. The tan δ should be monitored regularly, and upon further deterioration of the dissipation factor, proper action taken. However, the cable could have only a few isolated large defects, which could cause it to fail upon returning it to service or within days after it has been re-energized. Therefore, if the measured tan $\delta<4\times10^{-3}$, it is recommended that a VLF test at $3V_0$ be performed to identify the large defects, remove and repair them.

8.4 Measurement and Equipment

Bridge type circuits are used to measure cable capacitance and tan δ. The most common are a Schering bridge and transformer ratio arm bridge. Both test sets require an ac HV source and a loss-free capacitor standard. For balanced bridges, the dissipation factor and cable capacitance is:

Schering Bridge $\tan\delta=2\pi f C_1 R_1 \quad (17.3)$

$C_X=C_N R_1/R_2 \quad (17.4)$

Transformer Ratio
Arm Bridge $\tan\delta=2\pi f C_1 R_1 \quad (17.5)$

$C_X=C_N W_1/W_2 \quad (17.6)$

8.5 Advantages

□ Tan δ measurements are diagnostic tests that permit assessment of the state of aging or damage of the cable insulation

□ Cables are tested with an ac voltage at operating voltage levels

□ The tests are performed at operating or at VLF frequencies
□ The tan δ test can be used on extruded as well as on fluid-impregnated paper type insulations
□ When a cable does not pass the tan δ test, it can still be returned to service until repair or replacement has been scheduled
□ Monitoring of the tan δ will establish a cable history and a deterioration can be observed

8.6 Disadvantages

■ When a cable passes the tan δ test, it is not possible to declare the cable insulation sound
■ A VLF or breakdown test will have to be performed to identify any large defects in the cable system insulation

Table 17-1 Typical Values of Dissipation Factor

Type of Insulation	**ε_v**	**10^{-3}×tan δ**
Impregnated paper	3.5	2.3
Impregnated PPP	2.7	0.7
XLPE	2.3	0.1
TR-XLPE	2.3	0.2
HDPE	2.3	0.1
EPR	2.8 to 3.5	3.5

Figure 17-1 Equivalent circuit of a lossy portion of a power cable.

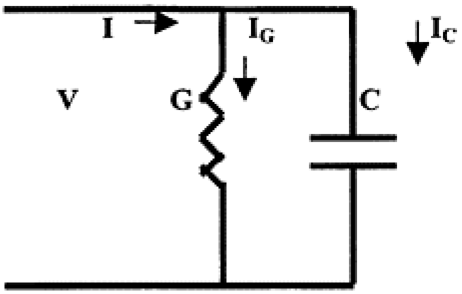
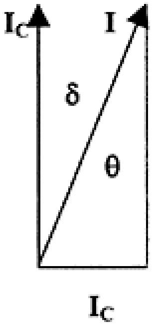


Figure 17-2 Phasor diagram for lossy dielectric.



8.7 Dissipation Factor with VLF Sinusoidal Wave Form

8.7.1 Method.

Bach et al. reported that loss factor (tan δ) measurements at VLF (0.1 Hz sinusoidal) could be used to monitor aging and deterioration of extruded dielectric cables. The 0.1 Hz loss factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of loss factor with 0.1 Hz sinusoidal waveform offers comparative assessment of the aging condition of PE, XLPE, and EPR type insulations. The test results permit differentiating between new, defective, and highly degraded cable insulations. The loss factor with a 0.1 Hz with sinusoidal waveform is a diagnostic test. Cables systems can be tested in preventative maintenance programs and returned to service after testing. The dissiption factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

8.7.2 Measurement Equipment.

A programmable high voltage VLF test generator with loss factor measurement capability is connected to the cable under test. If for a test voltage of V_0 the tan $\delta > 4\times10^{-3}$, the service aged cables should eventually be replaced. The test voltage should not be raised above V_0 in order to prevent insulation breakdown. If for test voltage of V_0 the tan $\delta <<$ than 4×10^{-3}, the service aged cables should additionally tested with VLF at 3 V_0 for 60 minutes. When the cables pass this test, it can be returned to service without reservation. Loss factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

8.7.3 Advantages

□ The test is a non-destructive, diagnostic test

□ Cables are tested with an ac voltage equal to the phase-to-ground voltage at which they operate

□ Cable system insulation can be graded as excellent, defective, or highly deteriorated

□ Cable system insulations can be monitored and history developed. Cable replacement and rejuvenation priority can be planned

□ Test sets are transportable and power requirements are comparable to standard cable fault locating equipment

8.8.4 Disadvantages

- ■ The maximum available test voltage is 36 kV rms and the maximum capacitive load is about 3 μF
- ■ The test works best after comparative cable system data have been developed

9.0 VERY LOW FREQUENCY (VLF, <1 HZ) TESTING

9.1 Introduction

Very low frequency (VLF) testing methods can be categorized as withstand or diagnostic. In withstand testing, insulation defects are caused to break down (fault) at the time of testing. Faults are repaired and the insulation is retested until it passes the withstand test. The withstand test is considered a destructive test. Diagnostic testing allows the identification of the relative condition of degradation of a cable system and establishes, by comparison with figures of merit, if a cable system can or cannot continue operation. Diagnostic testing is considered as non-destructive.

In extreme cases, when the cable system insulation is in an advanced condition of degradation, the diagnostic tests can aggravate the condition of the cable and cause of breakdown before the test can be terminated.

The VLF Withstand Test Methods for Cable Systems are

- VLF Testing with Cosine—Pulse Waveform
- VLF Testing with Sine Waveform
- VLF Testing with Square Wave with Programmable Slew Rate

The VLF Diagnostic Test Methods for Cable Systems are

- VLF Dissipation Factor (tan δ) Measurement
- VLF Partial Discharge Measurement

Field testing techniques frequently employ a combination of diagnostic and withstand test methods. They are selected based on their ease of operation and cost/benefit ratio. The various VLF test methods described are in commercial use and are accepted as alternate test methods in international standards.

9.2 VLF Withstand Testing

EPRI and CEA funded a study to evaluate the advantages and limitations of 0.1 Hz testing as a possible substitute for dc maintenance testing of in-service, aged power cables [17-6]. The use of dc was intended to confirm the soundness of a cable and to weed out weakened cables.

The subject of appropriate methods for fault location and maintenance testing of extruded dielectric distribution cables has been given considerable attention. This interest was generated by the knowledge that transient voltages and dc testing can reduce the life of XLPE and TR-XLPE insulated cables. There is an unanswered question as to the effect on EPR cables, but the concern exists.

The laboratory phase of this work evaluated a wide range of insulations and age of cables. During this laboratory evaluation, various voltages were applied to model cables and service-aged XLPE, 15 kV samples. Similar tests were run of full size EPR, PILC, and transition joints. The results of the study concluded that low frequency ac testing can detect cable imperfections in XLPE cable and transition joints at lower voltages than for a dc test, with none of the detrimental effects of dc.

Once the suitable magnitude and application time of the voltage was determined, field tests were conducted on four utility systems. It was concluded that 0.1 Hz is a satisfactory alternate for dc testing. The shape factor of the 0.1 Hz is the same as the operating system and no damage was found as judged by decrease in magnitude of ac breakdown. If the circuit fails during the test, the lower test voltage reduces the transient voltages that the system must endure.

Procedures were developed for 0.1 Hz testing of 15 kV cable systems at 22 kV for 15 minutes. Other values are suggested for 5 to 35 kV. A large eastern utility has been using this procedure for several years on mixed cable systems and is very satisfied with the results. Absence of long term effects on service aged extruded cables after this test remains to be established.

9.3 VLF Testing with Cosine-Pulse Waveform

9.3.1 Method.

The VLF cable test set generates a 0.1 Hz bipolar pulse wave, which changes polarity sinusoidal. Sinusoidal transitions in the power frequency range initiate a partial discharge at an insulation defect, which the 0.1 Hz pulse wave develops into a breakdown channel. Within minutes, a defect is detected and forced to become a failure. It can then be located with standard, readily available cable fault locating equipment. Cable systems can be tested in preventive maintenance programs or after a service failure. Identified faults can be repaired immediately and no new defects will be initiated during the testing process. When a cable system passes the VLF test, it can be returned to service.

9.3.2 Measurement and Equipment.

A dc test set forms the high voltage source. A dc to ac converter changes the dc voltage to the very low frequency ac test signal. The converter consists of a high voltage choke and a rotating rectifier that changes the polarity of the cable system being tested every five seconds. This generates a 0.1 Hz bipolar wave. A resonance circuit, consisting of a high voltage choke and a capacitor in parallel with the cable capacitance, assures sinusoidal polarity changes in the power frequency range. The use of a resonance circuit to change cable voltage polarity preserves the energy stored in the cable system. Only leakage losses have to be resupplied to the cable system during the negative half of the cycle.

The 0.1 Hz test set is easily integrated in a standard cable fault-locating and cable-testing system by making use of available dc high potential sets. Stand-alone VLF systems should be supplemented by cable fault locating equipment.

The cable system to be tested is connected to the VLF test set. In five to six steps, the test voltage is regulated to the test voltage level of 3 V_0 (V_0 is phase to ground voltage). The recommended testing time is 15 to 60 minutes. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the cable and test set are discharged and grounded. When a cable fails the test, the VLF test set is turned off to discharge the system. The fault can then be located with standard cable fault locating equipment.

9.3.3 Advantages

- The VLF test uses a 0.1 Hz pulse wave that changes polarity sinusoidal. The sinusoidal transitions in the power frequency range may initiate a partial discharge at a defect that the 0.1 Hz pulse wave may develop into a breakthrough channel
- Due to sinusoidal transitions between the HV pulses, traveling waves are not generated
- Due to continuous polarity changes, dangerous space charges cannot develop. Cables can be tested with an ac voltage up to three times the conductor to ground voltage with a device comparable in size, weight, and power requirements to a dc test set
- The VLF test can be used on extruded as well as oil impregnated paper insulations
- The VLF test with cosine-pulse waveform works best when eliminating a few singular defects from an otherwise good cable insulation. The VLF test is used to “fault” the cable defects without jeopardizing the cable system integrity
- When a cable passes the recommended 0.1 Hz VLF test, it can be returned to service

9.3.4 Disadvantages

- When testing cables with extensive water tree damage or ionization of the insulation, VLF testing alone is often “not conclusive.” Additional tests that measure the extent of insulation losses will be necessary
- Present limitations are the maximum available test voltage of 56 kV

9.4 VLF Testing with Sinusoidal Waveform

9.4.1 Method.

The VLF test set generates sinusoidal changing waves that are less than 1 Hz. When the local field strength at a cable defect exceeds the dielectric strength of the insulation, partial discharge starts. The local field strength is a function of applied test voltage, defect geometry, and space charge. After initiation of partial discharge, the partial discharge channels develop into breakthrough channels within the recommended testing time. When a defect is forced to break through, it can then be located with standard, readily available fault locating equipment. Cable systems can be tested in preventative maintenance programs of after failure. Identified faults can be repaired immediately. When a cable passes the VLF test, it can be returned to service.

9.4.2 Measurement and Equipment.

The VLF test set is connected to the cable or cable system to be tested. The test voltage is regulated to the test voltage level of 3 V_0. The recommended testing time is 60 minutes or less that can be found in VLF testing guides. VLF sets have to have sufficient capacity to be able to supply and dissipate the total cable system charging energy. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the test set and cable system are discharged and grounded. When a cable fails the test, the VLF test is turned off to discharge the cable system and test set and the cable fault can then be located with standard cable fault locating equipment.

In addition to standard 0.1 Hz sinusoidal very low frequency test sets, which have been in use for many years for VLF testing of electrical machines, several variations are also available to meet specific cable system test requirements:

(1) VLF, less than 0.1 Hz, high-voltage generator with programmable test voltage waveforms for cable systems with mixed insulation:

- Sine wave test voltage.
- Bipolar pulse wave with defined slew rate.
- Regulated dc test voltage with positive and negative polarity.
- Programmable step test for all voltage waveforms.

(2) VLF, 0.1 Hz, high voltage generator with dissipation factor (tan δ measurement capability.
(3) Partial discharge free, VLF, 0.1 Hz high voltage generator for partial discharge testing.
(4) Partial discharge free, VLF, bi-polar pulse with defined slew rate, high voltage generator for partial discharge testing.

9.4.3 Advantages

□ Cables are tested with an ac voltage up to three times the conductor to ground voltage. After initiation of a partial discharge, a breakthrough channel at a cable defect develops
□ Due to continuous polarity changes, dangerous space charges do not develop in the cable insulation.
□ Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.
□ The VLF test can be used on extruded as well as paper type cable insulations. The VLF test with sinusoidal waveform works best when eliminating a few defects from an otherwise good cable insulation. The VLF test is used to “fault” the cable defects

without jeopardizing the cable system integrity. When a cable passes the recommended 0.1 Hz VLF test, it can be returned to service.

□ VLF test sets with 0.1 Hz loss factor measurement capability for diagnostically identifying cables with highly degraded cable insulations are available and can be used with a 0.1 Hz withstand test.

9.4.4 Disadvantages

■ When testing cables with extensive water tree damage or ionization of the insulation, VLF withstand testing alone is often “not conclusive.” Additional tests that measure the extent of insulation losses will be necessary.

■ Limitations are the maximum available test voltage of 36 kV rms and the maximum capacitive load of approximately 3 µF at 0.1 Hz (30 µF at 0.01 Hz). The total charging energy of the cable has to be supplied and dissipated by the test in every electrical period. This limits the size of the cable system that can be tested. A long testing time must be seen as an inconvenience rather than a limitation.

9.5 Tan Delta Test with VLF Sinusoidal Waveform

9.5.1 Method.

Bahder et al. first used dissipation factor (tan δ) measurements to monitor aging and deterioration of extruded dielectric cables. Bach, et al., reported a correlation between an increasing 0.1 Hz dissipation factor and a decreasing insulation breakdown voltage level at power frequency. The 0.1 Hz loss factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of the loss factor with a 0.1 Hz sinusoidal waveform offers comparative assessment of the aging of PE, XLPE, and EPR type insulations. The test results permit differentiation between new, defective, and highly degraded cable insulations. The loss factor with a 0.1 Hz sinusoidal waveform can be used as a diagnostic test. Cables can be tested in preventative maintenance programs and returned to service after testing. The loss factor measurements at VLF can be used to justify cable replacement or cable rejuvenation expenditures.

9.5.2 Measurement and Equipment

A programmable, high voltage VLF, 0.1 Hz test generator with dissipation factor measurement capability is connected to the cable system under test. The dissipation factors of tan δ at V_0, tan δ at 2 V_0, and the differential loss factor A tan δ (tan δ at 2 V_0 minus tan δ at V_0) are measured. The measured values are used as figures of merit to grade the condition of the cable insulation as good, defective, or highly deteriorated.

For example, XLPE insulation is tested at a 0.1 Hz test voltage of V_0 and the tan δ $>2\times10^{-3}$, the service aged cables should be replaced. The test voltage should not be raised above V_0 in order to prevent an insulation breakdown. If for a 0.1 Hz test voltage of V_0, and the $\tan\delta >> 1.2\times10^{-3}$, the service aged cables should additionally be tested with VLF $3\times V_0$ for 60 minutes. When cable passes this test, it can be returned to service.

If for a 0.1 Hz test voltage at V_0 and 2 V_0, the loss factors are $1.2\times10^{-3} < \tan\delta < 2\times10^{-3}$ and the differential loss factor A $\tan\delta < 0.6$, the cable should be returned to service but monitored semi-annually.

If for a 0.1 Hz test voltage at V_0 and 2 V_0, the loss factors are $1.2\times10^{-3} < \tan\delta < 2\times10^{-3}$ and the $\Delta \tan\delta > 1.0$, the cable should be replaced.

It must be understood that, for different insulations, installations, and cable types, tan δ figures of merit can vary significantly from the values listed above. The test gives the best results when comparing present measurements against established historical figures of merit for a particular cable.

9.5.3 Advantages

□ This test is a diagnostic, non-destructive test. Cable systems are tested with an ac voltage equal to the conductor to ground voltage.

□ Cable system insulation can be graded between good, defective, and highly deteriorated.

□ Cable system insulation condition can be monitored over time and a cable system history developed. Cable replacement and cable rejuvenation priority and expenditures can be planned.

□ Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

9.5.4 Disadvantages

■ For a 0.1 Hz VLF test set, the maximum available test voltage is 36 kV rms and the maximum capacitive load in approximately 3 μF.

■ The test becomes useful after historical comparative cable system data have been accumulated.

The suitability, practicality, and effectiveness of these testing methods for service aged power cables with extruded dielectric insulation will have to be determined based on several criteria:

It is known that dc testing of extruded dielectric insulated cables is not very useful. In fact, it may cause cables to fail after having been returned to service. At this time, VLF test techniques are effective alternates for testing of service aged power cables with extruded dielectric insulation.

10.0 OSCILLATING WAVE TESTING

10.1 Introduction

Oscillating wave testing was selected by a CIGRE task force “alternative tests after laying” as an acceptable compromise using the following criteria:

- The ability to detect defects in the insulation that will be detrimental to the cable system under service conditions, without creating new defects or causing any aging.
- The degree of conformity between the results of tests and the results of 50 or 60 Hz tests.
- The complexity of the testing method.
- The commercial availability and costs of the testing equipment.

The purpose of the oscillating wave (OSW) testing method is to detect defects that may cause failures during service life without creating new defects that may threaten the life of the cable system.

Although OSW testing does not have a wide reputation with respect to cable testing, it is already used for testing in metal-clad substations and is being recommended for CGI cable testing.

10.2 General Description of Test Method

The test circuit consists basically of a dc voltage supply, which charges a capacitance C_1, and a cable capacitance C_2. After the test voltage has been reached, the capacitance is discharged over an air coil with a low inductance. This causes an oscillating voltage in the kHz range. The choice of C_1 and L depends on the value of C_2 to obtain a frequency between 1 and 10 kHz.

10.3 Advantages

□ The OW method is based on an intrinsic ac mechanism.
□ The principal disadvantages of dc (field distribution, space charge) do not occur.
□ The method is easy to apply.
□ The method is relatively inexpensive.

10.4 Disadvantages

■ Effectiveness of the OSW test method in detecting defects is better than with dc but worse when compared with ac (60Hz)
■ In particular for medium voltage cable systems, the factor f* OSW/60 Hz voltage is approaching 1, indicating the mutual equivalence
■ For HV cable systems f* OSW/60 Hz is significantly higher (1.2 to 1.9) which means that OSW is less effective than 60 Hz
■ For both HV and MV cable systems, f* OSW/dc is low (0.2 to 0.8) indicating the superiority of OSW over dc voltage testing
■ Since the capacitance of a cable is dependent on length, each length of otherwise identical cable, for instance, oscillates at a different frequency. This difference is frequency creates a change in measured properties

{*Note:* f* OSW/60 Hz is the ratio of breakdown values for a dielectric containing a standard defect when using respectively OSW voltage and 60 Hz voltage.}

10.5 Test Apparatus

The cable is charged with a dc voltage and discharged through a sphere gap into an inductance of appropriate value so as to obtain the desired frequency. The voltage applied to the cable is expressed by:

$$V(t) = V_1 e^{-\alpha t / \sqrt{LC}} \cos 2\pi f t \qquad (17.7)$$

where V_1=charging voltage provided by the generator
α=damping ratio
$C=C_1+C_2$
$f = 1/2\pi\sqrt{LC}$

Other test circuits are possible and give alternative solutions using different circuit configurations.

10.6 Test Procedure

Many tests carried out so far are of an experimental nature. Artificial defects like knife cuts, wrong positions of joints and holes in the insulation were created and subjected to different testing procedures of which one method was the OSW testing method.

These test procedures were intended to obtain breakdown as a criterion for comparison. The general testing procedure is as follows:

- Start to charge the cable with a dc voltage of about 1 or 2 times operating voltage.
- Increase with steps of 20 to 30 kV.
- Produce 50 shots at each voltage level.
- Time interval between shots 2 to 3 minutes.
- Proceed until breakdown occurs.

In one case, the Dutch testing specification for HV extruded cables, the OSW method is mentioned as a withstand test to be used as an after laying (installation) test. The test procedure is as follows:

- Charge the cable slowly, using the dc power supply.
- After reaching the value of 3 V_0, the dc source will be disconnected and the rapid closer activated.
- The cable circuit will be discharged through a reactor, causing the OSW testing voltage.
- This procedure should be repeated 50 times.

In the Netherlands the OSW testing method is applied several times as an after laying test for HV extruded cable systems.

10.7 Further Development Work

Since the effectiveness of the OSW testing method is not as high as would be desired, it might be very attractive to combine OSW with partial discharge (PD) site detection as an additional source of information. In the literature, details are given of an automatic PD measurement system, enabling statistical analysis and generating phase, time and amplitude resolved PD fingerprints. Compared to ac 50/60 Hz generated PD fingerprints, additional information results from the decreasing voltage amplitude of each OSW pulse. For medium voltage cable systems according to [17-9], this measuring system looks feasible.

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CHAPTER 18
TREEING

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1.0 INTRODUCTION

Treeing in extruded dielectric cable insulation is the term that has been given to a type of electrical pre-breakdown deterioration that has the general appearance of a tree-like path through the wall of insulation. This formation is radial to the cable axis and hence is in line with the electrical field.

Trees form in insulations such as polyethylene, cross-linked polyethylene, and ethylene propylene rubber cables and are considered as two distinct types:

☐ Water trees (also known as electro-chemical trees)
☐ Electrical trees

They are differentiated by the distinctions shown below and other parameters that will be discussed more fully later in this Chapter:

Water Trees

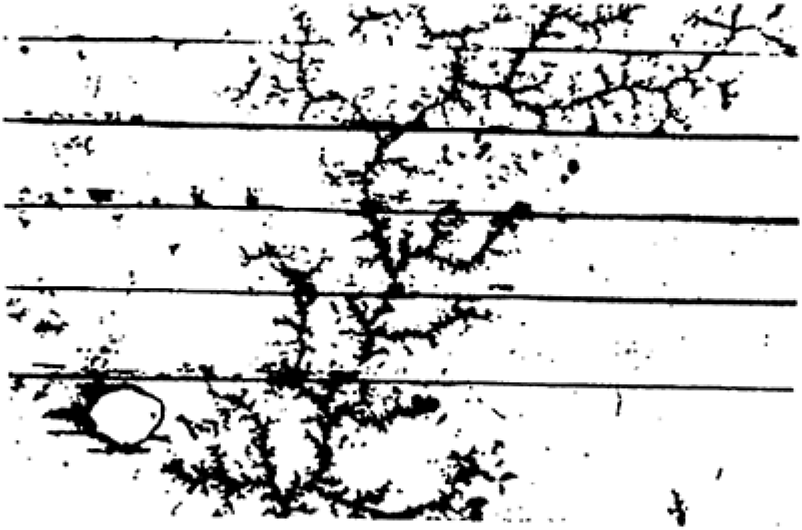
- Diffuse, indistinct small voids separated by somewhat deteriorated insulation
- Moisture is required
- Slow growth (months, years)
- Must be stained to see them. This may be from chemicals in or around the cable or be stained while the cable is examined
- May exist without immediate electrical failure

Electrical Trees

- Distinct hollow channels
- Water not required
- Rapid growth (seconds, minutes, hours)
- Electrical failure occurs very quickly

2.0 BACKGROUND

The phenomenon known as treeing in dielectrics was first described by Raymer in 1912 [18-1]. He had been investigating electrical breakdown in the presence of discharges in paper-insulated cables. The tree-like appearance of Lichtenberg figures was well known during the 1920s. These "trees" are totally different from what is seen in extruded dielectric cables because those older trees were carbon paths burned into the paper insulation that proceed concentrically around the insulating wall. In the photograph below, six adjacent tapes are shown together.



Treeing in extruded dielectric cables was described by Whitehead [18-2] in 1932 in his work on electrical breakdown. The development of corona detection equipment in 1933 by Tykociner, Brown, and Paine [18-3] made quantitative studies possible. Kreuger [18-4] thoroughly described methods for detection and measurement of discharges in 1965.

The announcements by Vahlstrom and Lawson [18-5 and 6] in 1971 and 1972 that direct buried HMWPE cables installed in the field in URD systems contained water trees made a significant impact on the cable industry. This was the first time that this type of treeing had been reported in a typical utility environment. Previously reported results, especially by the Japanese [18-7] that they called sulfide trees, now became required reading.

Up until that time, mechanical damage was considered to be the predominant mechanism of failure for cables in a utility installation. The remaining 10% were thought to be due to unknown causes that were not necessarily due to electrical deterioration in the cable.

3.0 WATER TREES

Water (also called electro-chemical or chemical) trees form at a slow rate that may take many years to propagate and grow. Water trees can occur in all solid (extruded) dielectric materials. The tree like appearance can be described by reference to many natural shapes that are sometimes obvious upon cutting wafers from aged cables. Examples are shown later in this chapter.

The visibility of water trees stems from the staining of the interior of the tree wall by some form of chemical staining. Non-stained water trees disappear when the sample is dried. Staining techniques are discussed later in this Chapter.

Water treeing is influenced by the following:

Moisture (an essential ingredient!)

Voltage stress

Voids

Contaminants

Ionic impurities

Temperature

Temperature gradient

Aging time

PH

3.1 Mechanisms of Water Treeing

There are three stages in the development of water trees in extruded insulation:

☐ Inception
☐ Propagation
☐ Conversion/Electrical Breakdown

3.1.1 Treeing Mechanisms.

Laboratory investigation of water tree inception has demonstrated that several probable mechanisms are involved:

a) Voltage stress concentration at a very small void or contaminant can be orders of magnitude higher than the average electrical stress at that location. Although very sensitive measuring equipment has been utilized (about 0.05 pC sensitivity), no partial discharge has been detected during this stage of inception or growth. Electron bombardment in such a cavity is capable of erosion of the dielectric in the cavity.

b) Mechanical stress can be produced by very high electrical fields around an electrical stress concentration. This may result in fatigue and the development of stress cracks in the dielectric. Partial discharges in such cracks may lead to local electrical breakdown and tree formation.

c) Electron bombardment can be sufficiently high to cause a cavity to form due to ionization of the dielectric that causes chain scission and decomposition.
d) Local intrinsic breakdown of the dielectric.

None of these, by itself, can explain the results of laboratory studies, so it is probable that initiation of a water tree involves more than one mechanism. The effect of high electrical stress is universally accepted, however.

3.1.2 Treeing Propagation.

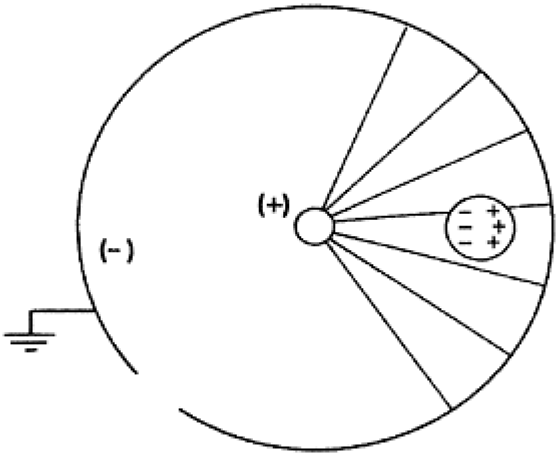
Propagation or growth of water trees seems as illusive as inception. Only the presence of an ac electrical field seems to be a unifying conclusion. Although dc can produce water trees, it is at a much slower rate and with a different shape. It is well established that polymers are readily permeable by moisture and that the presence of moisture in these insulations is deleterious.

Two significant forces to explain the penetration of moisture through extruded dielectrics are:

(1) Electrophoresis is a term used to describe the movement of charged particles in an electric field. Particles with a positive charge tend to move toward a negative electrode while negative ions tend to move toward the positive electrode. A practical application of this theory, when dc testing a cable, is to place the negative charge on the conductor. This pulls moisture in towards the center of the cable and makes the test more definitive.

(2) Dielctrophoresis describes the movement of uncharged but polarized particles or molecules in a divergent field. In the example of an otherwise uniform single conductor electrical cable, the field increases as a particle or molecule gets closer to the conductor. An uncharged particle will be polarized at any given point in time so that it will have a negatively charged dipole with its negative side, for instance, toward the conductor that is positive at that instant. Since the negative side of this dipole exists in a stronger field than the positive side, the particle will be attracted toward the field of greatest field intensity. In an alternating current system, as the conductor becomes negatively charged, the polarization process is reversed. This means that the particle is still attracted toward the conductor with its higher electric field.

Figure 18-1 Dielectrophoresis



The practical effect of dielectrophoresis is that moisture will be drawn to the higher dielectric field regions even in an alternating field. This high stress point is likely to be a small void that is a portion of the initial tree formation. The void that was initially filled with gas now becomes water filled. While this does not fully explain the formation of the water tree, it does shed some light on the growth of such trees and the dispersion of moisture in an energized cable.

Water tree growth is a slow mechanism of deterioration in extruded dielectrics when exposed to both moisture and voltage stress. They initiate from sites that create high electrical stress such as voids, contaminants, protrusions, and loose or rough shields. Such trees may grow from either shield and are known as vented trees. These are often known as fans, broccoli, etc. When water trees grow from imbedded voids or contaminants, they are often called bow ties and are usually not vented to the atmosphere.

Water trees have fine structures when seen with low magnification. Under high power magnification, they may be seen as discreet ellipsoids that basically line up with the electrical field. The insulation between these ellipsoids may be somewhat deteriorated through oxidation or other means, but remain as adequate electrical insulation—but may be sites for electron entrapment. (More on this later.)

In contrast to electrical trees, water trees are characterized by:

1. Slow growth. They may grow for many years before they contribute to breakdown.
2. Water trees are initiated and grow at much lower electric fields than do electrical trees.
3. The can be so large that they extend from shield to shield without resulting in breakdown.
4. Some moisture is required.
5. Temperatures above 70°F accelerate tree growth.
6. If partial discharge is present, we are not able to detect it at this time.
7. They disappear when allowed to dry unless stained. They reappear when placed in boiled water.

3.1.3 Examples of Water Trees.

Some examples of water trees are shown below along with the names that describe their shape.

Figure 18-2 Vented fan trees growing from high electrical stress points in a HMWPE cable with taped strand shielding and a taining antioxidant.

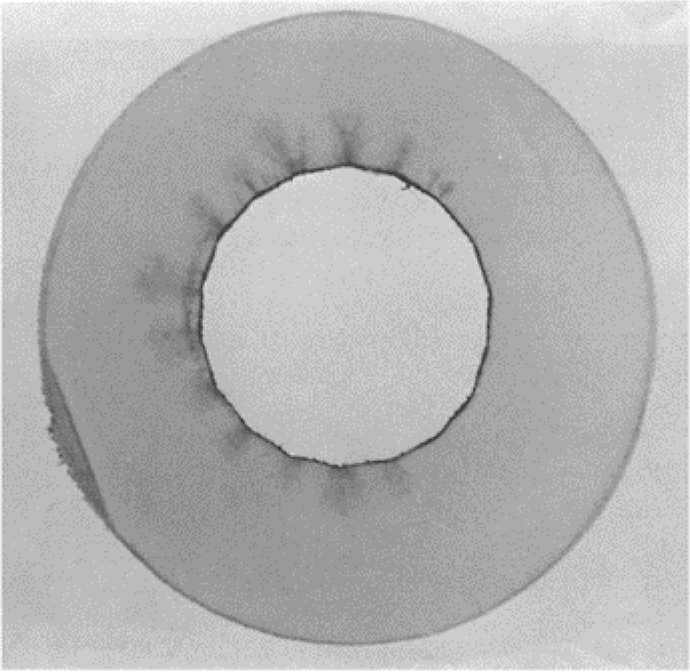


Figure 18-3 Vented water trees growing from a loose extruded strand shield in a 175-mill wall of cross-linked polythylene cable. (Note the halo that was formed during the steam curing of this 15 kV cable.)

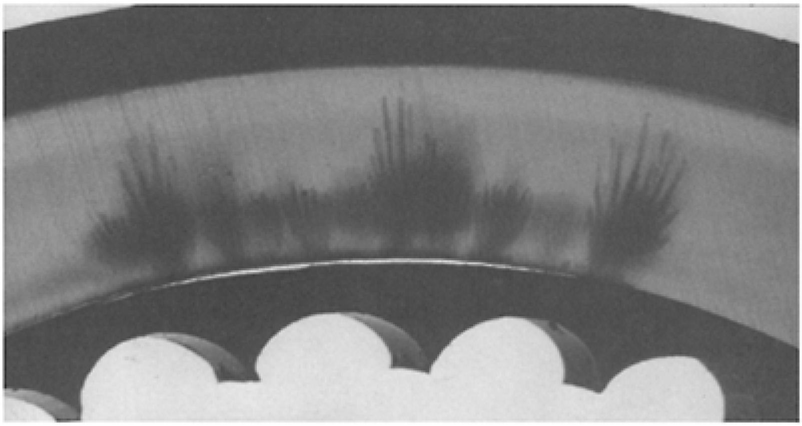


Figure 18-4 Water trees growing from taped insulation shield.

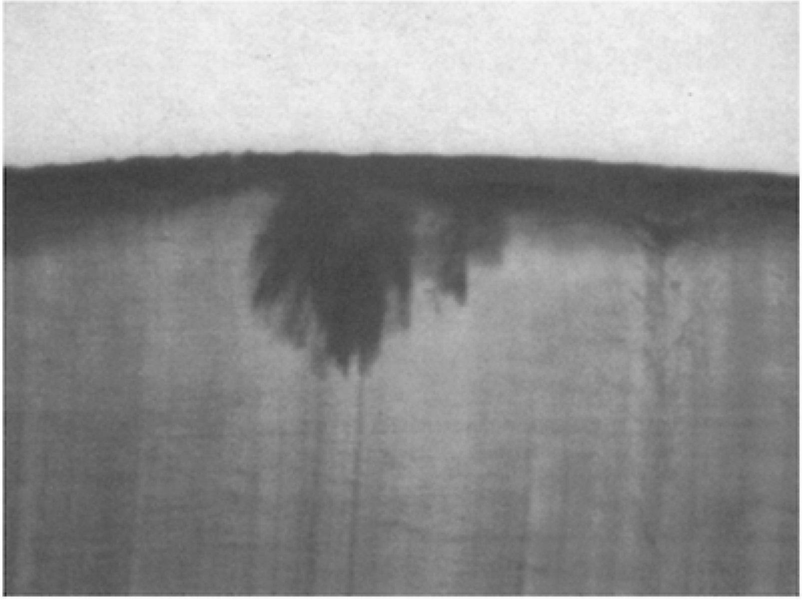


Figure 18-5 Two large water tress across a 220-mil HMWPE cable made with staining antioxidant. (Note that there is no electrical failure showing that even these water trees are capable of holding line voltage.)

3.1.4 Methods to Minimize Water Treeing

The most effective, if not economic, method to avoid the formation of water trees is to keep the insulation absolutely dry. This can be accomplished with an impervious metallic sheath such as lead, copper, or aluminum. Cables with these sheaths have been in service for over 40 years with no known deterioration. Of course, the problem is to keep the metal from corroding or being damaged mechanically. (This concern also applies to paper-insulated cables!)

Other possible deterrents to water tree formation include:

1. Smooth electrical interfaces at the shields, especially at the conductor shield where the electrical stresses are the highest.
2. Tightly bonded insulation shields that must be removed mechanically.

3. Semiconducting compounds with small amounts of ionic impurities. It has been shown that ions from the shields are concentrated at water tree sites in the insulation.
4. Solid conductors.
5. Strand blocking.
6. Internal pressure, such as nitrogen, to keep out moisture.
7. Reduction or elimination of voids and contaminants.

3.1 Introduction to Accelerated Testing

Over the years, there has been tremendous effort given to understanding water trees because of their influence on the life of extruded dielectric cables with the subsequent loss of life. Tests in laboratories can be separated into several methods:

1. Electrical properties of material specimens.
2. Miniature cable evaluations.
3. Typical full sized cables—usually 1/0 AWG, 175-mil wall cable.
4. Actual cable construction being considered.

The testing of specimens

(1) Testing of samples is the least expensive and is best suited for screening purposes. Here there are no complicating problems of extrusion and other manufacturing conditions.
(2) Miniature cables are the least expensive way to introduce the manufacturing and processing concerns, but have not shown to be in good correlation with full sized cables
(3) The 1/0 AWG, 175-mil cable has become the most commonly used full sized cable because it is a very common size among the utilities in North America and because it has modest cost to produce. Manufacturing and processing are factored into the results. These tests are still very costly with a typical AEIC Qualification Test requiring $50,000 or more and 12 months to accomplish.
(4) Tests on the actual cable under consideration are even more costly than that for the 1/0 cable described above.

4.0 ELECTRICAL TREES

Electrical trees in extruded dielectric cables are the result of internal electrical discharges that decompose the organic materials. No moisture is needed for this process. Over voltages are required and may occur because of imperfections in the structure that cause high, localized electrical stress. Stress enhancement calculations from the tip of a sharp conductive electrode having a radius of 2.5 microns vary from 240 to 480 times the average stress at that point [18-8].

Since a typical distribution cable has an average stress of about 35 volts per mil, the resultant stress level is considerable. Other over voltage situations include lightning strokes, switching surges, and test voltages.

Several mechanisms have been proposed to explain the initiation of electrical trees. Each requires a very high electrical stress to attain the energy level that would be required. Below are some of the possibilities:

1. Localized heating and thermal decomposition
2. Mechanical damage due to high electrical stress
3. Fatigue cracking from polarity changes
4. Small voids
5. Air inclusions around contaminants
6. Electron injection.

Partial discharges that decompose the organic material in insulations are generally considered the common factor in the formation of electrical trees. The intrinsic electrical strength of the commonly used material is many times higher than the electrical stresses that are encountered in actual service. How can these excellent materials fail at such low stresses? The presence of internal voids, contaminants and external stress points leads to electrical stress enhancements that are sufficiently high to originate water trees.

Impulses, surges, and dc stresses seem to create hollow channels through the insulation that we know as electrical trees. When seen in wafers, electrical trees are distinct and opaque. They usually do not have to be stained to see them, but staining is certainly a recommended practice. Electrical trees require high stress but not water, and they grow relatively fast—minutes to hours. Examples of electrical trees are shown below.

Figure 18-6 Bow tie growing from a contaminant (hence non-vented).

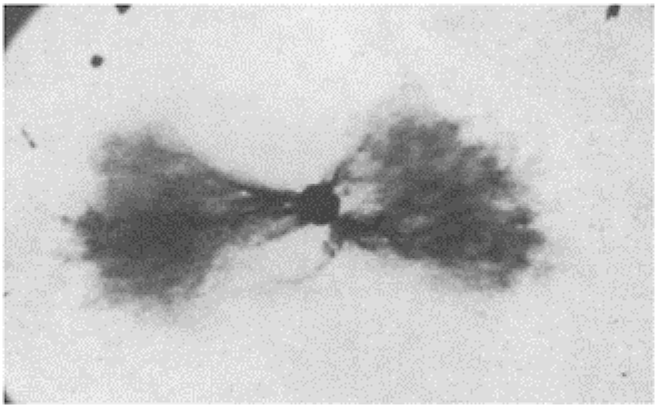


Figure 18-7 Bush tree growing from a shield (hence vented).

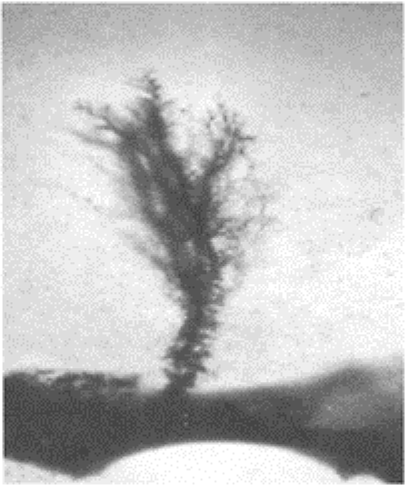
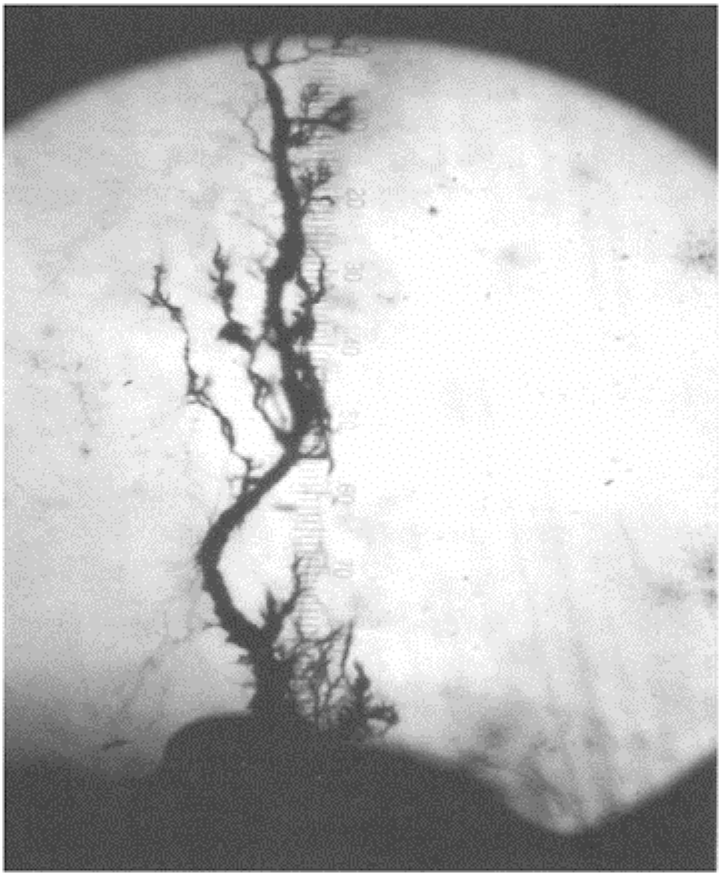


Figure 18-8 Electrical tree growing from a contaminant on conductor shield.



5.0 COMBINATIONS OF ELECTRICAL AND WATER TREES

“Under certain conditions, combinations of electrical and electrochemical trees can occur” said John Densley in his 1979 paper [18-11]. Over twenty years have passed and yet this combination seems to have been overlooked by many people in their attempt to have only two categories of trees in extruded dielectrics.

The fact is that field samples have shown this condition for an equal number of years. They generally appear as a water trees with small sections of dark, obvious electrical trees in the branch. Another form of this condition is found when installed cables are tested after service aging using diagnostic testing procedures. Wafers show the presence of a large, vented water tree with an electrical tree growing from the leading edge.

The importance of these observations is that they are most likely show the transition of water trees (benign as they may be) to partial electrical trees—where the end of life of the cable is at hand. This may explain why water trees are deleterious to extruded dielectric cables.

One concept of the mechanism where water trees are converted to sections having electrical trees is referred to as trapped space charges. Electrons with high energy levels are used to crosslink polyethylene in what is called radiation curing. Crosslinkable polyethylene is applied to a conductor, the conductor is grounded, and electrons are beamed through the dielectric with sufficient energy that they reach the conductor.

If the energy level is not high enough to penetrate the entire wall, electrons may be trapped in the insulation. Likely sites for such trapping are oxidized material (such as are found in water trees in service aged cables). In new cable, these trapped electrons can stay in a dormant condition for months. The mechanical effects of installation or increase in temperature can give these electrons sufficient energy to start moving. As the move toward the metallic member (conductor or shield), these electrons drill a channel through the insulation. This is not called an electrical tree, but it has many of the same characteristics. If the electron is trapped near the conductor for instance, the channel only extends from the site to the conductor—not both directions.

Trapped charges can affect installed cables. A high-energy lightning stroke can deposit electrons at sites in the insulation wall—just as described above. Again, these electrons may stay dormant until some additional energy is applied such as temperature increase. When the energy level is sufficiently high, the electron will move. Its travel may be to one of the metallic components or merely to one of the adjacent sites such as a void. The result of this action is to breech a portion of the good insulating wall. Another lightning stroke may do additional damage or the owner might use high-energy direct voltage or capacitor discharge equipment on the cable. All of these sources can provide electron entrapment with subsequent additional deterioration of the insulating wall.

It is very important to know that water trees can be the sites for the trapped charges. This means that after being in service for a period of time, cables having water trees are more prone to trapped charges because the sites for this entrapment have been developed. These sites may be in the microvoids or in the somewhat deteriorated insulation between those microvoids.

These combination water and electrical trees have also been seen on service aged cables that have been tested with modestly elevated voltages during diagnostic evaluations. A partial discharge site may be located with or without a failure in the field. A typical wafer examination of this area shows extensive water treeing patterns but one will have an electrical tree growing from the water tree. The opinion is that a partial discharge test will locate a water tree but during the test an electrical tree will begin to grow and hence be detected by the test.

Figure 18-9 shows a tree site with both water and electrical trees. Note that there is one water tree from a shield at the left of the picture and that the electrical tree has grown from the same site as the earlier water tree.

Figure 18-9 Combination water and electrical tree. (Photo courtesy of KEMA.)

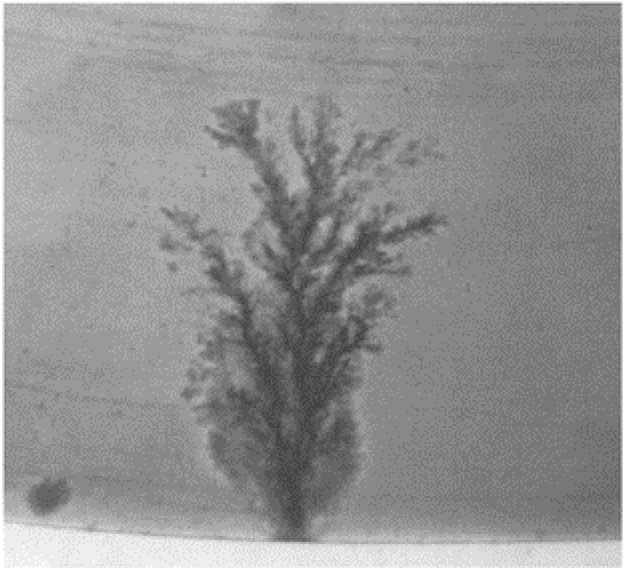


Figure 18-10 Another combination water and electrical tree.

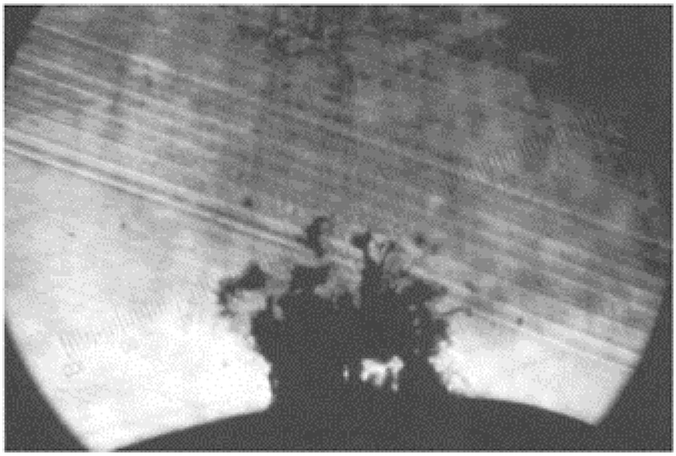
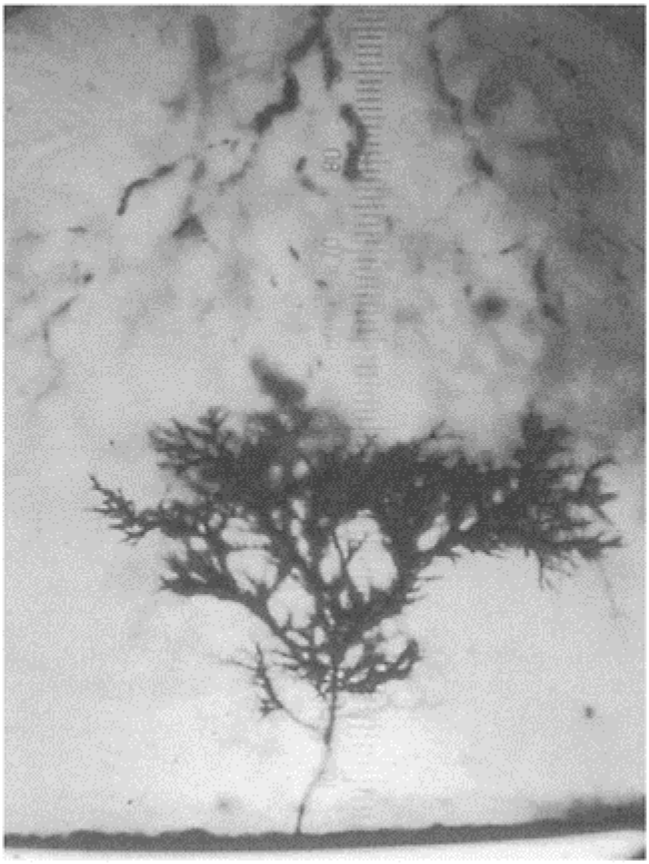


Figure 18-11 Another combination of electrical and water trees at the same site. Note that the water tree has

burned sections indicating the transition from water to an electrical tree.



An example of a field failure pattern may help illustrate this phenomenon. Service failures of extruded dielectric cables peak during lightning seasons, but even with the sophisticated lightning counter facilities now available, the actual field failure seldom occurs just as the lightning strikes in the vicinity of the cable. The failure is delayed by days or weeks, but the failure location and the lightning strike point are very close. It seems highly likely that the lightning strike converted a water treed area to a partial electrical tree that continued to grow until the insulation was no longer capable of serving its function under normal operating voltage.

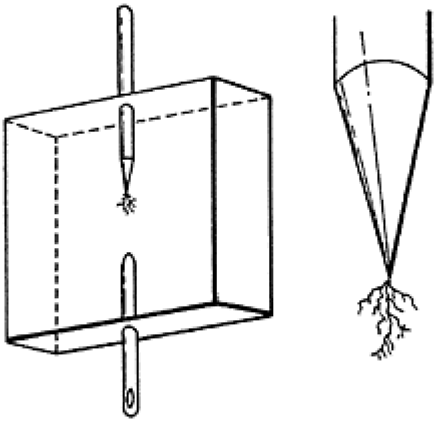
Conversion of a water tree to an electrical tree seems to be an important factor. This occurs by the formation of an electrical tree from the tip of a water tree as well as inside a water tree where a portion of the “branch” is an electrical tree that has not progressed sufficiently that it has caused complete electrical breakdown. This conversion can certainly be accelerated by the effect of trapped charges.

6.0 LABORATORY TESTING

Treeing was considered to be a laboratory “trick” until the 1970s. Some of the earliest work was done by Simplex Wire & Cable. Kitchens, Pratt, Ware, Crowdes, and others reported on work done with one needle embedded in small slabs of polyethylene beginning in 1956. From this work, they developed the first commercial tree retardant HMWPE insulation. They reported in 1958 that moisture was an inhibitor to tree growth. What was not known at that time was that they were looking only at electrical trees. They confidently predicted in 1958 that “HMWPE may last more than 40 years in water at operating stress up to 45 volts per mil.” They were not aware of the existence of water trees as we now understand them nor did they repeat that statement made in that first paper that “…at the end of 40 years, half the lengths of cable will have failed.”

Other researchers in that same time period began using two embedded needles. See Figure 18-12 for the test geometry of a double needle test. The “standard defect” consists of a specially sharpened sewing needle that is inserted into one of the small faces of a block of compression molded plastic that is 1”×1”× 0.25” and the point of the sharpened needle is 0.5” away from an ordinary (dull) needle. These needles are inserted under carefully controlled annealing conditions. McMahon and Perkins came up with similar conclusions and reported in 1960 that “corona life of a specimen of HMWPE in air is a strong function of humidity. A relative humidity of 95 to 100% gives approximately 15 times longer life than dry air.” They were also only looking at electrical trees.

Figure 18-12 Double needle test specimen.



After the reported findings of Lawson and Vahlstrom [18-5 and 6] and the Japanese reports in 1972 of “sulfide trees” [18-7] in cables removed from the field, laboratory work moved towards wet testing of insulating materials such as the test developed by McMahon and Perkins. Specimen testing for water treeing is generally done in this “pie plate.” This is a compression molded, dish-shaped specimen that has 24 conical depressions molded into the bottom—see Figure 18-13. The specimen dish is placed into a grounded bath that contains an electrolyte—usually made by placing 0.01 N NaCl in distilled water. A platinum wire connects a power supply to the upper portion of the dish. From 2 to 8 kV ac is applied. A LDPE specimen will develop water trees at the tips of the cones from 120 to 240 µm in length in 24 hours at 5 kV. The length of these water trees is then measured.

Figure 18-13 Water tree test specimen—“pie plate.”

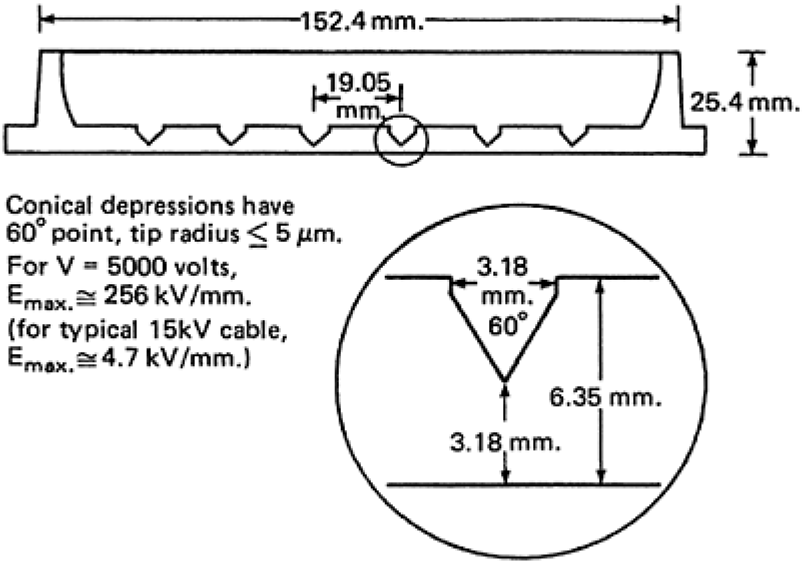
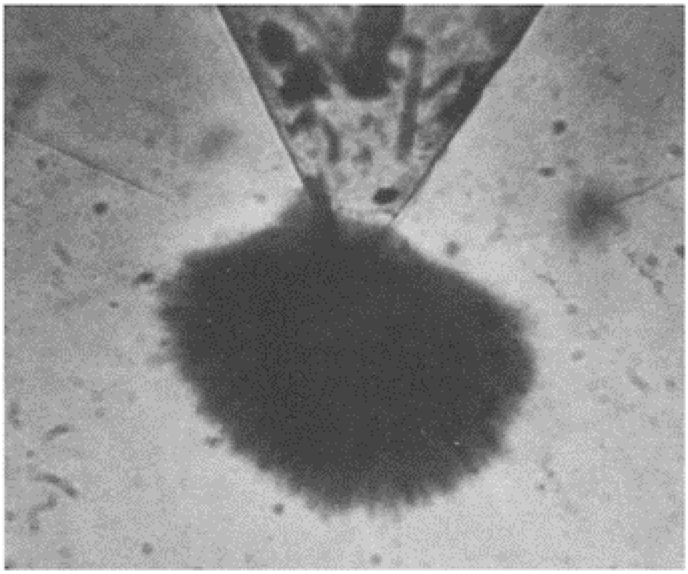


Figure 18-14 is a photograph of a water tree growing from one of the indents in a pie plate.

By 1975, AEIC had developed an accelerated water-treeing test (AWTT) on actual full sized cable samples placed in water filled pipes. This test is part of the qualification testing requirement to meet AEIC specifications.

Figure 18-14 Water tree from a pie plate indent. (Photo courtesy of Union Carbide.)



Tank tests were developed at the Marshall, Texas, facility of Alcoa by Lyle and Kirkland in 1981 [18-9]. Testing in tanks has continued for more than 20 years at that facility even with all of the changes in names that have occurred!

The test protocol is based on samples of full sized cables are formed into coils and placed in tanks filled with water. Water is also kept in the strands of the 30-foot long cable samples. Voltage is kept on continuously while the current is on for eight hours every day. Twelve samples are kept energized until one fails. That failed sample is replaced with a dummy cable while the remaining active samples are energized until the next one fails. After eight of the twelve samples, have failed, the remaining four samples are broken down with ac step-rise voltage application.

In the original work, nine different voltage stress/temperature combinations were applied: 60, 75 and 90°C; 2, 3, and 4 times rated voltage to ground. The results of these nine conditions are mathematically analyzed to obtain a model of a life curve that is used to demonstrate life at other stress/voltage levels such as would be found in typical operation.

This time-to-failure accelerated laboratory aging information that is developed is used to predict the life of that cable construction and processing. In this manner, other insulations, stress relief materials, and constructions can be compared directly. The significant advantage of the method is that twelve samples gives a much higher confidence level in the results than a smaller number and that time to breakdown is more nearly like real life than if an ac step breakdown is used.

7.0 TECHNICAL DISCUSSION OF TREEING

Treeing has been demonstrated as one of the most important factors involved in loss of life for medium voltage cables. Electrical trees are considered to be associated with the final cable failure and do not exist for a long period of time. Water trees are the slower growing variety. They can extend from one electrode to the other without a service failure. Once they have formed, water trees seem to be converted to electrical trees for part or all of their length by dc, surges, and impulses. Conclusions in recent research work show that treed cables that are subjected to dc, surges, or impulses have shorter life in service after that application than cables not subjected to those stresses.

There are several possible explanations for this “conversion” of a water tree to an electrical tree, but the more commonly accepted explanation is that charges are trapped in the insulation wall. When these trapped charges are disturbed by heat or mechanical motion, they can literally bore a hole through the insulation wall. A likely scenario is that the trapped charges bore a tunnel from one void or contaminant to the next one. The insulation between these voids may be in a deteriorated condition, thus speeding up the damaged from the trapped charges. This continues until the wall has been virtually destroyed and the cable can’t hold even line voltage.

Inception of water trees is likely to be the result of voltage enhancements at voids, contaminants, or other imperfections in the cable. Another significant factor is that the presence of ionic impurities is especially deleterious to cables. At one time it was thought that the source of these ions was from ground water or the like. It is now established that the frequent source of these impurities is the materials in the cable—basically contaminants in the older semiconducting shield materials. Microscopically small “chunks” of sand make the insulation/shield interface another source of voltage enhancement. Growth or propagation of the water tree is apparently quite slow—several years in a well-made cable. Bow tie trees may stop propagating as they grow large enough to decrease the voltage stress at their extremities.

We know that voltage stress and temperature accelerate this propagation of water trees. Cross-linked and thermoplastic polyethylene are adversely effected by temperatures above about 75°C—as demonstrated by laboratory aging studies [18-10].

As briefly mentioned previously, there is only a small distinction between water and electrochemical trees that results from a “natural” staining of the interior or the voids. Pre-1970 HMWPE insulation was formulated with a staining antioxidant. These cables did not require any dying to see the trees. The change to non-staining antioxidant around 1970 resulted in water trees that could not be seen unless the wafers were put in a dye solution. In the transition period, it was thought that possibly the staining antioxidant was what had caused the trees! The dying procedure is given at the end of this section.

Trees also exist and are visible in EPR insulated cable but they can only be seen at the surface of the cut. A similar dying procedure is used for EPR but the staining time must be increased considerably. There are also proprietary methods for staining EPR cable samples. Tree counts in EPR are lower than for the non-opaque types because of not being able to see down into the material, but they also may be lower because they simply don’t tree the same as XLPE cables.

Trees positively initiate at defects within the cable such as at discontinuities between the interfaces of the insulation and the two shields, and at voids and contaminants—metal particles, threads, oxidized bits of insulation (ambers), and even at chunks of undispersed antioxidant.

Trees that have one of their points of origin at the insulation/shield interface are called "vented" trees. They always show up as the dangerous trees as compared to ones that stay completely within the wall of insulation—the non-vented tree. The probable explanation here is that pressure can build up within the non-vented tree and this suppresses the partial discharge.

8.0 METHYLENE BLUE DYING PROCEDURE

Prepare the specimen for dying by removing the conductor to obtain a sufficient length of insulation for examination. Using a very sharp tool (lathe, micro tome, or trimmer) make slices of the insulation that are 25 mils thick.

In a 500 ml beaker with watch glass cover, place:

A. 250 ml distilled water
B. 0.50 gm methylene blue
C. 8 ml concentrated aqueous ammonia

Heat to boiling with continuous stirring. Use a fume hood or other adequate ventilation.

Place the specimens to be stained in the solution using a wire for installation and removal.

Remove specimens from hot solution from time to time to be certain that the staining is neither too light nor too dark. The time will be dependent on the thickness of the sample as well as the type of insulation.

When the specimens are adequately stained, remove from the hot solution, rinse in hot water, and wipe dry.

A thin film of oil on the surface of the sample makes observation with a microscope much less confused by scratches. A 30-power lens should be used for initial observation purposes.

Record the number of bow ties trees (originating within the insulation wall) and the vented trees (originating from the conductor or insulation shields) that are greater than 2 mils in length. The length for bow ties shall be the peak-to-peak length. For vented trees, the length shall be the maximum distance from the surface of the shield to the tip of the tree. List the numbers in size ranges and by type.

9.0 OBSERVATION IN SILICONE OIL

An excellent method of observing several inches of insulation at one time is to place a one-foot sample on the insulated cable (the semiconducting insulation shield must be removed!) in a glass beaker with silicone oil that has been heated to about 130°C. At about this temperature, all of the crystallinity is gone and the insulation becomes quite clear. The surface of the conductor shield can be observed for smoothness. Voids or contaminants in the insulation wall can be readily seen. Note: "voids" can be created during the test by moisture in the insulation resulting from service conditions. Such "voids" will grow in size during the observation period so that they are obviously caused by the moisture. A way to eliminate this possibility is to dry the field sample in an oven prior to the observation.

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CHAPTER 19
LIGHTNING PROTECTION OF DISTRIBUTION CABLE SYSTEMS

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1.0 INTRODUCTION

Distribution cable systems have peak failure rates during the summer months throughout North America. Research work has shown that impulse surges to cables shorten their service life [19-1]. Both temperature and rainfall may peak during the same time period. All of these factors may influence this failure rate. It is also well documented that water trees reduce the impulse level of extruded dielectric insulated cables and contribute to the failure situation. Most of the effort that has been spent in the past on lightning protection of distribution system components has been on overhead transformers. This is logical when you consider that the companies that build transformers are also the ones that sell arresters.

The older paper insulated cables were manufactured with an inherently high impulse level and that level was maintained over the 40 plus years of life of the system. Today, the extruded dielectric insulated cables that are used so extensively in underground systems, exhibit a dramatic drop in electrical strength in just a few months of service. It is important to note that cross-linked polyethylene (XLPE) cables start with a much higher impulse level than ethylene propylene (EPR) or paper cables. EPR cables have initial impulse strengths less than the others, but their impulse level doesn’t drop as quickly and levels out. With time, both XLPE and EPR have impulse levels that are much nearer the basic impulse level (BIL) of the system than for paper cables. Because of this, lightning protection is a significant consideration for these newer cables.

2.0 SURGE PROTECTION TERMINOLOGY

2.1 Protective Margin

This is defined as:

$$\frac{\text{Insulation Withstand Level}}{\text{Arrester Protection Level}} \times 100$$

Another form of this equation for protective margin is:

$$\left[\frac{\text{Equipment BIL in kV}}{\text{Arrester Discharge Voltage in kV + Discharge Voltage of Arrester Leads in kV}} - 1\right] \times 100$$

A minimum protection margin of 20% over BIL is usually recommended for transformers.

2.2 Voltage Rating

Voltage rating of an MOV arrester is based on its duty-cycle test. The duty-cycle test defines the maximum permissible voltage that can be applied to an arrester and allow it to discharge its rated current. Another way to consider this is that it is the voltage level at which power follow current can be interrupted after a surge discharge has taken place. At voltage levels above this, power follow current interruption is doubtful. The safe arrester rating is usually determined by the highest power voltage that can appear from line to ground during unbalanced faults and shifting of the system ground.

2.3 Highest Power Voltage

The highest power voltage can be calculated by multiplying the maximum system line-to-line voltage by the coefficient of grounding at the point of arrester placement.

2.4 Coefficient of Grounding

This is defined as the ratio, expressed in percent, of the highest rms line-to-ground voltage on an unfaulted phase during a fault to ground. Systems have historically been referred to as being effectively grounded when the coefficient of grounding does not exceed 80%.

2.5 Sparkover

This refers to the initiation of the protective cycle that occurs when the surge voltage reaches the level at which an arc develops across the device’s electrodes to complete the discharge circuit to ground. In terms of voltage across gapped arresters, this is somewhat indefinite since sparkover of a simple gap structure is a function of both the wave front and the voltage of the incoming surge.

The essential requirement of a proper sparkover level is the speed of response to steep fronts such as natural lightning yet give a consistent response to waves with slower rates of rise which are typical of indirect strokes and system generated surges. Sparkover of an arrester should not be confused with “flashover”. Flashover refers to the exterior arcing that may occur, for instance, when surfaces become contaminated.

2.6 Surge Discharge

Surge discharge refers to the situation where the arrester must handle the power frequency line current as well as the momentary surge current. This power follow current continues to flow until the arrester can extinguish the arc.

2.7 IR Discharge Voltage

The IR discharge voltage of an arrester is the product of the discharge current and the resistance or inductance of the discharge path. While the resistance may be very low, the discharge current can be very high and the IR discharge voltage can reach levels that equal or exceed the arrester sparkover voltage. The inductance of the combined line and ground leads must be kept as short as possible. This is accomplished by placing the arrester as close as practical to the cable termination and always connecting the arrester closer to the incoming line than the termination. See Fig. 19-5.

3.0 WAVE SHAPE AND RATE OF RISE

Natural lightning must be simulated in the laboratory to test and evaluate lightning protection devices and equipment. This is accomplished with a surge generator. A group of capacitors, spark gaps and resistors are connected so that the capacitors are charged in parallel from a relatively low voltage source and then discharged in a series arrangement through the device being tested.

The terms used to describe both natural and artificial lightning are “wave shape” and “rise time”. The wave crest is the maximum value of voltage reached. Wave shape is expressed as a combination of the time from zero to crest value for the front of the wave and the time from zero to one-half crest of the wave tail. Both values of time are expressed in microseconds. The rate of rise is determined by the slope of a line drawn through points of 10 and 90 percent of crest value.

Testing of surge arresters has historically been done with an 8×20 microsecond wave, but more recent work has been done at 4×10 even though a direct stroke of natural lightning is more nearly 1×1000. See Figure 19-1 to see how these times are defined.

Figure 19-1 Wave shape.

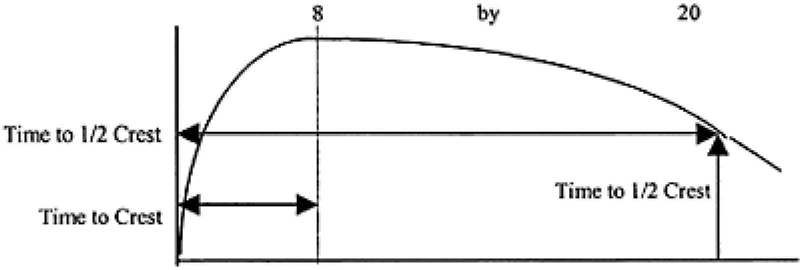
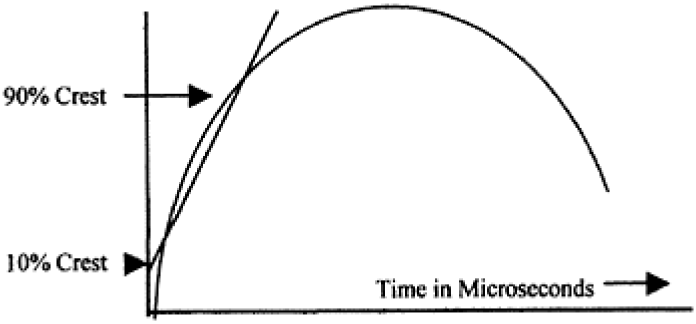


Figure 19-2 Rate of rise.



4.0 OPERATION OF A SURGE ARRESTER

4.1 Air Gaps

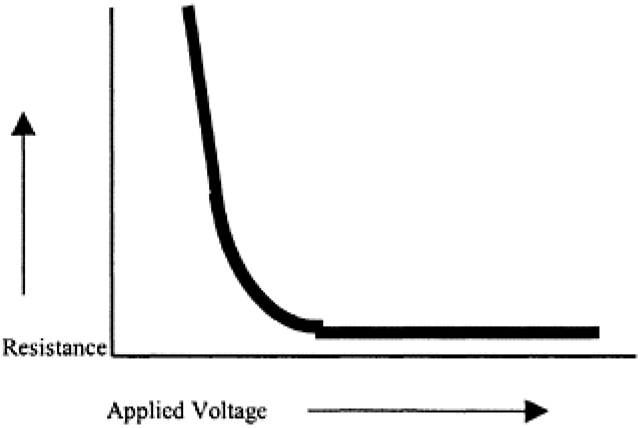
The original surge arrester was a simple air gap. They were made of a simple rod or spheres installed between line and ground that were far enough apart to keep the line voltage from sparking over but close enough to discharge when a surge occurred. Air gaps have the disadvantage of allowing system short circuit current to continue to flow until the breaker, fuse or other backup device operates.

Air gaps have another disadvantage. Electrically speaking they are sluggish and their response varies as stated above. Sparkover may not occur until a considerable portion of a rapidly rising lightning surge has been impressed on the system. The short gap spacing necessary to provide adequate protection against steep front lightning waves may result in frequent and unnecessary sparkovers on minor power frequency disturbances.

4.2 Valve Arresters

Non-linear resistance can best be considered as resistance that varies inversely with applied voltage. Under normal voltage conditions, the resistance is high; under unusual high voltages the resistance is low.

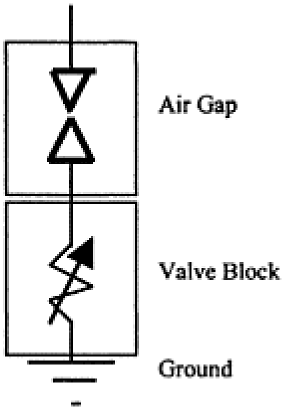
Figure 19-3 Non-linear resistance.



The material that, in the past, has been used so extensively in valve arresters is silicon carbide. It is blended with a ceramic binder, pressed into blocks under high pressure and fired in kilns at temperatures of over 2,000°F. This component is the valve block. The number of valve blocks used in an arrester is determined by resistance requirements for the rating of the system.

For silicone carbide blocks, it is essential that an air gap be in series with the blocks since they would conduct a large amount of current at operating voltage. This gap must ionize the atmosphere in the arc chamber to break down that gap before the blocks encounter any voltage. After the air gap breaks down, the valve blocks begin to conduct the combination of surge current and power current. The high voltage of the lightning surge decreases the resistance of the valve blocks and the current flows to ground. The voltage now across the blocks is approximately the line-to-ground voltage of the system. The valve blocks revert to their normal high resistance. This forces the power flow current to be reduced to a value that the series blocks can interrupt at the next system current zero.

Figure 19-4 Schematic of a silicone carbide arrester.



4.3 Metal Oxide Arresters

Commonly known as MOVs, metal oxide varistors became available for distribution systems in about 1978. Their first use on distribution systems were on terminal poles, hence the riser pole arrester term.

Gaps are not required because the material is extremely non-linear. The lower half of the schematic shown in Figure 19-4 represents a MOV arrester. A voltage increase of just over 50% results in a conduction current change of 1 to 100,000. The absence of gaps allows these devices to operate much faster than the older gapped silicone carbide arresters. The absence of gaps is a major factor in allowing MOVs to be used in load break elbow arresters.

Grounding resistance/impedance must be treated more seriously now that the URD systems are using conduit and/or jacketed neutral wires. With bare neutral wires, the stroke energy was dissipated along the cable run. The insulation provided by the jacket or conduit makes low resistance grounds at the terminals an essential factor. Customer’s grounds helped older systems have low resistance before those pipes became plastic. Even gas pipes are now plastic!

5.0 NATURAL LIGHTNING STROKES

The understanding of natural lightning has increased tremendously since the early 1980s. EPRI efforts led to the construction of antennas throughout the United States, and beyond, to record lightning strokes. These systems are now capable of pinpointing the time, location, magnitude, and polarity of strokes that occur between clouds and ground. What has been determined is that the rate of rise and the current magnitudes of natural lightning is much more severe than previously assumed.

From this information, we now have recorded strokes of over 500,000 amperes. Although these high stroke currents do occur, examination of arresters removed from service do not show that they have discharged such high values of current. One possible explanation is the division of stroke currents into multiple paths. Another is that the majority of strokes terminate to buildings, trees, or the ground without directly striking the electrical system. Recent research indicates that indirect strokes may be the biggest cause of failures on today's distribution systems.

Rate of rise is extremely important because the faster the rate, the higher the discharge voltage will be for all types of arresters. Recorded data shows that natural lightning strokes have rise times between 0.1 and 30 µs with 17% of the recorded strokes having rise times of 1 µs or faster and 50% are less than 2.5 µs. For the same wave shape, the average rate of rise increases with the crest magnitude. Using the "standard" 8×20 microsecond wave and a 9 kV-gapped arrester, the discharge voltage is about 40 kV. For the same 20 kA stroke but rising to crest in one microsecond, the arrester would have a 54.4 kV discharge, or a 36% increase. Metal oxide arresters (without gaps, of course) commonly exhibit a 12 to 29% increase under similar circumstances.

The inductance (hence length and shape) of the arrester leads becomes more pronounced with the faster rate of rise. Applying the generally used value of 0.4 microhenries per foot, the lead voltage is 8 kV per foot of total lead length at 20 kA per microsecond and 16 kV per foot at 40 kA. Assuming new arresters and two feet of total lead length, the total voltage at 20 kA and 40 kA would be 70 and 96 kV respectively. Saying this in a different way, a stroke having a 40 kA per microsecond rate of rise would add 32 kV to the arrester discharge voltage given in a typical manufacturer's literature.

Prudent engineering suggests that the level of protection should be calculated for a family of possible values of current and rates of rise for the anticipated lightning activity in the service area under study. This suggests currents such as 40 kA for parts of central Florida but only 10 kA or lower for California. Rates of rise of 1 to 3 microseconds are commonly used in calculations.

For an interesting note, these systems are of use to many organizations. Lightning stroke information is used by the forest service to warn of fires rather than the old fire towers or airplanes. Antennas near Anchorage, Alaska, warn of volcanic eruptions that produce lightning.

6.0 TRAVELING WAVE PHENOMENA

Whenever a lightning stroke encounters an electric system, energy is propagated along the circuit from the point of origin in the form of a traveling wave. The current in the wave is equal to the voltage divided by the surge impedance of the circuit. Surge impedance is approximately equal to the square root of the ratio of the self-inductance to the capacitance to ground of the circuit. Both the inductance and capacitance are values per given unit length making the surge impedance of a circuit independent of the actual length of the circuit.

A traveling wave will keep moving without change in a circuit of uniform surge impedance except for the effects of attenuation. As soon as the wave reaches a point of change in impedance, reflections occur.

A wave reaching an open circuit is reflected without change in shape or polarity. The resultant voltage at the open end will be the vector sum of the incident wave and the reflected wave. This is the source of the voltage doubling circumstance. If an arrester is located at the open point, this doubling does not occur after the arrester begins to discharge.

When a wave arrives at a ground or other value of impedance that is lower than the surge impedance of the circuit, the incident wave is reflected without change in shape but with a reversal in polarity.

No reflections will occur on a circuit that is connected to ground through a resistance/impedance that is equal to the surge impedance of the circuit since there is no change in impedance.

It is convenient to think of traveling waves as having square shapes to illustrate the points just mentioned, but since real surges have a finite time to crest, the results of the superposition of the actual wave shapes are quite different than the square waves, which are the worst-case scenarios.

7.0 VELOCITY OF PROPAGATION

For practical purposes, a traveling wave on an overhead line travels at the speed of light—984 feet per microsecond. The velocity of propagation of a traveling wave in cables commonly used today is about half the speed of light, or 500 to 600 feet per microsecond. This can be derived from the fact that, in an insulated and shielded cable, the speed is reduced depending on the specific inductive capacity, or permittivity, of the insulating material.

$$V = 1/\sqrt{LC} = 984 \text{ ft per } \mu\text{sec.} \tag{19.1}$$

This calculates out to 659 ft/µsec for TR-XLPE and 577 ft/µsec for an EPR. The use of time domain reflectometry (TDR) for finding faults, neutral corrosion, and so forth uses this velocity to locate the problem. A reasonably accurate location will be obtained using this formula, but it must be noted that there are other factors involved such as the type of shield. A cable with a longitudinally corrugated shield will have a velocity of propagation that is slightly slower than what would be calculated using Equation 19.1, for instance. Cable with an overlapped flat tape shield that has corroded may slow the time down by several percentage points or be so severe that the wave is so greatly attenuated that it never reflects back to the sending point.

Velocity of propagation becomes important to the protection of distribution cables because the travel time from the junction arrester to the end of the cable run is very short as compared to the conduction time of the arrester. Consider a typical 5,000-foot long loop that is open at the midpoint. At 500 feet per microsecond, the travel time to the end is only 5 microseconds to the end and 10 microseconds for the round trip. The arrester conduction time for an 8×20 microsecond wave is about 50 microseconds. This means that the junction arrester still has 90% of its conduction time left when the wave has traveled to the end of the cable. If the end does not have an arrester, the reflected wave will travel back towards the junction point and add to the incoming voltage wave throughout the length of the cable. Thus the entire cable is exposed to the “doubled” wave. The amount of time the incoming wave is maintained becomes an important consideration as to the exposure of the cable to this full doubling of voltage.

Attenuation has a negligible effect on the reflected voltage because the low loss insulations that are in use today do not attenuate the wave appreciably in the relatively short runs used for distribution systems.

8.0 PROPER CONNECTION OF ARRESTERS

There are several extremely important installation rules for arresters:

- ☐ Keep both the line and ground side leads as short and straight as possible. (It is the sum of the two lead lengths that must be used in the calculations).
- ☐ The lead from the line should go to the arrester FIRST—then to the termination.
- ☐ The ground resistance should be as low as practical. This means ten ohms if the cable has an insulating jacket or is in a conduit.

8.1 Lead Lengths

The issue of lead length on the voltage that will be impressed on a cable has been discussed earlier in this chapter. All of that is correct. There is, however, one more issue here. Does that lead carry the lightning current? If the lightning current flows in that lead, its length is a factor. If, on the other hand, the lead does not carry lightning current its length and impedance are not factors. In the real world, the current generally flows through all the paths that are available. The amount of current times the length of each lead establishes the voltage that is impressed on the cable. The practical point is that the circuit must be analyzed in its entirety, which includes both the hot lead and the ground lead.

8.2 Route of Current Flow

In the beginning of this section, it was stated that the lead from the incoming line should first be attached to the arrester—then to the termination. Wait a minute. This isn’t the way we have always done it! Are you certain of that?

Yes. If we can visualize the flow of lightning current as a flood of water, we can easily recognize that we would be much better off if we could divert that flood around our house—not through it. That is why the arrester is the first connection point. The bulk of the current flows through the arrester to and through its ground. The termination lead length is not very significant because it isn’t carrying that much current.

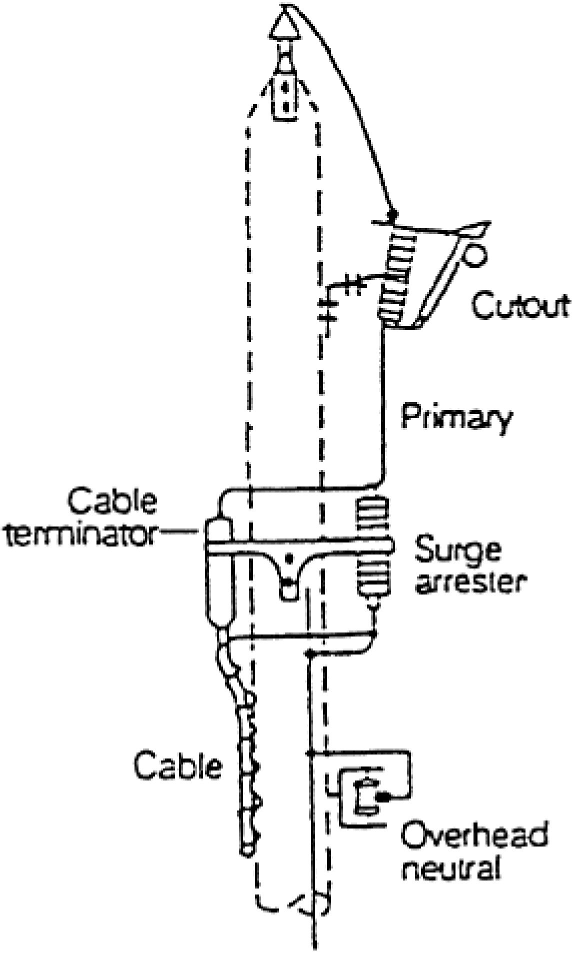
8.3 Ground Resistance/Impedance

Why is the ground resistance/impedance important? We are concerned about voltage and voltage is the product of current and impedance (length). Almost all of the current that goes through the arrester must flow to ground at the arrester location. Remember that the impedance of an overhead line (the neutral for our purposes) is about 50 to 60 ohms.

If the ground at the arrester is very high, then all of that lightning current must flow along those neutrals. That means that the "footing" resistance is 60 ohms. The voltage that is developed is the current multiplied by 60 ohms. Even if there are two directions for the ground current to flow, this can be a very high voltage.

The voltage build-up through the arrester is increased by the voltage build-up in the ground circuit.

Figure 19-5 Correct arrester connection diagram.



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CHAPTER 20
CABLE PERFORMANCE

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1.0 INTRODUCTION

Cable failure reporting in the United States had its beginning by action of the Edison Electric Institute and its predecessor the National Electric Light Association. A significant early report covered the performance of paper-insulated, lead-covered cables, splices, and terminations beginning in 1923. Failure rates of cable were reported in units per 100 installed miles for a variety of causes. Splice and termination reports were based on failures per 1,000 units that were in service. These reports were continued through 1966 and served both as a useful performance guide as well as a barometer of the effectiveness of the cable specifications in effect. The National Electric Light Association prepared the first U.S. paper cable specification in 1920 for cables rated up to 15 kV. The Association of Edison Illuminating Companies took over this responsibility and upgraded this to 45 kV in 1930 [20-1].

The advent of underground residential distribution (URD) systems with the extensive use of extruded dielectric cable convinced the U.S. utility group to become involved in specifications for this evolving type of cable. Later usage in conventional urban duct and manhole systems to take the place of the backbone paper insulated cables finalized this requirement.

During the early 1970s, isolated reports of early cable failures on the extruded dielectric systems began to be documented in many parts of the world. “Treeing” was re-introduced to the cable engineer’s vocabulary, but with an entirely new meaning from the paper cable use of the word.

The Edison Electric Institute’s last attempt to report distribution cable failures was in 1973. A vacuum was therefore developed in the United States for distribution cable failure reporting and no system for similar reporting exists in the world.

2.0 CABLE FAILURE DATA

The data coming from a few U.S. utilities and work funded by EPRI by 1975 [20-2] showed that thermoplastic polyethylene insulated cables were failing at a rapidly increasing rate and that XLPE and EPR cables had a lower failure rate.

The next compilation of data began in 1976 with 16 and later 21 utilities in North America reporting their failure rates on an annual basis for both polyethylene and crosslinked polyethylene insulated cables [20-3].

Failure data kept by the utilities was rather meager. It was decided to only request data based on type of insulation, number of failures for each year and the total amount of each of those insulation types were in service at the end of the year. It was also decided to only ask for failures of known electrical causes, such as defective cable, insulation deterioration, lightning, etc., and then include all “unknown” causes since treeing analysis was not easily obtainable.

3.0 PERFORMANCE

Comparable data from EEI for paper insulated, medium voltage power cables installed in the United States is included as Figure 20-1 for the years of 1923 through 1966—when the data was no longer collected. Similar data showing the electrical failures of polyethylene and crosslinked polyethylene for 21 North American utilities is shown in Figure 20-2. AEIC then began to collect and report similar data in 1984 except that data was requested from all utilities. A major future step was to request information on jackets, ducts, voltage stress levels, etc. The old 21-company base was not separately recorded, however. They also began to collect data for tree retardant XLP as well as EPR. See Figures 20-3, 20-4, 20-5 and 20-6.

AEIC strongly suggests that this data be carefully analyzed and understood. This is important since the age of the cables were not known and could skew the results. For instance, jacketed cable is probably newer than non-jacketed cable and hence the failure rate of the older cables may not be entirely the result of a jacket.

The European community also began to collect data and their results were published as UNIPEDE-DISCAB that represents most of the European countries. Their data includes PE, XLP, EPR and PVC.

4.0 ANALYSIS OF DATA

Cable failure rates in the U.S. have historically been calculated on the basis of failures per 100 miles of installed cable. The rest of the world reports failures per 100 kilometers. All data is shown as rates per 100 miles for ease of comparison.

The most frequently used form for the data shows the number of failures per 100 miles for each year. The disadvantage of such depiction is that older cable is looked at in the same light as new cable. This data is more readily available, but a preferred method is to take into account the years in service for all cables. This is accomplished by integrating the miles installed with the years of service. The expression is:

Service Index $Aj=\sum i(MiNj-i)$

(20.1)

where A = system age in year j in terms of service mile-years,

M_i=the number of miles of cable installed in year i,

N_{j-i}=the number of years from i to j.

Years	Miles of Cable Multiplied by Age

A	a					
B	2a	b				
C	3a	2b	c			
D	4a	3b	2c	d		
E	5a	4b	3c	2d	e	
F	6a	5b	4c	3d	2e	f, etc.

At the end of the year F, the age of the system is:

$$A_F=6a+5b+4c+3d+2e+f \tag{20.2}$$

where a, b, c, represent the number of miles of cable installed in A, B, C….

This analysis can be shown as a summation of failures per 1,000 mile-years.

Cumulative Miles ofCable at End of Year

Year		Summation
A	a	a
B	b	a+b
C	c	a+b+c
D	d	a+b+c+d
E	e	a+b+c+d+e
	Σ =	5a+4b+3c+2d+e

It is only necessary to add the miles of cable installed each year to the summation of cable installed in all previous years to obtain updated mile-years from this equation.

5.0 PRESENT SITUATION

There is no new data to report regarding cable failure statistics. This is the result of two factors:

□ New cable performance is very good. The few problems with new cable makes collecting data seem unnecessary.
□ There are not enough people to do the essential work.

The last North American data was collected for 1991 performance by AEIC. The data shows an extremely low failure rate for TR-XLPE and EPR. The XLPE rate is not escalating to a troublesome level. The European collection of data has also been discontinued.

This is certainly an indication of the effort that has been directed toward improved cables—both from the material suppliers standpoint as well as the cable manufacturers.

Figure 20-1 PILC cable failures in the United States.

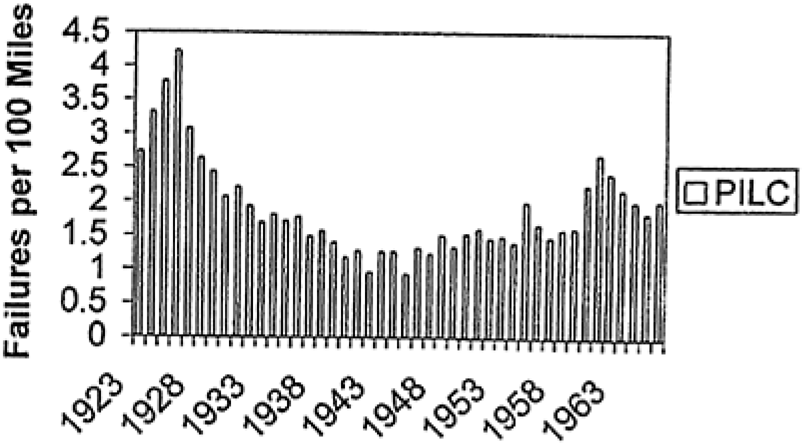


Figure 20-2 Electrical failures of extraded dielectric cables.

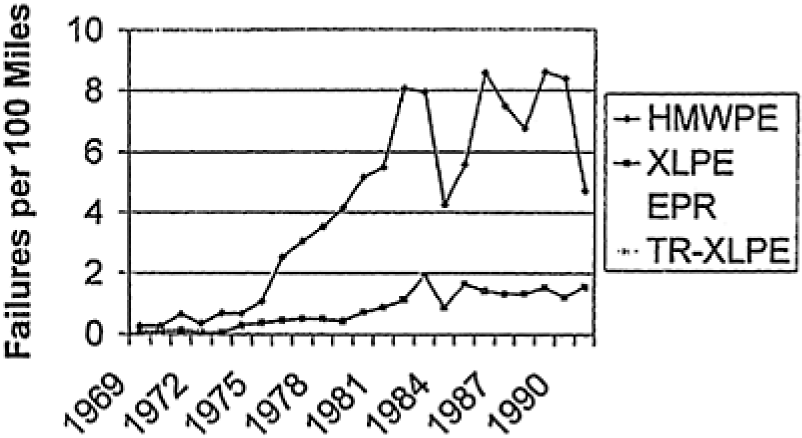


Figure 20-3 AEIC cable failure data with high and low electrical stress.

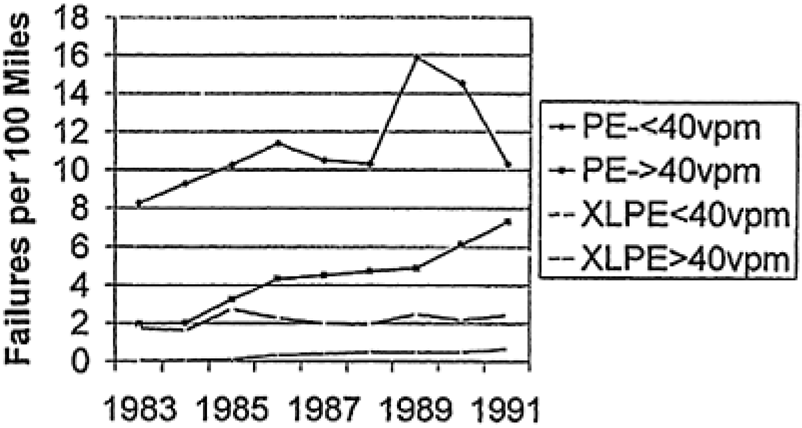


Figure 20-4 AEIC cable failure data of duct versus direct buried.

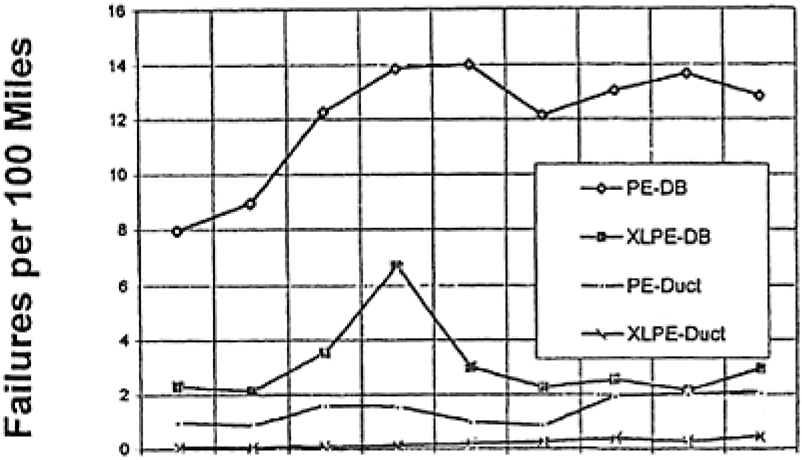


Figure 20-5 AEIC cable failure data of jacket versus non-jacket construction.

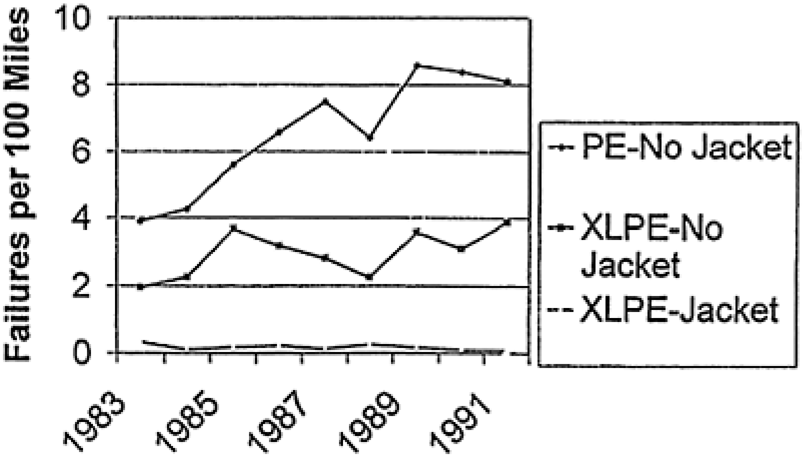
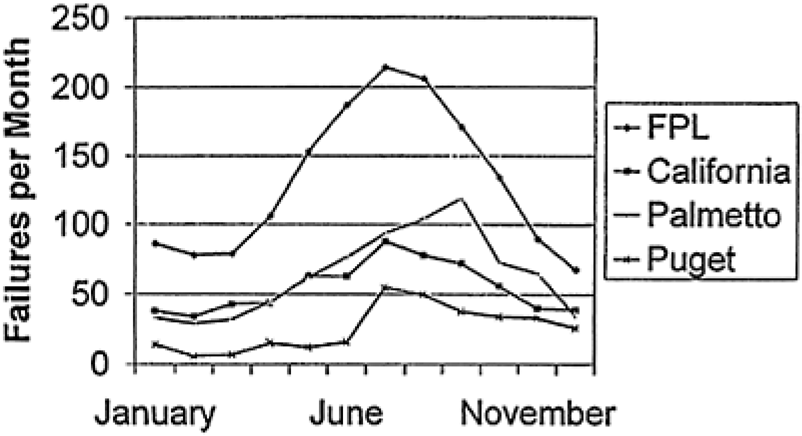


Figure 20-6 Cable failure data with seasonal pattern.



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CHAPTER 21
CONCENTRIC NEUTRAL CORROSION

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1.0 INTRODUCTION

In nature, metals are usually found in combinations such as oxides or sulfides, not as a pure metal. Nature wants to change those pure metals back to their original state after we have refined them to an almost pure metal. That process is known as corrosion [21-1,21-2,21-3].

One hundred years ago, this interesting article was published [21-4], “Practicallythe only factor which limits the life of metal is oxidation, under which name are included all the chemical processes whereby the metal is corroded, eaten away, or rusted. In undergoing this change, the metal always passes through or into a state of solution, and as we have no evidence of metal going into aqueous solution except in the form of ions, we have really to consider the effects of conditions upon the potential difference between a metal and its surroundings. The whole subject of corrosion is simply a function of electromotive force and resistance of the circuit.”

Corrosion may be defined as the destruction of metals by chemical or electrochemical reaction with the environment. The fundamental reaction involves a transfer of electrons where in a moist or wet environment some positive ions lose electrical charges. These positive charges are acquired by the metallic member and a portion of the metal surface goes into solution, hence is corroded. The entire process may be divided into an anodic reaction (oxidation) and a cathodic reaction (reduction). The anodic reaction represents acquisition of charges by the corroding metal and the cathodic reaction represents the loss of charges by hydrogen ions that are discharged. The flow of electricity between the anodic and cathodic areas may be generated by local cells set up either on a single metallic surface, or between dissimilar metals.

1.1 Electromotive Series

The tendency for metals to corrode by hydrogen ion displacement is indicated by their position in the electromotive series shown in Table 21-1. To achieve these precise voltages, the metals must be in contact with a solution in which the activity of the ion indicated is one mol per 1,000 grams of water and at 77°F (25 °C). Different values of voltage will be obtained in other solutions.

Metals above hydrogen displace hydrogen more readily than do those below hydrogen in this series. A decrease in hydrogen ion concentration (acidity), tends to move hydrogen up relative to other metals. An increase in the metal ion concentration tends to move the metals down relative to hydrogen. Whether or not hydrogen evolution will occur in any case is determined by several other factors besides the concentration of hydrogen and metallic ions.

Table 21-1 Electromotive Series

(Anodic End)

Metal	**Ion**	**Volts**
Magnesium	Mg+2e*	−2.34
Aluminum	Al+3e	−1.67
Zinc	Zn+2e	−0.76
Chromium	Cr+3e	−0.71
Iron	Fe +2e	−0.44
Cadmium	Cd+2e	−0.40
Nickel	Ni+2e	−0.25
Tin	Sn+2e	−0.14
Lead	Pb+2e	−0.13
Hydrogen	H+e	Arbitrary 0.00
Copper	Cu+2e	+0.34
Silver	Ag+e	+0.80
Palladium	Pd+2e	+0.83
Mercury	Hg+2e	+0.85
Carbon	C+2e	+0.90
Carbon	C+4e	+0.90
Platinum	Pt+2e	+1.2
Gold	Au+3e	+1.42
Gold	Au+e	+1.68

(Cathodic End)
* *Note:* “e” stands for electrons (negative charges)

1.2 Electrochemical Equivalents

The electrochemical equivalent of a metal is the theoretical amount of metal that will enter into solution (dissolve) per unit of direct current transfer from the metal to an electrolyte. Table 21-2 shows that theoretical amount of metal removed in pounds per year with one ampere of direct current flowing continuously from the material.

Table 21-2 Electrochemical Equivalents

Metal	**Pounds Removed per Amp per Year**
Carbon (C++++)	2.16
Carbon (C++)	4.23
Aluminum	6.47
Magnesium	8.76
Chromium	12.5
Iron	20.1
Nickel	21.1
Cobalt	21.2
Copper (Cu++)	22.8
Zinc	23.5
Cadmium	40.5
Tin	42.7
Copper (Cu+)	45.7
Lead	74.2

1.3 Hydrogen Ion Concentration

A normal solution is one that contains an “equivalent weight” (in grams) of the material dissolved in sufficient water to make one liter of the solution. The equivalent weight of hydrogen is 1 and therefore one gram of hydrogen ions in a liter of water is a normal acid solution. The hydroxyl ion has an equivalent weight of 17 (1 for the hydrogen and 16 for oxygen). Therefore, 17 grams in a liter is equal to the normal alkaline solution.

Since acids produce hydrogen ions when dissolved in water, the concentration of the hydrogen ions is a measure of the acidity of the solution. The hydrogen ion concentration is expressed in terms of pH. Stated mathematically, the pH value is the logarithm of the reciprocal of the hydrogen ion concentration in terms of the normal solution. A change of one in pH value is equivalent to a change of ten times in concentration.

In any aqueous solution, the hydrogen ion concentration multiplied by the hydroxyl ion concentration is always a constant. When the concentrations are expressed in terms of normal solution, the constant is equal to 10^{-14}. It follows that a solution having a pH equal to 7 is neutral, less than 7 has an acidic reaction, and more than 7 has an alkaline reaction

Table 21-3 Significance of Hydrogen Ion Concentration

pH	**Hydrogen Ion Concentration**	**Hydroxyl Ion Concentration**	Reaction
0	1.0×10^{-0}	1.0×10^{-14}	Acidic
1	1.0×10^{-1}	1.0×10^{-13}	Acidic
2	1.0×10^{-2}	1.0×10^{-12}	Acidic
3	1.0×10^{-3}	1.0×10^{-11}	Acidic
4	1.0×10^{-4}	1.0×10^{-10}	Acidic
5	1.0×10^{-5}	1.0×10^{-9}	Acidic
6	1.0×10^{-36}	1.0×10^{-8}	Acidic
7	1.0×10^{-7}	1.0×10^{-7}	Neutral
8	1.0×10^{-8}	1.0×10^{-6}	Alkaline
9	1.0×10^{-9}	1.0×10^{-5}	Alkaline
10	1.0×10^{-10}	1.0×10^{-4}	Alkaline
11	1.0×10^{-11}	1.0×10^{-3}	Alkaline
12	1.0×10^{-12}	1.0×10^{-2}	Alkaline
13	1.0×10^{-13}	1.0×10^{-1}	Alkaline
14	1.0×10^{-14}	1.0×10^{-0}	Alkaline

2.0 MECHANISM OF CORROSION

The basic nature of corrosion is almost always the same, a flow of electricity between certain areas of a metal surface through a solution capable of conducting electric current. This electrochemical action causes the eating away of the metal at areas where metallic ions leave the metal (anodes) and enter the solution. This is the critical step in the corrosion process.

The first basic requirement for corrosion is the presence of an electrolyte and two electrodes—an anode and a cathode. These electrodes may consist of two different kinds of metal, or may be different areas of the same piece of metal. In any case, there must be a potential difference between the two electrodes so that current will flow between them. A wire or some path is necessary for the flow of electrons that are negatively charged particles moving in the wire from the negative to the positive.

At the anode, positively charged atoms of metal detach themselves from the solid surface and enter into solution as ions while the corresponding negative charges, in the form of electrons, are left behind in the metal. For copper:

$$Cu^{0} \longrightarrow Cu^{++} + 2e^{-}$$

The detached positive ions bear one or more positive charges. The released electrons travel through the metal or other conducting media to the cathode area. The electrons reaching the surface of the cathode through the metal meet and neutralize some positively charged ions (such as hydrogen), which have arrived at the same surface through the electrolyte. In losing their charge, the positive ions become neutral atoms again and may combine to form a gas.

$$2H^{+} + 2e^{-} \longrightarrow H_2$$

The release of hydrogen ions results in the accumulation of OH ions that are left behind and increase the alkalinity at the cathode—hence making the solution less acidic. Other common reactions occurring at the cathode are shown below. Their occurrence depends on such factors as pH, type of electrolyte, etc.

$$4H^{+} + O_2 + 4e^{-} \longrightarrow 2H_2O$$

$$O_2 + 2H_2O + 2e^{-} \longrightarrow H_2O_2 + 2OH^{-}$$

$$O_2 + 2H_2O + 4e^{-} \longrightarrow 4OH^{-}$$

For corrosion to occur, there must be a release of electrons at the anode and a formation of metal ions through oxidation or disintegration of the metal. At the cathode, there must be a simultaneous acceptance of the electrons by a mechanism such as neutralization of the positive ions or formation of negative ions. Actions at the cathode and anode must always go on together, but corrosion occurs almost always at areas that act as anodes.

3.0 TYPES OF CORROSION

There are numerous types of corrosion, but the ones that are discussed here are the ones that are most likely to be encountered with underground power cable facilities.

In this initial explanation, lead will be used as the referenced metal. Copper neutral wire corrosion will be discussed as a separate topic later.

3.1 Anodic Corrosion (Stray dc Currents)

Stray dc currents come from sources such as welding operations, flows between two other structures, and—in the days gone by—street railway systems.

Anodic corrosion is due to the transfer of direct current from the corroding facility to the surrounding medium—usually earth. At the point of corrosion, the voltage is always positive on the corroding facility. In the example of lead sheath corrosion, the lead provides a low resistance path for the dc current to get back to its source. At some area remote from the point where the current enters the lead, but near the inception point of that stray current, the current leaves the lead sheath and is again picked up in the normal dc return path. The point of entry of the stray current usually does not result in lead corrosion, but the point of exit is frequently a corrosion site.

Clean-sided corroded pits are usually the result of anodic corrosion. The products of anodic corrosion such as oxides, chlorides, or sulfates of lead are carried away by the current flow. If any corrosion products are found, they are usually lead chloride or lead sulfate that was created by the positive sheath potential that attracts the chloride and sulfate ions in the earth to the lead.

In severe anodic cases, lead peroxide may be formed. Chlorides, sulfates, and carbonates of lead are white, while lead peroxide is chocolate brown.

3.2 Cathodic Corrosion

Cathodic corrosion is encountered less frequently than anodic corrosion—especially with the elimination of most street railway systems.

This form of corrosion is usually the result of the presence of an alkali or alkali salt in the earth. If the potential of the metal exceeds-0.3 volts, cathodic corrosion may be expected in those areas. In cathodic corrosion, the metal is not removed directly by the electric current, but it may be dissolved by the secondary action of the alkali that is produced by the current. Hydrogen ions are attracted to the metal, lose their charge, and are liberated as hydrogen gas. This results in a decrease in the hydrogen ion concentration and the solution becomes alkaline.

The final corrosion product formed by lead in cathodic conditions is usually lead monoxide and lead/sodium carbonate. The lead monoxide formed in this manner has a bright orange/red color and is an indication of cathodic corrosion of lead.

3.3 Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals in an electrolyte have a metallic tie between them. One metal becomes the anode and the other the cathode. The anode corrodes and protects the cathode as current flows in the electrolyte between them. The lead sheath of a cable may become either the anode or the cathode of a galvanic cell. This can happen because the lead sheath is grounded to a metallic structure made of a dissimilar metal and generally has considerable length. Copper ground rods are frequently a source of the other metal in the galvanic cell.

The corrosive force of a galvanic cell is dependent on the metals making up the electrodes and the resistance of the electrolyte in which they exist. This type of corrosion can often be anticipated and avoided by keeping a close watch on construction practices and eliminating installations having different metals connected together in the earth or other electrolyte.

3.4 Chemical Corrosion

Chemical corrosion is damage that can be attributed entirely to chemical attack without the additional effect of electron transfer. The types of chemicals that can disintegrate lead are usually strong concentrations of alkali or acid. Examples include alkaline solutions from incompletely cured concrete, acetic acid from volatilized wood or jute, waste products from industrial plants, or water with a large amount of dissolved oxygen.

3.5 ac Corrosion

Until about 1970, ac corrosion was felt to be an insignificant, but possible, cause of cable damage [21-6]. In 1907, Hayden [21-7], reporting on tests with lead electrodes, showed that the corrosive effect of small ac currents was less than 0.5 percent as compared with the effects of equal dc currents.

Later work using higher densities of ac current has shown that ac corrosion can be a major factor in concentric neutral corrosion. See Section 4.2.4.

3.6 Local Cell Corrosion

Local cell corrosion, also known as differential aeration in a specific form, is caused by electrolytic cells that are created by a non-homogeneous environment where the cable is installed. Examples include variations in the concentration of the electrolyte through which the cable passes, variations in the impurities of the metal, or a wide range of grain sizes in the backfill. These concentration cells corrode the metal in areas of low ion concentration.

Differential aeration is a specific form of local cell corrosion where one area of the metal has a reduced oxygen supply as compared with nearby sections that are exposed to normal quantities of oxygen. The low oxygen area is anodic to the higher oxygen area and an electron flow occurs through the covered (oxygen starved) material to the exposed area (normal oxygen level).

Differential aeration corrosion is common for underground cables, but the rate of corrosion is generally rather slow. Examples of situations that can cause this form of corrosion include a section of bare sheath or neutral wires that are laying in a wet or muddy duct or where there are low points in the duct run that can hold water for some distance. A cable that is installed in a duct and then the cable goes into a direct buried portion is another good example of a possible differential aeration corrosion condition. Differential aeration corrosion turns copper a bright green.

3.7 Other Forms of Corrosion

There are numerous other forms of corrosion that are possible, but the most probable causes have been presented. An example of another form of corrosion is microbiological action of anaerobic bacteria that can exist in oxygen-free environments with pH values between 5.5 and 9.0. The life cycle of anaerobic bacteria depends on the reduction of sulfate materials rather than on the consumption of free oxygen. Corrosion resulting from anaerobic bacteria produces sulfides of calcium or hydrogen and may be accompanied by a strong odor of hydrogen sulfide and a build-up of a black slime. This type of corrosion is more harmful to steel pipes and manhole hardware than to lead sheaths.

4.0 CONCENTRIC NEUTRAL CORROSION

This section will concentrate on the corrosion mechanisms associated with concentric neutral, medium voltage power cables [21-11]. The most probable causes of concentric neutral corrosion include:

- Differential aeration.
- Stray dc current flow.
- dc current generated through ac rectification.
- ac current flow between neutral and earth.
- Galvanic influence with semiconducting layer (unjacketed cables).
- Galvanic influence of alloy coating and copper neutral wires and other action from dissimilar metals.
- Soil contaminants.

Electric power systems had used copper directly buried in the ground for over 60 years without problems being experienced. Most of the applications consisted of butt wraps under poles and substation ground grids. The successful operation led to complacency when underground residential distribution cables began to be installed in vast quantities after 1965.

Although the number of cable failures caused by neutral corrosion were very small, when these cables did fail for other reasons it became clear that neutral corrosion was taking place in situations that were not anticipated.

4.1 Research Efforts

EPRI funded a series of projects to study the problem and to suggest remedies: [21-9]–[21-15]. The subjects include mechanisms of corrosion, cathodic protection methods, procedures for locating corrosion sites, and step-and-touch potential data for jacketed as well as unjacketed cable.

4.2 Composition of Soils

Both the physical and chemical characteristics of soils are important although it is difficult to separate these effects. The significant properties of a soil include:

1) Its water retaining capacity
2) Its power of adsorption on the metal surface
3) Its conductivity
4) Dissolved matter in the soil
5) Concentration variations
6) Grain size

The soluble constituents of the soil water include dissolved gases; inorganic acids, bases, and salts; organic compounds (including fertilizers), and other related substances.

4.3 Mechanisms of Concentric Neutral Corrosion

Differential aeration is one specific type of local cell corrosion and is probably the most frequent cause of neutral corrosion. Fortunately, this is a relatively slow form of attack. This type of corrosion is caused when metal is exposed to soils or water having a difference in oxygen content. Examples of this are:

- Soils with different grain sizes.
- Cable going from a direct buried environment to a conduit.
- A conduit run that has a section with standing water and another section that has an unlimited supply of oxygen.
- Jacketed cable spliced to unjacketed cable.

The key concept here is the dissimilar environment and oxygen supply for a run of cable. It can occur in a small crevice made by a large grain of sand or stone in contact with the copper neutral conductor. Areas of low aeration change to an area that is well aerated. This form of corrosion is frequently caused when special backfills are brought in to replace the native soil. The native soil usually has a consistent grain size while the imported material may have quite a different grain size. Pockets are thereby formed.

Another very frequent cause of this form of corrosion is where an unjacketed cable leaves a conduit (such as under a street) and enters the earth. The same sort of cell is created by having a low section of conduit that is filled with water while the adjacent section is in a dry conduit The use of an overall jacket (either insulating or semiconducting) eliminates this condition.

Stray dc current flow problems are very similar to the lead sheath condition previously described. This situation is frequently encountered when an anode that is used to protect a gas pipeline that is installed in close proximity to an unjacketed cable. This damage occurs very rapidly.

Stray dc current causes dissolution of the copper where anions are present that contribute to the reaction. The rate of dissolution may not follow Faraday’s law precisely because of other electrochemical oxidation reactions that occur in parallel.

A dc current flow can be generated through ac rectification across a film of copper oxide. Copper neutral wires quickly develop an oxide coating. This coating provides a rectification boundary so that ac current is restricted from flowing back to the neutral wires. This is similar to the situation in 4.2.4.

Since ac corrosion was not recognized as a serious problem in the initial URD systems. The opinion was that while ac current flow might take off metal during one half cycle, the other half cycle would bring it back. The concept of rectification was commonly discussed as a possible explanation for ac corrosion in the 1960s. It was not until the 1970s that ac corrosion was recognized as a major concern for copper neutrals. The Final Report of EPRI EL-4042 [21-13] published in 1985 stated that the effect of high ac current density was creating this rapid corrosion mechanism on bare URD and UD cables.

Above some threshold of ac current density, the positive cycle tends to dissolve more metal than the negative cycle can plate back. Especially in cables with large conductors that are heavily loaded (such as feeder cables), the amount of current that can flow off the neutral wires at one point and then back on at another is quite large. Another explanation of this flow of current off and then back on the neutral wires is that shifts in potential exist along the cable length due to the differences in the current densities.

Galvanic influence with the semiconducting insulation shield material and bare or tinned copper is another form of concentric neutral corrosion. A voltage differential exists between the carbon in the semiconducting layer and the neutral wires. Corrosion, although not a widespread cause of failure, must be considered.

Dissimilar metal corrosion is probable if plating is used on the neutral wires and no jacket is applied over these wires. Areas of bare copper may exist during the factory plating process or are created by mechanical scraping during handling and field installation efforts. The result is local cell corrosion due to the two different metals.

Research has shown that bare wires out perform plated wires in the field. When jackets are used, bare copper wires are recommended and are almost always specified.

Soil contaminants and other direct chemical action is another source of problems for URD cables. Examples of this are high quantities of chemicals in the soil such as from fertilizers, peat, cinders and decaying vegetation. Decaying vegetation produces hydrogen sulfide that reacts rapidly to deteriorate copper.

Combinations of the previously discussed corrosion mechanisms do occur in the real world. Multiple sources of corrosion accelerate the problem.

5.0 JACKETS

An overall jacket is the preferred construction for new cable. Both insulating and semiconducting jackets have demonstrated their ability to virtually eliminate corrosion of the neutral wires. An encapsulated jacket made with linear low-density polyethylene is the type most frequently specified. See Chapter 8 for a complete discussion of jackets.

6.0 CATHODIC PROTECTION

Cathodic protection [21-8] can be applied to the copper neutral wires of existing cable that did not have a jacket or where the jacket may be damaged. An obvious place where cathodic protection should be considered is where a bare neutral cable goes from a direct buried environment to a conduit as under a road. Another is where a long section of jacketed cable is spliced onto a short section of existing bare neutral cable. Here the short section will be even more vulnerable to corrosion.

Noteworthy efforts have been expended towards solving this concern and the reference section contains excellent sources of advice regarding design and installation recommendations.

7.0 LOCATION OF CORROSION SITES

The existence of deteriorated copper neutral wires is an unpleasant fact. How to identify their existence and then locate the precise site of the corrosion has shown great advancement in recent years. Several technologies are presently available.

7.1 Resistivity Measurements of Neutral Wires

Resistive techniques are used to measure the resistance of neutral wires of installed cables. Instruments are available for testing the resistance of the neutral wires while the cable is energized. This value is compared with the original resistance for that length of cable and the size and number of original wires. A new or undamaged cable would show a resistance ratio of 1 while a cable that has half of the wires remaining would have a ratio of 2.

7.2 Location of Deteriorated Sites

If the reading of the resistance ratio warrants, the precise location of the corroded area can be obtained by using a form of time domain reflectometry (TDR). This equipment is similar to that used for locating cable faults [21-16].

Damage to a neutral wire must be great enough so that a reflection can be seen on the screen of the TDR. This may mean that a wire with only pitting may not be identifiable, and the cable would appear to be sound. The reflection of that wave from the end of the cable has a lower amplitude than intact wires. A cable with uniform corrosion may not be seen, but discreet sites cause reflections and are readily detected.

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CHAPTER 22
ARMOR CORROSION OF SUBMARINE CABLES

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1.0 INTRODUCTION

Submarine cables generally have a metallic armor consisting of one or two layers wound around the outside of the cable. The main function of the armor is to provide mechanical strength during the installation and recovery of the cable since the conductor alone may not have sufficient tensile strength for this purpose.

The armor provides another function as the path for conduction of the return current. Single conductor submarine cables are frequently spaced apart a considerable distance to preclude the chance of more than one cable being mechanically damaged as a result of a single incident. When the spacing is about 100 feet on centers (300 to 500 times the diameter of a single cable), the return current approaches the current in the central conductor. The effect of an increase in spacing above 100 feet is negligible. Paths that may be available for this return current are:

- A metallic sheath
- Reinforcing tapes used in pressurized cables
- Shielding tapes
- Sea and soil surrounding the cables

The choice of a three conductor or single conductor cables for large power cables is an important decision. For this moment, we will decide that single conductor cables have been chosen. We will deal with that situation since it may be of critical importance.

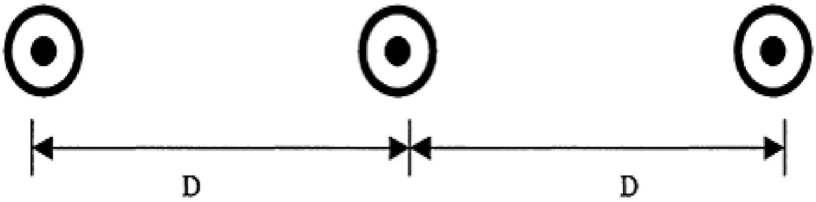
When the line length is more than three kilometers (two miles), consideration must be given to connecting the components in the cable together. Frequently a metallic sheath is protected by an insulating jacket to reduce the possibility of corrosion. To prevent electrical breakdown of the insulating jacket, electric connections are usually made at suitable intervals between sheath, armor, and the sea/soil. This may be done during the manufacturing process so that no visible signs of interconnection are available or they may be made externally.

2.0 CURRENTS IN ARMOR SYSTEMS

This Chapter is going to concentrate on the effects of ac corrosion as a result of return current flow in the “armor system”—the parallel paths formed by the metallic armor wires, any reinforcing tapes, a metallic sheath, and/or a metallic shield. If all of the current stayed in the metallic path or paths, there would not be ac corrosion. The fact is that the current flows off the metal and into the sea or seabed and later returns. It is this process of current leaving and returning to the surface that results in the deterioration. The greater the current, the greater the damage. This is called ac corrosion. See Chapter 21.

The amount of current will now be considered for single conductor cables on a system where the phase rotation is A, B, C. and the cables are arranged in a flat configuration as shown in Figure 22-1.

Figure 22-1 Single conductor cables spaced apart.



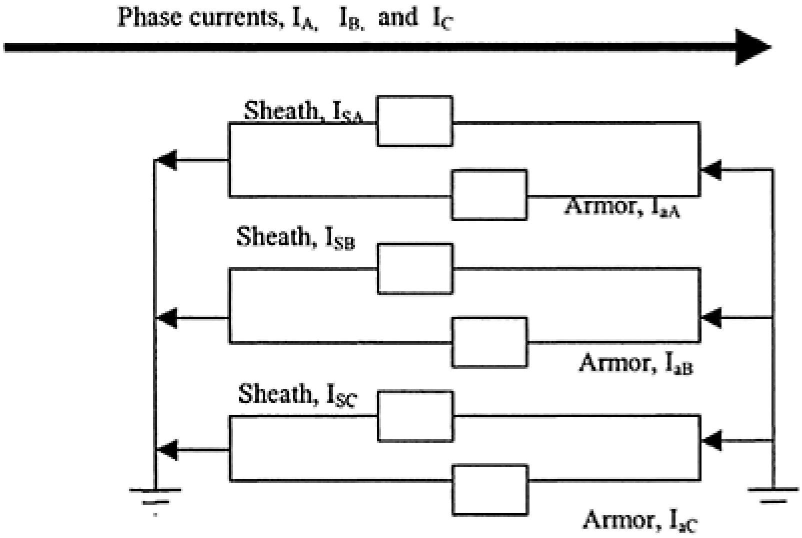
In the case of these three cables with a balanced load three-phase system, the vector sum of the three currents is zero. That is, the currents in each phase all have the same effective value and are 120 degrees out of phase with one another. Hence:

$I_A+I_B+I_C=0$

We are now going to make the very reasonable assumption that the armor system is connected to ground at more than one location. Even though two grounding points might be a few feet apart, the currents that will be described will flow between these points! The more realistic situation is that the armor system is grounded for the entire route and hence these currents will flow everywhere in the armor system circuit.

A schematic of the system is shown in Figure 22-2. Only two of the possible components in the armor system are shown to keep the system somewhat simple.

Figure 22-2 Parallel currents in spaced single-conductor cables.



The shield loss for each phase of a multi grounded cable may be calculated from the following formulas:

$$\text{A and C phases: } W_{LS(A,C)} = I_{AC}^{2} R_S \left[\frac{(P^2+3Q^2)\pm 2\sqrt{3}(P-Q)+4}{4(P^2+1)(Q^2+1)}\right] \tag{22.1}$$

$$\text{B phase cable: } W_{LS(B)} = I_B^{2} R_S \left[\frac{1}{Q^2+1}\right] \tag{22.2}$$

where W_{LS}=micro watts per foot

$$\text{Total loss: } W_{LS(T)} = 3\, I^{2} R_S \left[\frac{P^2+Q^2+2}{2(P^2+1)(Q^2+1)}\right] \tag{22.3}$$

$P=R_S/Y$

$Q=R_S/Z$

and

$Y=XM+A$

$Z=X_M-A/3$

$X_M=2\pi f\,(0.1404 \log_{10} S/r_M)$ in µ-ohms/foot

(22.4)

$$A=2\pi f\,(0.1404 \log_{10} 2=15.93\ \mu\text{-ohms/foot} \tag{22.5}$$

$$B=2\pi f\,(0.1404 \log_{10} 5=36.99\ \mu\text{-ohms/foot} \tag{22.6}$$

$$R_S=\rho/8\ r_M=\text{resistanse of armor in } \mu\text{-ohms/foot} \tag{22.7}$$

t=thickness of metal tapes/sheath in inches

f=frequency in hertz

D=distance (spacing) between centers of cables in inches

r_M=mean radius of shield in inches

I=conductor current in amperes

ρ=apparent resistivity of shield in ohms-cmils per foot at operating temperature

Effective values of ρ in ohms-cmils per foot:

Overlapped copper tape	30
Overlapped bronze tape 90–10	47
Overlapped monel tape	2500
Overlapped cupro-nickel tape 80–20	350
Lead sheath	150
Aluminum sheath	20
Aluminum interlocked armor	28
Galvanized steel armor wire	102
5052 aluminum alloy	30
Galvanized steel interlocked armor	70
Stainless steel SS304	43

See the discussion of ampacity in Chapter 13 and metallic shield losses in paragraph 3.6 for additional insight into the general problem. Chapter 15, Section 3 also discusses this situation for land cables. The fact is that the conductor and shield arrangement in a multi grounded system is a one-to-one transformer so the greater the current in the phase conductor of most cable systems, the greater the current will be induced in the armor system—and hence the chances of corrosion escalate. This is a catch 22 in that the desire for additional armor strength runs contrary to the need to reduce sheath currents and hence losses!

Another way to consider this situation is that the more metal there is in the armor system, the closer the current flow comes to the full phase current in the central conductor.

Three conductor cables have negligible current in the armor system as long as the load is reasonably balanced. An unbalanced load does induce current in the armor system and may create some of the same concerns about armor corrosion as single conductor cables.

The same is true if the three single conductor cables are tightly laid together—in the form of a triangle. This defeats the concept of spacing them apart to avoid the same ship or anchor breaking all of them at one time.

The point is that the corrosion of a three conductor or three tightly spaced single conductor submarine cables is considerably less of a factor than for the spaced single conductor cables. An unbalanced load here may become significant.

3.0 CORROSION

Although the armor is occasionally insulated, this discussion will assume that the armor is bare and hence in contact with the sea for its entire length. Even in the situation of insulated armor wires, it is prudent to anticipate some damage to the insulating layer during installation or service-inflicted conditions. One single break in the insulating layer could be a very serious corrosion point unless other measures are taken.

The contact between the metallic armor and the sea, in the presence of an electric field, requires a thorough study of the corrosion factors that could be possible. Only a brief overview of the problems will be addressed here. Three types of metals are used for the armor wires of submarine cables:

- Galvanized steel
- Copper
- Aluminum alloys

3.1 Corrosion Under DC Conditions

The corrosion properties of metals in seawater are frequently analyzed in the laboratory by making weight loss studies. An example of such a test is shown in Table 22-1.

The test setup consisted of samples of cold drawn wire having diameters of 4 to 6 mm. Direct current was circulated between two parallel lengths of the same material about 100 mm long and maintained at a separation of 80 mm in a solution of 3.5% NaCl.

Aluminum, aluminum alloys, and steel corrode according to their electrochemical equivalent and to the transfer of electric charge when subjected to direct current in anodic circumstances. Weight loss on anodic copper was diminished due to the formation of a Cu_2O layer that stopped the current flow with these test conditions. Very low weight loss was observed in cathodic conditions.

Table 22-1 Weight Loss Under dc and 1,000 A/M^2 for 30 Minutes

Metal	Weight Loss for Anode (in kg/m^2)	Weight Loss for Cathode (in kg/m^2)
Aluminum Alloy	0.21	0.004
Copper	0.14	0.0012

Galvanized steel	0.65	0.0008

3.2 Corrosion Under AC Conditions

Weight loss tests for the same materials were performed under ac conditions for different current densities but for the same 1,000 hour time and in accordance with ASTM G1-72.

There is a well-defined threshold of ac density for these materials. Below this threshold, weight loss is not dependent on current density and follows the rules for chemical weight loss—hence they are dependent on their electrochemical potentials.

Table 22-2 Weight Loss Under DC and 1,000 A/M^2 for 1,000 Hours

Metal	**Weight Loss for 10 A/m^2, in kg/m^2**	**Weight Loss for 100 A/m^2 (in kg/m^2)**	**Weight Loss for 1,000 A/m^2 (in kg/m^2)**	**Weight Loss 7000 for A/m^2 (in kg/m^2)**
Alum. Alloy	3.5×10^{-2}	6.0×10	2.0×10^{3}	11.0×10^{3}
Copper	2.5×10^{-2}	7.0×10^{-1}	1.5×10^{2}	0.4×10^{3}
Galv. Steel	1.5×10^{-1}	1.2×1	0.7×10	1.5×10^{2}

3.3 Field Experience

Examination was made of this same aluminum alloy armor from a submarine cable with 5 years of service. Almost all of the corrosion was due to chemical corrosion since there was negligible ac current in the cable and the weight loss of 0.054×10^{-3} kg/m^2 compared closely with the data from Table 22-2.

Copper and galvanized steel show a uniform pattern of corrosion in an ac environment while aluminum alloys demonstrate pitting and localized corrosion.

CHAPTER 23
SEMICONDUCTING JACKETS

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1.0 INTRODUCTION

With the advent of the underground residential distribution (URD) systems in the early 1960s, the emphasis on reducing the costs of those systems led to finding ways to reduce installation costs. One factor was the elimination of jackets for most of the primary cable installed in the United States. The justification for eliminating the overall jacket could be found in the trade journals of the day:

- Better grounding when the copper concentric "neutrals" were placed directly in the ground with bare or coated tin or lead alloy wires.
- Copper wires (<u>especially</u> when coated) resisted corrosion.
- A jacket added over 30% to the cost of the cable at that time.
- Bare concentric neutral cables had shown satisfactory performance since the 1930s—giving the industry a sense of security.

Directly buried cables in Europe continued to use copper shielding tapes and did not bow to the pressure for less expensive non jacketed construction.

"Joint trench" with the power and telephone cables in random separation created a safety concern and tests were conducted to assure the safety of the crews working near those cables. A joint task force under the auspices of the Edison Electric Institute and the Bell System conducted field tests that simulated real world conditions of dig-ins at Franksville, Wisconsin, during the 1960s [23-1,23-2]. Test results led to requirements imposed by the National Electrical Safety Code (ANSI C-2) where such joint trenches with cables in random separation could be built as long as the primary concentric neutral was bare or a buried, bare copper conductor was placed in close proximity to the primary cable. Again costs were considered and the bare concentric neutral cables won the contest. This action was deemed advisable in order to minimize step and touch potentials under fault conditions and hence make it safer for the workers.

Semiconducting jackets made in the early 1960s through the 1980s used the same jacket compounds as the insulation shields. Their properties varied over a wide range. A new class of semiconducting compounds was developed in the 1990s to address the need for an improved jacketing material.

2.0 TECHNICAL DEBATE

A series of papers—all written by one author in the 1970s—reported that semiconducting jackets would have a deleterious effect on other buried metals such as iron and copper [23-3,23-4,23-5]. The basis for this hypothesis was that "semiconducting compounds contain carbon which is cathodic to most common metals." The evidence that semiconducting compounds behave like carbon comes from a small test site in Chevy Chase, MD. Six samples, each ten feet long, were buried in this test plot in 1975 and evaluated for over two years. The six samples were:

(1) tinned copper neutral wires from a cable
(2) complete bare concentric neutral cable from same piece of cable as sample (1)
(3) cable similar to sample 2 but with a semiconductive jacket
(4) number 6 AWG bare copper wire
(5) and (6) both the same as sample 2

The one sample of prime interest now, Sample (3), had the "conductive SPE jacket over the concentric neutral wires." Within a few months, this sample began a slow drift in potential from 0.0 in the beginning to +0.2 in about ten months when compared to a copper-copper sulphate half cell. It remained in the +0.2 to +0.3 volt range for next 20 months of testing. The results are shown in Table 23-1. The source and type of this jacketing material was never presented. The bare neutral cable drifted from −0.28 to +0.5 over the same test period. This confirmed to the author that "SPE insulation shield is a significant factor in corrosion of copper neutral wires." His conclusions included:

1. Potentials of the isolated SPE (semiconducting polyethylene) jacketed cable and bare neutral cable have become significantly more positive than they were the first two years after burial. Both of these specimens are at potentials likely to result in corrosion of copper in soil.
2. For SPE jacketed cable, the cathodic current collected may be increased in the presence of ac.
3. For a copper specimen, small ac voltages may result in anodic currents and corrosion of copper that would not occur in absence of ac.

3.0 FUNCTIONS AND BENEFITS OF A JACKET

Benefits of jackets for URD cables have been given renewed recognition since the early 1970s. Studies showed that jackets reduced water penetration into the insulation—and hence water treeing, improved pulling properties, gave corrosion protection, and demonstrated longer life for cables with a jacket. By 1980, 40% of the URD cable made in North America had a jacket. The cost of a jacket came down rapidly as a percentage of the cost of the base cable to the point that it required only a 6 to 10% premium by 1985.

An overall jacket for a power cable may be either insulating or semiconducting. The type of construction can be divided into two descriptions: (1) embedded, and (2) overlaying, or sometimes called a “tubed” jacket. In the first instance, the jacket material is extruded directly around each wire so that there is virtually no air space around each wire. The overlaying type of jacket is extruded over the wires in a manner that leaves an air space between the wires and sandwiches the neutral wires between the top of the insulation shield and the bottom of the jacket. Both types perform the functions of a jacket that:

1. Protects the underlying cable from physical abuse
2. Protects the underlying cable from chemical attack
3. Protects the neutral wires from corrosion
4. Increases the fault duty of the neutral wires
5. Reduces moisture ingress into the insulation and hence water treeing
6. Adds sunlight resistance
7. Adds flame resistance

Encapsulated jackets also increase the sidewall bearing pressure limits because the wires are held in position during tight pulls.

4.0 EPRI RESEARCH ON SEMICONDUCTING JACKETED CABLES

Recently the use of semiconducting jackets for power cable has been given renewed interest because of improvements of newer, specifically designed compounds. Rather than repeating research efforts on semiconducting jackets, it was realized that answers to the question of corrosion potentials were contained in previously unpublished reports produced by the Electric Power Research Institute [23-6].

4.1 EL-619, Project 671–1, Volume 1, December 1977, “Evaluation of Semiconducting Jacket for Concentric Neutral URD Cable”

Beginning around 1975, this project [23-7] examined:

- □ The mechanisms of corrosion of copper concentric neutrals and test procedures for early detection and mitigation of corrosion on installed cable.
- □ Evaluation of then commercially available semiconducting thermoplastic jacket compounds.
- □ A study of the effects of ac on corrosion of neutral wires.

Eleven semiconducting compounds that were submitted for the study had been compounded for semiconducting shield layers. Five were eliminated by initial screening tests. The remaining six semiconducting materials were applied as jackets over 15 and 35 kV cables. (Bare and insulating jackets were also studied for #2 aluminum, 175 mil XLPE and #1/0 aluminum 345 mil XLPE cables.)

The conclusions from the fault current tests showed that bare and semiconducting jacketed concentric neutral cables exhibited approximately the same step and touch potentials when tested under equivalent conditions. This equivalent performance was contingent on the radial resistivity of the semiconducting jacket being comparable to that of the earth and remaining essentially stable in service. Another conclusion reached regarding these early compounds included was that semiconducting thermoplastic materials are complex structures and their properties vary significantly from one formulation to another.

Section 7 of that report covered the measurement of potentials in underground corrosion studies. A significant finding was that "errors might be encountered in measurements between electrodes in contact with a heterogeneous soil at spacings of a few feet to several hundred feet due to the liquid junction concentration potentials in the earth." Another pertinent statement was that "the permanent copper sulfate electrodes were many millivolts negative to the standard saturated copper sulfate electrode and varied positively and negatively with time." This led to an abandonment of permanent half cells but points out the possibility of errors being made during such testing.

4.2 EL-619, Project 671–1, Volume 2, December 1977, "Cable Neutral Corrosion"

This portion of the project concentrated on outdoor high voltage and high current short circuit tests on the cable mentioned above. The tests were run in Franksville, WI, where faults were triggered in the center of the 100 foot runs to simulate dig-ins. The conclusions were:

1. The voltage at the fault is determined by the supply voltage and circuit impedances.
2. Bare and semiconducting jacketed cables exhibit approximately the same touch and step voltages when tested under equivalent conditions.
3. The touch voltage for a cable with insulating type jacket will be higher than for bare or semiconducting jackets.
4. Voltage gradient in the earth during short circuit conditions is a function of the voltage at the point of fault and the conductance of the backfill and earth to remote ground.

4.3 EL-4042, Project 1144–1, May 1985, "Corrosion of the Concentric Neutrals of Buried URD Cables"

By the early 1980s, considerable advances had been made in semiconducting materials for cable jackets. EPRI funded another project [23-13] that studied 59 different primary cable constructions that included: bare copper neutrals, tinned copper neutrals, lead-alloy coated copper neutrals, iron coated copper neutrals, aluminum neutrals, insulating jackets, and three types of commercially available semiconducting jackets of then state of the art materials.

The purpose of this EPRI project was "To conduct a controlled field and laboratory investigation to determine the contribution of [many corrosion factors] to the concentric neutral corrosion process."

A large site in Florida utilized 100 foot samples of cable that were placed in a designed and uniform soil that had a resistivity of about 2,500 ohm-cm. The test period was 110 weeks.

Results of this project are in direct contrast with the results of the previously described group of six 10-foot samples that were tested in Maryland [23-3,23-4, 23-5]. Table 23-1 shows the potentials of the three semiconducting jacketed cables with respect to a copper-

copper sulphate half-cell in this test site over a 27 month period. The sample marked SC#4N had aluminum wires rather than copper. It is important to note that the potentials of these three samples were always negative to the half-cell and generally in the broad range of −0.2 to −0.6 volts to the reference cell. Another important part of the test was to determine the effect of high current densities on this potential. Note how sample SC#4L swung to a negative one volt when subjected to this high current in the neutral—hence even less likelihood of causing corrosion of nearby materials.

Also included in Table 23-1 is the data from the Maryland test site. Within the first few months, the voltages from the single semiconducting jacket to the reference cell were all positive (rather than negative as in the EPRI work).

Not only did the voltage of all of the semiconducting jacketed cables stay in the negative range for the entire test period, but they were slightly more negative than the ones with bare copper wires. The average value of the voltage to the copper-copper sulphate half-cell of the semiconducting jacketed cables varied from a −0.04 to −1.05. The conclusions of this test included the following:

1. The passage of ac current between the earth and the metallic neutral wires shifted the potential to earth of these wires.

2. There is a threshold of ac current density at which corrosion accelerates: no acceleration below 1.5 mA/cm^2 but greatly accelerated above that value.

3. AC caused a coating of silica or other sand particles to be cemented to the wires. No coating was observed at low current densities, but always found at current densities above the threshold.

The copper remained positive to the semiconducting layer that was a surprise. This would confirm observations by others that the semiconducting material did not produce a bi-metallic corrosion process.

Another point to consider is the fact that all bare neutral cables had the same semiconducting material in contact with the earth as well as touching the neutral wires. If corrosion of steel is possible from that class of materials, then corrosion should be caused by bare neutral cables. This is not the case.

Table 23-1 Potentials in Volts over Cables: Maryland vs. EPRI Results

Months	Maryland	EPRI		
		#3H	#4L	#4N
1	−0.02	−0.54	−0.57	−0.59
2	−0.01			
3	+0.07			
4	+0.12			
5	+0.13	−0.55	−0.25	−0.25
6	+0.14			
7	+0.16			

8	+0.22			
9	+0.23			
10	+0.24	−0.54	−0.24	−0.68
11	+0.24			
12	+0.23			
13	+0.22			
14	+0.22			
15	+0.22			
16	+0.18			
17	+0.18			
18	+0.20			
19	+0.20			
20	+0.25	−0.43	−0.027	−0.63
21				
22				
23				
24	+0.28	−0.53	−1.05	
25	+0.28			
26	+0.28			
27	+0.28			
28	+0.28			
29	+0.28			

5.0 SEMICONDUCTING JACKETS: COMPOSITION AND HISTORY

The semiconducting material used as a jacket for medium voltage URD cable is a resistive thermoplastic composition. This requirement is met by a polymer containing a suitable conductive material as a filler. When semiconducting jackets were first employed in the 1970s, the only available thermoplastic semiconducting materials were the compositions being used for conductor and insulation shields. Several materials were available that were based on thermoplastic ethylene/ethyl acrylate (EEA) or ethylene/vinyl acetate (EVA) copolymers and carbon black. These polymers are relatively amorphous and can tolerate the high filler loading required for conductivity while providing reasonably good physical properties. Other polymers are used in special circumstances. ICEA Publication S-66–524 recognizes Type I and Type II Jackets. The basic difference being that the Type II Jacket has a higher use temperature. This is the well-known DRTP (deformation resistant thermoplastic) shield that was used as a strippable insulation shield on URD cable prior to the introduction of the triple extruded cross-linked strippable insulation shield in the 1980s.

The carbon blacks used to obtain the desired degree of conductivity in these compositions are complex aggregates of very small carbon particles in the 10 to 70 nanometer range. The individual carbon particles may be nearly solid spheres or may be very porous resembling egg-shells. The early semiconducting jacket materials were based on various Furnace Process blacks and contained up to nearly 50 pph (parts per hundred parts of resin) of black. A description of these carbon blacks was previously given in [23-12]; additional detail on blacks can be found in *Carbon Black* edited by Donnet [23-15]. While many physical parameters are required to completely describe a carbon black, a black can be roughly defined by primary particle size, surface area and a measure of the size and complexity of the aggregates. Several authors in Donnet's book discuss this subject and how carbon blacks are used to form semiconductive compositions.

The carbon black is compounded in the polymer by intensive shear and dispersive mixing in one of a variety of suitable apparatus. A common device for this is the Banbury internal mixer. In this batch process, the ingredients are charged into the mixing chamber, which is sealed by a ram to maintain pressure on the batch throughout the mixing cycle. When mixing is complete the batch is discharged into a pelletizing extruder where approximately 1/8 inch cylindrical pellets are formed for subsequent extrusion as a jacket on the cable. In the cable jacket extrusion operation where the semiconductive shield composition is extruded over the cable to form a jacket, it is important that the neutral wires be encapsulated by the jacket. When encapsulation is complete there is good surface contact and conductivity to ground is assured. Without this contact, the grounding of the cable through the jacket is compromised. Also if a pin hole in the jacket should develop with well encapsulated neutrals, there is no opportunity for ground moisture to travel longitudinally along the cable and pool at low spots. There is additional discussion of semiconducting compounds in Chapter 5.

The use of the available thermoplastic semiconducting materials for URD cable jackets in the 1970s and 1980s has been reasonably successful and many miles of cable with these semiconducting jackets are in service. There were several shortcomings that became apparent over time: some of the early semiconducting materials would become less conductive at elevated temperatures. ICEA Publication T25–425 was developed to address this issue and improved, more conductive compositions were developed.

The EEA and EVA polymer based compositions were often the same composition being used for the insulation shield so when the jacket was extruded, adhesion to the insulation shield prevented easy removal of the jacket at joints and terminations. This required a separator such as a layer of talc. While possible, it is difficult to maintain a uniform and continuous layer of separator and a better solution to this problem was desired. Additionally when AEIC CS5 introduced the "Thermo-mechanical bending test," these jackets often cracked and they were occasionally found cracked in the field as well. Finally, the moisture transmission through these jackets was on the order of 10 times greater than the LLDPE (linear low density polyethylene) insulating jackets that reduce the progress of moisture induced treeing in the insulation. To address this issue, a new class of thermoplastic semi-conductive material was developed in the early 1990s. This material performs very nearly up to the values attained by LLDPE insulating jackets. Moisture transmission is nearly as low as with the insulating jacket and the new material consistently passes the thermo-mechanical test in all cable sizes and constructions [23-13]. The new jacket material also does not adhere to the crosslinked insulation shield and no troublesome separator is required.

Table 23-2 Properties of Jacketing Materials

	Semiconducting	**Insulating**
Radial Res., ohm-m	40	na
Tensile, psi	1700	2200
Elongation, %	400	600
Brittleness, °C	−50	−60
Moisture vapor transmission	1.5	0.8

Over the years the availability of high quality thermoplastic semiconducting materials for jackets on URD cables has evolved. The current materials perform well in all respects.

6.0 FIELD EXPERIENCE WITH SEMICONDUCTING JACKETS

Cables with semiconducting jackets have been successfully used for over 35 years on power circuits with no reports of cable failures due to corrosion nor to the corrosion failures of any adjacent equipment.

Semiconducting jackets are being used over URD type cables as a deterrent to corrosion and to provide effective grounding to the cable during lightning strikes and faults. Tests have shown that cables with insulating jackets are prone to lightning punctures of the jacket. Puncture thresholds of 150 to 160 kV for 50 mil jackets and 155 to 170 kV for 80 mil insulating jackets have been reported. When cables with semiconducting jackets were measured under similar circumstances in the laboratory, the neutral to ground voltages were held to less than 50 kV [23-13]. Semiconductive jackets reduce the neutral to ground impulse voltage by improving grounding efficiencies [23-14].

Another value of a semiconducting jacket is the jacket does not have to be removed for the installation of more frequent ground connections—only four per mile as required by the National Electrical Safety Code rather than eight. Such grounding points increase the chance of water penetration as well as other construction errors.

Special semiconducting jacket compounds have now been developed that have low moisture vapor transmission rates that are similar to insulating jacket compounds [23-12]. These new materials are based on LLDPE materials as used in insulating jackets rather than the previously used EVA based materials.

7.0 CONCLUSIONS

1. Semiconducting jackets improve the efficiency of grounding for directly buried cables.
2. Insulating and semiconducting jackets have shown to be effective deterrents to corrosion of concentric neutral wires.
3. Semiconducting jackets have been improved dramatically over the past 25 years for resistance stability, toughness, lower moisture vapor transmission, etc.
4. Cables with semiconducting jackets may be grounded less frequently than cables with insulating jackets—four times per mile per NESC rather than eight times.
5. The potentials in EPRI Project EL-4042 demonstrated that semiconducting jackets from three runs of commercially available cable would not corrode other buried structures such as steel or copper.
6. Field readings of the potential of present day semiconducting jacket material confirms the results of the earlier EPRI project and they cannot corrode nearby iron or copper.
7. Field experience of URD cables with semiconducting jackets in North America has now reached 35 years with about 300 million feet of cable in service with no reported corrosion problems nor adverse effects on other buried structures.
8. The behavior of semiconducting cable sample from the 1970s study in Maryland has not been substantiated in subsequent tests or trials.

8.0 WORK IN PROGRESS

Work is in progress (2002 and 2003) under the sponsorship of the National Rural Electric Cooperative Association to determine if semiconducting materials can cause corrosion in nearby equipment. Their Project is titled “Experimental Investigation of the Effect of Semiconducting Cable Jackets on Adjacent Steel Structures.” This information is scheduled for presentation after this book goes to press and is hence not included.

9.0 ACKNOWLEDGMENTS

Mr. Norman M.Burns, now retired after many years with Union Carbide, contributed the information on the technical perspective of the properties of semiconducting compounds and his contribution has been extremely helpful in obtaining an understanding of these materials.

The author also thanks Joseph H.Dudas, consultant, for the data provided on the amount of semiconducting jacketed cable that has been manufactured.

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CHAPTER 24
GLOSSARY

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Note: this Glossary contains many of the cable terms used throughout this book and is furnished as an aid to understanding the text. The reader is encouraged to utilize the more complete definitions that may be found in the *IEEE Standard Dictionary of Electrical and Electronics Terms,* IEEE Standard 100–1996).

Abrasion Resistance Ability to resist surface wear.

Accelerated Life Test Subjecting a product to test conditions more severe than normal operating conditions, such as voltage and temperature, to accelerate aging and thus to afford some measure of probable life at normal conditions or some measure of the durability of the equipment when exposed to the factors being aggravated.

Acceptance Test A test to demonstrate the degree of compliance with specified requirements or a test demonstrating the quality of the units of a consignment. The term "conformance test" is recommended by ANSI to avoid any implication of contractual relations.

ACLT An acronym that represents 'accelerated cable life test'.

Aging The irreversible change of material properties after exposure to an environment for an interval of time.

Ampacity The current carrying capacity of a cable, expressed in amperes. The current that a cable can carry under stated thermal conditions without degradation.

Ampere (Amp) The basic SI unit of the quantity of electric current. That constant current that if maintained in two straight parallel conductors of infinite length, or negligible cross section, and placed one meter apart in vacuum, would produce a force equal to 2×10^{-7} newton per meter of length.

Amplitude The maximum value of a sinusoidally varying wave form.

Annealing The process of removing or preventing mechanical stress in materials by controlled cooling from a heated state, measured by tensile strength.

Anti-oxidant A chemical additive incorporated into poly-olefins to prevent degradation during extrusion, the process that converts insulation materials into cable insulation over conductors

Asymmetrical Not identical on both sides of a central line; not symmetrical.

Backfill The materials used to fill an excavation, such as sand in a trench.

Bedding A layer of material that acts as a cushion or inter-connection between two elements of a device, such as the jute or polypropylene layer between the sheath and wire armor in a submarine cable.

Bending Radius The inner radius of a cable, such as when it is trained or being installed.

BIL (Basic Impulse Level) The impulse voltage that electrical equipment is required to withstand without failure or disruptive discharge when tested under specified conditions of temperature and humidity. BILs are designated in terms of the crest voltage of a 1.2×50 microsecond full-wave voltage test.

Braid An interwoven cylindrical covering usually of fiber or wire.

Branching Term use to describe that portion of the polymeric insulation that ‘hangs off’ the main chain like a “T”

Bridge A circuit that measures by balancing a number of impedances through which the same current flows.

Butt Lap Complete turn of tape where the adjacent layers are next to each other but do not overlap.

Cable, Aerial An assembly of one or more insulated conductors that are lashed or otherwise fastened to a supporting messenger.

Cable, Belted A multi-conductor cable having a layer of insulation over the assembled insulated conductors.

Cable, Spacer An aerial cable system made of covered conductors supported by insulating spacers; generally for wooded areas.

Cable, Submarine A cable designed for crossing under bodies of water; having mechanical strength for installation and removal, and limited protection from anchors, debris, and other mechanical damage.

Cable, Triplexed A helical assembly of three covered or insulated conductors; sometimes with one bare conductor used as a neutral.

Cable Tray A rigid structure to support cables. A type of raceway normally having the appearance of a ladder. May be open at the top (or side) to facilitate changes, or be covered with a ventilated or solid cover.

Cambric A fine weave of linen, cotton, or other fiber that is used as an insulation base.

Capacitance The storage of electricity in a capacitor. The opposition to voltage change, measured in Farads.

Capacitor Any device having two conductors separated by insulation with the conductors having opposite electrical charges.

Capstan A rotating drum used to pull cables or ropes by friction as they are wrapped around the drum.

Carbon Black A black pigment produced by the incomplete burning of natural gas or oil; used for semiconducting purposes.

Catalyst A material used to induce polymerization of monomers to convert them into polymeric insulation materials These may be peroxide or metallocenes

Catenary The natural curve assumed by a completely flexible material hanging freely between two supports. A cable curing tube having a catenary curvature.

Cellulose Material derived form wood that is used to manufacture paper for cables

Corona Extinction Voltage (CEV) The voltage at which partial discharge is no longer detectable within the dielectric structure when measured with instrumentation having specific sensitivity, following the application of a higher voltage to achieve corona inception.

Charge The quantity of positive or negative ions in or on an object; unit: coulomb.

Corona Inception Voltage (CIV) The voltage at which partial discharge is initiated within the dielectric structure with instrumentation having specific sensitivity.

Coefficient of Friction The ratio of the tangential force needed to start or maintain relative motion between two contacting surfaces to the perpendicular force holding them in contact.

Conduit Fill The percentage of cross-sectional area used in a conduit as compared with the cross-sectional area of the conduit.

Continuous Vulcanization A system utilizing heat, and frequently pressure, to vulcanize materials after extrusion onto a conductor.

Copolymer An insulation material comprised of more than one type of monomer. Examples of copolymers are ethylene-propylene rubbers, ethylene-ethyl acrylate and ethylene-vinyl acetate (both used as shields)

Corona An electrical discharge caused by ionization of a gas by an electrical field.

Corrosion The deterioration of a substance (usually a metal) as a result of a chemical reaction with its environment.

Crosslinking A molecular structure where different polymer insulation material chains are joined to form a three-dimensional network. This is in contrast to where the chains are entangled together, but not joined. Cross-linking improves mechanical and physical properties.

Crosslinking Agent A chemical the causes different polymer insulation material chains to join together. The most common type is an organic peroxide, such as di-cumyl peroxide.

Crystallinity Refers to the tendency that certain insulation materials have to ‘align’ and form ordered regions (instead of being random). Insulation materials such as polyethylene (or polypropylene) are considered to be ‘semi-crystalline’ as portions of their polymer chains have this tendency.

Current, Charging The current needed to bring a cable, or other capacitor, up to voltage; determined by capacitance of the cable. After withdrawal of voltage, the charging current returns to the circuit. For ac circuits, the charging current will be 90 degrees out of phase with the voltage.

Current, Induced Current in a conductor due to the application of a time-varying electromagnetic field.

Current, Leakage That small amount of current that flows through insulation whenever a voltage is present. The leakage current is in phase with the voltage and is a power loss.

Curing A term used interchangeably with ‘cross-linking’, but generally within the context of processing

Density (physics) The ratio of mass to volume at a specified temperature. Term also used to describe the ‘tightness ‘of the packing of the polymer molecules in an insulation; the more tight the packing, the higher the density.

Dielectric Absorption The storage of charges within an insulation (dielectric); evidenced by the decrease of current flow after application of dc voltage.

Dielectric Constant The capacitance of a dielectric in comparison with the capacitance of a vacuum where both capacitors have identical geometry. Also referred to as specific inductive capacity (SIC).

Dielectric Loss The time rate at which electrical energy is transformed into heat when a dielectric is subjected to a changing electric field.

Dielectric Strength The maximum voltage that an insulation can withstand without breaking down; usually expressed as a gradient—volts per mil or kilovolts per millimeter.

Direction of Lay The longitudinal direction in which the components of a cable (stands) run over the top of the cable as they recede from an observer looking along the axis of a cable; expressed as left-hand or right-hand.

Dissipation Factor The energy lost when voltage is applied across an insulation due to reactive current flow. Also known as power factor and tan delta.

Drain Wires A group of small gage wires helically applied over a semiconducting insulation shield that is designed as a path for leakage current return—as opposed to fault current or a system neutral.

Eccentricity A measure of the centering of an item within a circular area. The ratio, expressed as a percentage, of the difference between the maximum and minimum thickness (or diameter) of an annular area.

Eddy Currents Circulating currents induced in conducting materials by varying magnetic fields; usually considered undesirable because they represent loss of energy and create heat.

Electrical Treeing An aging-induced defect that occurs in electrical insulation materials resulting from the application of voltage stress in the absence of water. These trees develop over periods of time significantly longer that do water trees.

Elongation The fractional increase in length of a material as it is stressed under tension. The amount of stretch of a material in a given length before breaking.

Endosmosis The penetration of water into a cable insulation by osmosis. Aggravated and accelerated by dc and ac voltage across the insulation where it is also known as electro-endosmosis.

EPDM An insulation material comprised of three monomers, ethylene, propylene and a third monomer generally referred to as a ‘diene-monomer.

EPR An insulation material comprised of a co-polymer of ethylene and propylene.

Extrusion The process that converts insulation material, generally in pellet form, into cable insulation over the conductor and conductor shield.

Filler A relatively inert and low-cost material added to a compound to improve physical properties and make it less costly.

Flame Retardant Does not support or spread flame. An additive that enhances the flame resistance of a compound.

Gel Fraction The crosslinked portion of ‘crosslinked’ polyethylene or EPR.

Hard Drawn A relative measure of temper; drawn to obtain maximum tensile strength.

Hardness Resistance to plastic deformation; stiffness or temper; resistance to scratching, abrasion, or cutting.

Heat Shrink A term employed for certain types of joints that will shrink upon heating after they are applied in the field. The ‘shrinking’ process is a result of the polymeric material (polyolefin) being expanded after manufacture, and provided to the user in the expanded form.

High Molecular Weight Molecular weight is a function of the number of polymer molecules in an insulation material. For example, polyethylene is comprised of many ethylene molecules. High molecular weight means that there are “many” such molecules, rather than a few. A low molecular weight polyethylene (not used as an insulation would have few molecules.

Hypalon Trade name for chlorosulphanated polyethylene.

Impedance (Z) The opposition to current flow in an ac circuit; impedance consists of resistance, capacitive reactance, and inductive reactance.

Insulated Separated from other surfaces by a substance permanently offering a high resistance to the passage of energy through that substance.

Insulation Level The thickness of insulation for circuits having ground fault detectors which interrupt fault currents within one minute (100% level), one hour (133% level), or over one hour (173% level).

Intercalated Tapes Two or more tapes applied simultaneously so that each tape overlays a portion of the other. Example: copper and carbon shielding tapes in paper insulted cables.

Interstices A space between strands of a conductor or between individual phases of a multi-conductor cable.

Ionization (1) The process or the result of any process by which a neutral atom or molecule acquires charge. (2) A breakdown that occurs in gaseous phases of an insulation when dielectric stress exceeds a critical value without initiating a complete breakdown of the insulation system.

Ionization Factor The difference between dissipation factors at two specified values of electrical stress. The lower of the two stresses is usually selected that the effect of the ionization on dissipation factor is negligible.

Insulation Resistance The measurement of dc or ac resistance of a dielectric at a specified temperature. May be either volume or surface resistivity.

Irradiation Bombardment with a variety of subatomic particles that usually causes changes in physical properties. A form of crosslinking by bombardment with high-energy electrons.

Lignin The material in the wood that holds the cellulose and other components together; it is removed prior to paper manufacture due to it lossy nature

Jacket A non-metallic polymeric protective covering over cable insulation or shielding.

Jamming The wedging of three or more cables in a conduit such that they can no longer be moved during cable pulling.

Jam Ratio The ratio of the overall diameter of one cable to the inner diameter of the conduit I from which they are being pulled. For three cables in a conduit, the critical jam ratio is between 2.8 and 3.2.

Lay The axial length of one turn of the helix of any component of a cable.

Lay Length Distance along the axis for one turn of a helical component.

Load Factor The ratio of the average to the peak load over a specified period of time.

Magnetic Field The force field surrounding any current carrying conductor.

MCM Old form of “thousand circular mils” for conductor size in English system; presently kcmil.

Mil Unit of measure of a conductor equal to 0.001 inch.

mm Millimeter. Unit of measure equal to 0.001 meter.

Monomer A term denoting a single property or ingredient. A molecule of low molecular weight used as a starting material to produce molecules of larger molecular weight called polymers.

Mouse A device that is attached to one end of a line and blown into a duct or pipe for use in installation of a pulling line. Usually consists of a series of rubber gaskets sized to fit the duct or pipe.

Mutual Inductance The common property of two electric circuits whereby an electromotive force in induced in one circuit by a change of current in the other circuit.

MW Megawatt, equal to 1,000 kilowatts and 1,000,000 watts.

Nominal A term used to describe functional behavior as being within expected norms or as designed.

Ohm The SI unit of electrical resistance; one ohm equals one volt per ampere.

Organic Matter originating from plant or animal life; composed of chemicals—such as carbon and hydrogen.

Oscillation The variation, usually with time, of the magnitude of a quantity which is alternatively greater or smaller than a reference.

Oscillograph An instrument for recording or making visible the oscillations of a electrical quantity.

Osmosis The diffusion of fluids through a membrane.

Oxidize (1) To combine with oxygen, (2) to remove one or more electrons, (3) to dehydrogenate.

Oxygen Index A test to rate flammability of materials in a mixture of oxygen and nitrogen.

Ozone A form of oxygen, O^3, produced by a high electrical stress; active molecules of oxygen.

Parameter The characteristic of a circuit from which other voltages or currents are referenced with respect to magnitude and time displacement—usually under steady-state conditions.

Permeability (1) The passage or diffusion of a vapor, liquid, or solid through a barrier without physically or chemically affecting either, (2) the rate of such passage.

pH An expression of the degree of acidity or alkalinity of a substance on a scale of one to ten. Acid is less than 7.0, neutral is 7.0, and alkaline is over 7.0.

Phase Angle The measure of the progression of a periodic wave in time or space from a chosen instant or position.

Phase Conductor Any of the main conductors of a cable other than the neutral.

Phase Sequence The order in which the successive members of a periodic wave reach their positive maximum values.

Pig (1) A device to isolate a portion of a pipeline to permit the local application of a test pressure. (2) An ingot of metal, such as lead.

Pilot Wire An auxiliary insulated conductor in a circuit used for control or data transmission.

Plasticizers Chemical agents added during compounding of certain polymeric materials (most commonly PVC-polyvinyl chloride) to make them more flexible and pliable.

Polarization Index Typically the ratio of insulation resistance after ten minutes to the measured value at one minute.

Polyethylene An insulation material comprised of many ethylene molecules

Polymer A high molecular weight compound whose structure can usually be represented by a repetition of small units of that compound.

Polyolefin A term that encompasses all insulation materials that are comprised of carbon and hydrogen. This included polyethylene, cross-linked polyethylene, polypropylene and ethylene-propylene copolymers.

Pothead (1) A termination of a cable (potential head). (2) A device for sealing the end of a cable while providing insulated egress for the conductor or conductors. Most commonly associated with the porcelain housings for paper insulated cables.

Power Factor (power) The cosine of the phase angle between the voltage and the current. Power factor is of interest because it is the measure of useful work. A unity power factor means that all of the current is used for useful work.

Power Factor (cable) A typical cable has a power factor of about 0.1 or less—meaning that it is almost a perfect capacitor and the majority of the current consumed by the charging current of the cable is not “useful” power. For cable purposes, the power factor is expressed as the tangent of the angle delta between the current and the voltage. For the small angles found in typical medium voltage power cables, the sin δ, tan δ and cos Θ are essentially equal.

Power Loss Losses due to internal cable impedances, such as the conductor I^2R and the dielectric losses in the insulation. These losses create heat.

Pulling Compound The lubricating compound applied to the surface of a cable to reduce the coefficient of friction during installation in conduits and ducts.

Pulling Eye A device attached to the end of a cable to facilitate field connection of the pulling ropes.

Quadruplexed Four conductors twisted together.

Relative Capacitance The ratio of the material’s capacitance to that of a vacuum of the same configuration. Also known as specific inductive capacitance (SIC).

Reverse Lay Reversing the direction of lay. For multiple conductor aerial cables, a reversal in lay at a specified distance to facilitate field connections.

Rockwell Hardness A measure of hardness of a material to indentation by a diamond or steel ball under pressure at two levels of stress.

Screen Pack A series of metal screens used in an extruder for straining out impurities.

Semiconducting A conducting medium where conducting is by electrons. The resistance of these materials is generally in the range between that of conductors and insulators.

Shield An electrically conducting layer that provides a smooth surface with the surface of the insulation. In Europe, this is called a “screen.”

Sidewall Bearing Pressure The normal force on a cable under tension at a bend. This is a force that tends to flatten or crush the cable and is usually given as an allowable force for a given distance.

Silane A silicone-based monomer that can be used to impregnate polyethylene or cross-linked polyethylene insulated cables and react with water, and undergoes in-situ cross-linking.

Skin Effect The tendency of current to crowd toward the outer surface of a conductor that increases with conductor diameter and frequency of the applied current.

Sol Fraction The uncross-linked portion of ‘cross-linked’ polyethylene or EPR.

Specific Inductive Capacitance The energy lost when voltage is applied across an insulation due to the reactive current flow. Also known as dissipation factor.

Strand, Sector A stranded conductor formed into sectors of a circle to reduce the overall diameter of the cable.

Strand, Segmental A stranded conductor formed of sectors that are insulated from one another to reduce the ac resistance of the conductor.

Strand, Unilay A stranded conductor having a unidirectional lay of the various wires. Frequently used in low voltage power cables.

Stress Relief Cone A mechanical component of a termination to reduce electrical stress levels on a shielded cable, originally in the shape of a cone.

Stripping Strength Refers to the ease (or lack of) when the insulation shield is ‘peeled’ from the insulation surface.

Tandem Extrusion Extruding two or more layers on a conductor where the extruders are in close proximity to one another.

Thermoplastic A polymeric insulation materials that possesses the quality of softening when heated.

Thermosetting Materials that, upon curing, undergo an irreversible chemical and physical property change as a result of the cross-linking process.

Tinned A strand having a thin coating of pure tin or an alloy of tin and lead. Used over copper to reduce the effect of sulfur from certain rubber compounds and to facilitate solder connections. Many aluminum connectors are also tin plated to minimize the formation of aluminum oxide.

Treeing An aging induced defect in insulation materials that imparts a tree like appearance to the affected region. Treeing is generally refereed to as electrical treeing or water treeing.

Triplexed Three conductors or cables that are twisted together.

Voltage Rating The designated maximum permissible phase-to-phase ac (or direct current) voltage at which a cable is designed to operate.

Vulcanize To cure by chemical reaction. Produces changes in the physical properties of the material by the reaction of an additive (originally sulfur) at an elevated temperature.

Water Tree An aging induced defect in insulation materials that results from the application of voltage stress in the presence of water. This may result at normal operating stress over periods of time that are relatively short compared to electrical treeing.

CHAPTER 25
TABLES AND DATA

1.0 GREEK ALPHABET

Greek Letter		Greek Name	English Equivalent	
Α	**α**	**Alpha**	**A**	**a**
Β	**β**	**Beta**	**B**	**b**
Γ	**γ**	**Gamma**	**G**	**g**
Δ	**δ**	**Delta**	**D**	**d**
Ε	**ε**	**Epsilon**	**E**	**e**
Ζ	**ζ**	**Zeta**	**Z**	**z**
Η	**η**	**Eta**	**E’**	**e’**
Θ	**θ**	**Theta**	**th**	
Ι	**ι**	**Iota**	**i**	
Κ	**k**	**Kappa**	**K**	**k**
Λ	**λ**	**Lambda**	**L**	**l**
Μ	**μ**	**Mu**	**M**	**m**
Ν	**v**	**Nu**	**N**	**n**
Ξ	**ξ**	**Xi**	**X**	**x**
Ο	**ο**	**Omicron**	**O**	**o**
Π	**π**	**Pi**	**P**	**p**
p	**ρ**	**Rho**	**R**	**r**
Σ	**σ**	**Sigma**	**S**	**s**
Τ	**τ**	**Tau**	**T**	**t**
Υ	**υ**	**Upsilon**	**U**	**u**
Φ	**ϕ**	**Phi**	**ph**	
Χ	**χ**	**Chi**	**ch**	
Ψ	**ψ**	**Psi**	**ps**	
Ω	**ω**	**Omega**	**o**	

2.0 TABLES

The tables in this chapter have been copied by permission of the groups that are specifically mentioned. It did not seem wise to abridge these tables since they are the basis for most North American cable designs—especially in the power field.

Figure 25-1 Stress concentration at tip of a conductive ellipsoid in a uniform electrical field.

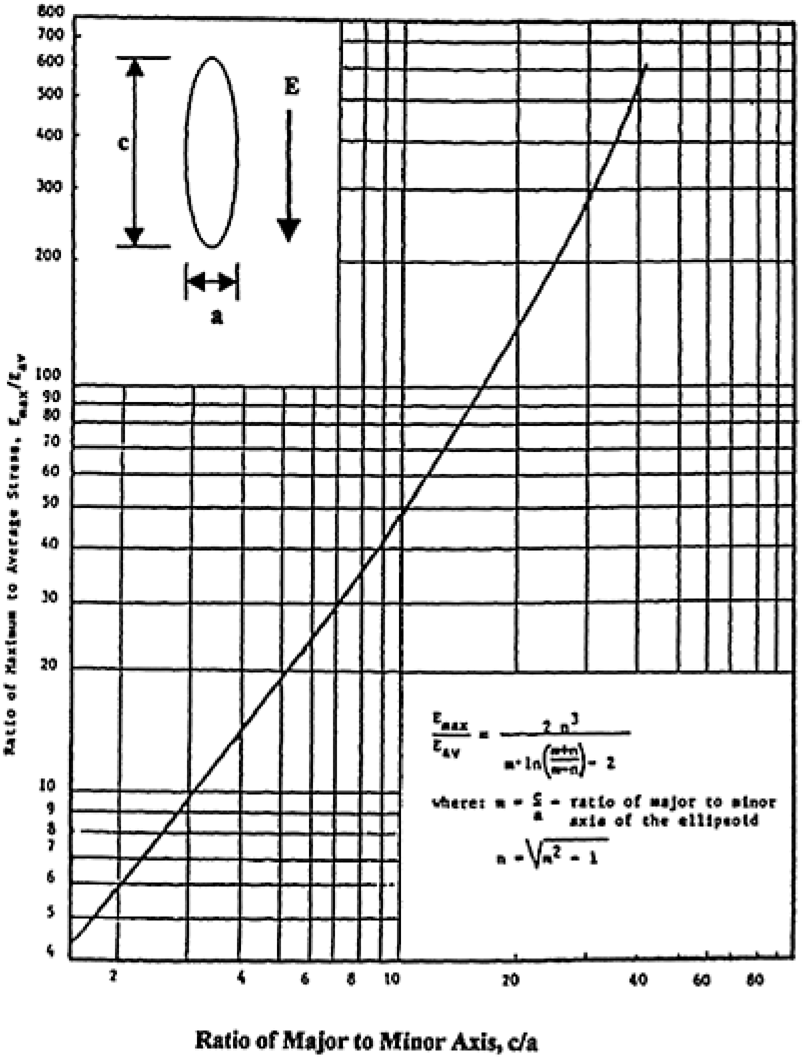

Figure 25-2 Typical leakage curve of dc current, assuming constant voltage.

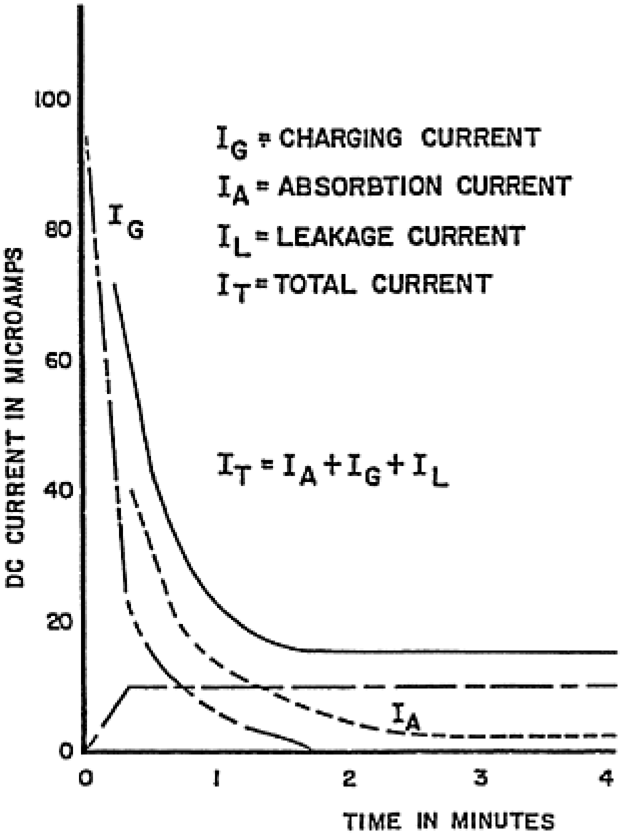

Table 25-1

Nominal Direct Current Resistance in Ohms Per 1000 Feet** at 25°C (77°F) of Solid and Concentric Lay stranded Conductor

Conductor Size	Solid			Concentric Lay Stranded*				
	Aluminum	Copper		Aluminum	Copper			
AWG or kcmil		Uncoated	Coaled	Class, B, C, D	Uncoated	Coaled		
					Class B, C, D	Class B	Class C	Class D
22	27.1	16.5	17.2	27.4	16.7	17.9	…	…
20	16.9	10.3	10.7	17.3	10.5	11. 1	…	…
19	13.5	8.20	8.52	13.7	8.33	8.83	…	…
18	10.7	6.51	6.76	10.9	6.67	7.07	…	…
17	8.45	5.15	5.33	8.54	5.21	3.52	…	…
16	6.72	4.10	4.26	6.85	4.18	4.43	…	…
15	5.32	3.24	3.37	5.41	3.30	3.43	…	…
14	4.22	2.57	2.67	4.31	2.63	2.73	2.79	2.83
13	3.34	2.04	2.12	3.41	2.08	2.16	2.21	2.22
12	2.66	1.62	1.68	2.72	1.66	1.72	1.75	1.75
11	2.11	1.29	1.34	2.15	1.31	1.36	1.36	1.39
10	1.67	1.02	1.06	1.70	1.04	1.08	1.08	1.11
9	1.32	0.808	0.831	1.35	0.825	0.856	0.856	0.874
8	1.05	0.640	0.659	1.07	0.652	0.678	0.678	0.680
7	0.833	0.508	0.522	0.851	0.519	0.538	0.538	0.538
6	0.661	0.403	0.414	0.675	0.411	0.427	0.427	0.427
5	0.524	0.319	0.329	0.534	0.325	0.338	0.339	0.339
4	0.415	0.253	0.261	0.424	0.258	0.269	0.269	0.269
3	0.329	0.201	0.207	0.336	0.205	0.213	0.213	0.213
2	0.261	0.159	0.164	0.266	0.162	0.169	0.169	0.169
1	0.207	0.126	0.130	0.211	0.129	0.134	0.134	0.134
1/0	0.164	0.100	0.102	0.168	0.102	0.106	0.106	0.106
2/0	0.130	0.0794	0.0813	0.133	0.0810	0.0842	0.0842	0.0842

3/0	0.103	0.0630	0.0645	0.105	0.0642	0.0667	0.0669	0.0669
4/0	0.0819	0.0500	0.0511	0.0836	0.0510	0.0524	0.0530	0.0530
250	0.0694	…	…	0.0707	0.0431	0.0448	0.0448	0.0448
300	0.0578	…	…	0.0590	0.0360	0.0374	0.0374	0.0374
350	0.0495	…	…	0.0505	0.0308	0.0320	0.0320	0.0320
400	0.0433	…	…	0.0442	0.0269	0.0277	0.0280	0.0280
450	0.0385	…	…	0.0393	0.0240	0.0246	0.0249	0.0249
500	0.0347	…	…	0.0354	0.0216	0.0222	0.0224	0.0224
550	…	…	…	0.0321	0.0196	0.0204	0.0204	0.0204
600	…	…	…	0.0295	0.0180	0.0187	0.0187	0.0187
650	…	…	…	0.0272	0.0166	0.0171	0.0172	0.0173
700	…	…	…	0.0253	0.0154	0.0159	0.0160	0.0160
750	…	…	…	0.0236	0.0144	0.0148	0.0149	0.0150
100	…	…	…	0.0221	0.0135	0.0139	0.0140	0.0140
900	…	…	…	0.0196	0.0120	0.0123	0.0126	0.0126
1000	…	…	…	0.0177	0.0108	0.0111	0.0111	0.0112
1100	…	…	…	0.0161	0.00981	0.0101	0.0102	0.0102
1200	…	…	…	0.0147	0.00899	0.00925	0.00934	0.00934
1250	…	…	…	0.0141	0.00863	0.00888	0.00897	0.00897
1300	…	…	…	0.0136	0.00830	0.00854	0.00861	0.00862
1400	…	…	…	0.0126	0.00771	0.00793	0.00793	0.00801
1500	…	…	…	0.0118	0.00719	0.00740	0.00740	0.00747
1600	…	…	…	0.0111	0.00674	0.00694	0.00700	0.00700
1700	…	…	…	0.0104	0.00634	0.00653	0.00659	0.00659
1750	…	…	…	0.0101	0.00616	0.00634	0.00640	0.00640
1800	…	…	…	0.00982	0.00599	0.00616	0.00616	0.00622
1900	…	…	…	0.00931	0.00568	0.00584	0.00584	0.00589
2000	…	…	…	0.00885	0.00539	0.00555	0.00555	0.00560
2500	…	…	…	0.00715	0.00436	0.00448	…	…
3000	…	…	…	0.00596	0.00363	0.00374	…	…
3500	…	…	…	0.00515	0.00314	0.00323	…	…
4000	…	…	…	0.00451	0.00275	0.00283	…	…

4500	**…**	**…**	**…**	**0.00405**	**0.00247**	**0.00254**	**…**	**…**
5000	**…**	**…**	**…**	**0.00364**	**0.00222**	**0.00229**	**…**	**…**

*** Concentric lay stranded includes compressed and compact conductors.**
**** Resistance values in milliohms per meter shall be obtained by multiplying the above values by 3.28.**

Table 25-2 Nominal Direct Current Resistance in Ohms Per 1000 Feet* At 25°C (77°F) For Flexible Aluminum Conductors

Conductor Size	Class G	Class H	Class I
AWG or kcmil			
8	…	…	1.07
7	0.858	…	0.850
6	0.681	…	0.687
5	0.540	…	0.545
4	0.428	…	0.432
3	0.340	…	0.343
2	0.269	0.272	0.272
1	0.216	…	0.216
1/0	0.171	0.172	0.172
2/0	0.136	0.136	0.137
3/0	0.107	0.108	0.109
4/0	0.0852	0.0857	0.0861
250	0.0725	0.0728	0.0735
300	0.0604	0.0607	0.0613
350	0.0518	0.0520	0.0525
400	0.0453	0.0455	0.0460
450	0.0403	0.0405	0.0409
500	0.0363	0.0364	0.0368
550	0.0331	0.0334	0.0334
600	0.0304	0.0306	0.0306
650	0.0280	0.0283	0.0286
700	0.0260	0.0263	0.0265
750	0.0243	0.0245	0.0247

800	**0.0228**	**0.0230**	**0.0232**
900	**0.0202**	**0.0204**	**0.0206**
1000	**0.0182**	**0.0184**	**0.0186**
1100	**0.0166**	**0.0167**	**0.0169**
1200	**0.0152**	**0.0153**	**0.0155**
1250	**0.0146**	**0.0147**	**0.0148**
1300	**0.0140**	**0.0141**	**0.0143**
1400	**0.0130**	**0.0131**	**0.0133**
1500	**0.0121**	**0.0123**	**0.0124**
1600	**0.0115**	**0.0115**	**0.0116**
1700	**0.0108**	**0.0108**	**0.0109**
1750	**0.0105**	**0.0105**	**0.0106**
1800	**0.0102**	**0.0102**	**0.0103**
1900	**0.00968**	**0.00968**	**0.00977**
2000	**0.00919**	**0.00919**	**0.00928**

*** Resistance values in milliohms per meter shall be obtained by multiplying the above values by 3.28.**

Table 25-3

Nominal Direct Current Resistance in Ohms Per 1000 Feet* At 25°C (77°F)

For Flexible Annealed Copper Conductors

Conductor Size	Uncoated					Coated				
	Class G	Class H	Class I	Class K	Class M	Class G	Class H	Class I	Class K	Class M
AWG or kcmil										
20	…	…	…	10.6	10.6	…	…	…	11.4	11.4
18	…	…	…	6.66	6.66	…	…	…	7.15	7.15
16	…	…	…	4.18	4.18	…	…	…	4.49	4.49
14	2.65	…	…	2.62	2.62	2.81	…	…	2.82	2.82
12	1.67	…	…	1.65	1.68	1.77	…	…	1.77	1.81
10	1.05	…	1.04	1.04	1.06	1.11	…	1.08	1.12	1.14

9	0.832	…	0.824	0.840	0.840	0.884	…	0.857	0.902	0.902
8	0.660	0.666	0.653	0.666	0.666	0.701	0.708	0.679	0.715	0.715
7	0.523	0.528	0.518	0.528	0.533	0.544	0.561	0.539	0.567	0.573
6	0.415	0.419	0.419	0.419	0.423	0.432	0.445	0.436	0.450	0.454
5	0.329	0.332	0.332	0.332	0.336	0.342	0.353	0.346	0.357	0.360
4	0.261	0.263	0.263	0.263	0.266	0.271	0.280	0.274	0.283	0.286
3	0.207	0.209	0.209	0.211	0.213	0.215	0.222	0.217	0.227	0.227
2	0.164	0.166	0.166	0.167	0.169	0.171	0.172	0.172	0.180	0.181
1	0.131	0.132	0.131	0.133	0,134	0.137	0.140	0.137	0.142	0.144
1/0	0.104	0.105	0.105	0.105	0.106	0.108	0.109	0.109	0.113	0.114
2/0	0.0826	0.0830	0.0834	0.0842	0.0850	0.0859	0.0863	0.0868	0.0904	0.0913
3/0	0.0655	0.0659	0.0662	0.0668	0.0674	0.0682	0.0685	0.0688	0.0717	0.0724
4/0	0.0520	0.0522	0.0525	0.0530	0.0535	0.0541	0.0543	0.0546	0.0569	0.0574
250	0.0442	0.0444	0.0448	0.0448	0.0453	0.0460	0.0462	0.0466	0.0481	0.0486
300	0.0368	0.0370	0.0374	0.0374	0.0377	0.0383	0.0385	0.0389	0.0401	0.0405
350	0.0316	0.0317	0.0320	0.0323	0.0323	0.0328	0.0330	0.0333	0.0347	0.0347
400	0.0276	0.0278	0.0280	0.0283	0.0283	0.0287	0.0289	0.0291	0.0304	0.0304
450	0.0246	0.0247	0.0249	0.0251	0.0251	0.0255	0.0257	0.0259	0.0270	0.0262
500	0.0221	0.0222	0.0224	0.0226	0.0226	0.0230	0.0231	0.0233	0.0243	0.0243
550	0.0202	0.0204	0.0204	0.0206	0.0206	0.0210	0.0212	0.0212	0.0221	0.0221
600	0.0185	0.0187	0.0187	0.0189	0.0189	0.0192	0.0194	0.0194	0.0203	0.0202
650	0.0171	0.0172	0.0174	0.0174	0.0174	0.0178	0.0179	0.0181	0.0187	0.0187
700	0.0159	0.0168	0.0162	0.0162	0.0162	0.0165	0.0167	0.0168	0.0174	0.0174
750	0.0148	0.0149	0.0151	0.0151	0.0151	0.0154	0.0155	0.0157	0.0162	0.0162
800	0.0139	0.0140	0.0141	0.0141	0.0141	0.0144	0.0146	0.0147	0.0152	0.0152
900	0.0123	0.0125	0.0126	0.0126	0.0126	0.0128	0.0130	0.0131	0.0135	0.0135
1000	0.0111	0.0112	0.0113	0.0113	0.0113	0.0115	0.0117	0.0118	0.0122	0.0121
1100	0.0101	0.0102	0.0103	…	…	0.0105	0.0106	0.0107	…	…
1200	0.00925	0.00934	0.00943	…	…	0.00962	0.00971	0.00981	…	…
1250	0.00888	0.00897	0.00905	…	…	0.00924	0.00933	0.00941	…	…
1300	0.00854	0.00862	0.00870	…	…	0.00888	0.00897	0.00905	…	…
1400	0.00793	0.00801	0.00808	…	…	0.00825	0.00833	0.00841	…	…

1500	0.00740	0.00747	0.00754	…	…	0.00770	0.00777	0.00785	…	…
1600	0.00701	0.00701	0.00707	…	…	0.00729	0.00729	0.00735	…	…
1700	0.00659	0.00659	0.00666	…	…	0.00686	0.00686	0.00692	…	…
1750	0.00641	0.00641	0.00647	…	…	0.00666	0.00666	0.00672	…	…
1800	0.00623	0.00623	0.00629	…	…	0.00648	0.00648	0.00654	…	…
1900	0.00590	0.00590	0.00596	…	…	0.00614	0.00614	0.00619	…	…
2000	0.00561	0.00561	0.00566	…	…	0.00583	0.00583	0.00588	…	…

Resistance values in milliohms per meter shall be obtained by multiplying the above values by 3.28.

Table 25-4

Nominal Diameters for Copper and Aluminum Conductors

Conductor Size		Nominal Diamelers•					
			Concentric Lay Stranded				
		Solid	Compact	Compressed	Class B	Class C	Class D
AWG	kcmil	Inch	Inch	Inch	Inch	Inch	Inch
22	0.812	0.0253	…	…	…	…	…
20	1.02	0.0320	…	…	…	…	…
19	1.29	0.0359	…	…	…	…	…
18	1.62	0.0403	…	…	…	…	…
17	2.05	0.0453	…	…	…	…	…
16	2.58	0.0508	…	…	…	…	…
15	3.26	0.0571	…	0.0629	0.0648	…	…
14	4.11	0.0641	…	0.0704	0.0727	0.0735	0.0735
13	5.18	0.0720	…	0.0792	0.0816	0.0825	0.0826
12	6.53	0.0808	…	0.0888	0.0915	0.0925	0.0931
11	8.23	0.0907	…	0.0998	0.103	0.104	0.104
10	10.38	0.1019	…	0.112	0.116	0.117	0.117
9	13.09	0.1144	…	0.126	0.130	0.131	0.132
8	16.51	0.1285	0.134	0.141	0.146	0.148	0.148
7	20.82	0.1443	…	0.158	0.164	0.166	0.166
6	26.24	0.1620	0.169	0.178	0.184	0.186	0.186
5	33.09	0.1819	…	0.200	0.206	0.208	0.209

4	41.74	0.2043	0.213	0.225	0.232	0.234	0.235
3	52.62	0.2294	0.238	0.252	0.260	0.263	0.264
2	66.36	0.2576	0.268	0.283	0.292	0.296	0.297
1	83.69	0.2893	0.299	0.322	0.332	0.333	0.333
1/0	105.6	0.3249	0.336	0.361	0.372	0.374	0.374
2/0	133.1	0.3648	0.376	0.406	0.418	0.420	0.420
3/0	167.8	0.4096	0.423	0.456	0.470	0.471	0.472
4/0	211.6	0.4600	0.475	0.512	0.528	0.529	0.530
	250	0.5000	0.520	0.558	0.575	0.576	0.576
	300	0.5477	0.570	0.611	0.630	0.631	0.631
	350	0.5916	0.616	0.661	0.681	0.681	0.682
	400	0.6325	0.659	0.706	0.728	0.729	0.729
	450	0.6708	0.700	0.749	0.772	0.773	0.773
	500	0.7071	0.736	0.789	0.813	0.814	0.815
	550	…	0.775	0.829	0.855	0.855	0.855
	600	…	0.813	0.866	0.893	0.893	0.893
	650	…	0.845	0.901	0.929	0.930	0.930
	700	…	0.877	0.935	0.964	0.965	0.965
	750	…	0.908	0.968	0.998	0.999	0.998
	800	…	0.938	1.000	1.030	1.032	1.032
	900	…	0.999	1.061	1.094	1.093	1.095
	1000	…	1.060	1.117	1.152	1.153	1.153
	1100	…	…	1.173	1.209	1.210	1.211
	1200	…	…	1.225	1.263	1.264	1.264
	1250	…	…	1.251	1.289	1.290	1.290
	1300	…	…	1.275	1.314	1.316	1.316
	1400	…	…	1.323	1.365	1.365	1.365
	1500	…	…	1.370	1.412	1.413	1.413
	1600	…	…	1.415	1.459	1.460	1.460
	1700	…	…	1.459	1.504	1.504	1.504
	1750	…	…	1.480	1.526	1.527	1.527
	1800	…	…	1.502	1.548	1.548	1.549

1900	**…**	**…**	**1.542**	**1.590**	**1.590**	**1.591**
2000	**…**	**…**	**1.583**	**1.632**	**1.632**	**1.632**

*** Diameters in millimeters shall be obtained by multiplying the above values in inches by 25.4.**

Table 25-5

Factors** for Determining Nominal Resistance of Stranded Conductors Per 1000 Feet

	All Sizes, Uncoated		**Diameter of Individual Coated Copper Wires in Inches for Stranded Conductors**				
Conductivity, Percent	**Aluminum**	**Copper**	**0.460 to 0.290 Inclusive**	**Under 0.290 to 0.103, Inclusive**	**Under 0.103 to 0.0201, Inclusive**	**Under 0.0201 to 0.0111, Inclusive**	**Under 0.0111 to 0.0010, Inclusive**
	61	**100**	**97.66**	**97.16**	**96.16**	**94.16**	**93.15**
	25°C	**25°C**	**25°C**	**25°C**	**25°C**	**25°C**	**25°C**
Rope Stranded							
49 strands	**17865**	**10892**	**11153**	**11210**	**11327**	**11568**	**…**
133 strands	**18038**	**10998**	**11261**	**11319**	**11437**	**11681**	**…**
259 strands	**18125**	**11051**	**11315**	**11374**	**11492**	**11737**	**…**
427 strands	**18212**	**11104**	**11370**	**11428**	**11547**	**11793**	**…**
Over 427 strands	**18385**	**11209**	**11478**	**11537**	**11657**	**11905**	**…**
Bunch Stranded							
All sizes	**17691**	**10786**	**…**	**…**	**11217**	**11456**	**11579**
Rope-stranded Bunches							
7 ropes of bunched strand	**18038**	**10998**	**…**	**…**	**11437**	**11681**	**11806**
19, 37, or 61 ropes of bunched strand	**18212**	**11104**	**…**	**…**	**11547**	**11793**	**11920**

7×7 ropes of bunched strand	**18385**	**11209**	**…**	**…**	**11657**	**11905**	**12033**
19, 37, or 61×7 ropes of bunched strand	**18559**	**11315**	**…**	**…**	**11767**	**12018**	**12147**
Concentric Stranded							
Up to 2000 kcmil	**17692**	**10786**	**11045**	**11102**	**11217**	**11456**	**11580**
>2000 10 3000 kcmil	**17865**	**10892**	**11153**	**11211**	**11327**	**11568**	**11694**
>3000 to 4000 kcmil	**18039**	**10998**	**11261**	**11319**	**11437**	**11680**	**11807**
>4000 to 5000 kcmil	**18212**	**11104**	**11369**	**11428**	**11547**	**11792**	**11921**

The factors given in Table 21-5 are based on the following
Resistivity
1. A volume resistivity of 10.575 Ω-cmil/ft (100% conductivity) at 25°C for uncoated (bare) copper.
2. A 25°C volume resistivity converted from the 20°C values specified in ASTM B 33 or ASTM B 189 for coated copper.
3. A volume resistivity of 17.345 Ω-cmil/ft (61.0% conductivity) at 25°C for aluminum.

Table 25-6

Copper Conductors, Class M Each Individual Strand 34 AWG, 0.0063 Inch (0.160 mm)

Conductor Size, AWG or kcmil.	Suggested	Approximate Number of Strands	Approximate Outisde Diameter		Approximate Weight	
			Inches	mm	Pounds per 1000 Feet	g/m
20	1×26	26	0.038	0.97	3.2	4.74
18	1x41	41	0.048	1.22	5.0	7.48
16	1×65	65	0.060	1.52	8.0	11.9
14	1×104	104	0.078	1.98	12.8	19.0
12	7×24	168	0.101	2.57	21.0	31.2
10	7×37	259	0.126	3.20	32.5	48.2
9	7×48	336	0.146	3.71	42	62.5
8	7×60	420	0.162	4.11	53	78.1
7	19×28	532	0.196	4.98	67	100.0

6	19×35	665	0.215	5.46	84	125
5	19×44	836	0.240	6.10	105	157
4	19×56	1064	0.269	6.83	134	200
3	7×7×27	1323	0.305	7.75	169	251
2	7×7×34	1666	0.337	8.56	212	316
1	7×7×43	2107	0.376	9.55	268	399
1/0	7×7×54	2646	0.423	10.7	337	501
2/0	19×7×25	3325	0.508	12.9	427	636
3/0	19×7×32	4256	0.576	14.6	547	814
4/0	19×7×40	5320	0.645	16.4	684	1020
250	19×7×48	6384	0.713	18.1	821	1220
300	19×7×57	7581	0.768	19.5	975	1450
350	37×7×34	8806	0.825	21.0	1130	1685
400	37×7×39	10101	0.901	22.9	1300	1930
450	37×7×44	11396	0.940	23.9	1465	2180
500	37×7×49	12691	0.997	25.3	1630	2430
550	61×7×32	13664	1.035	26.3	1755	2615
600	61×7×35	14945	1.084	27.5	1920	2860
650	61×7×38	16226	1.133	28.8	2085	3105
700	61×7×41	17507	1.183	30.0	2250	3350
750	61×7×44	18788	1.207	30.7	2415	3595
800	61×7×47	20069	1.256	31.9	2580	3840
900	61×7×53	22631	1.331	33.8	2910	4330
1000	61×7×59	25193	1.404	35.7	3240	4820

Table 25-7

ADDITIONAL CONDUCTOR INFORMATION

Solid Aluminum and Copper Conductors

Conductor Size, AWG or kcmil	Approximate Weight			
	Aluminum			Copper
	Pounds Per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
22	…	…	1.94	2.88
20	…	…	3.10	4.61
19	…	…	3.90	5.81
18	…	…	4.92	7.32
17	…	…	6.21	9.24
16	…	…	7.81	11.6
15	…	…	9.87	14.7
14	…	…	12.4	18.5
13	…	…	15.7	23.4
12	6.01	894	19.8	29.4
11	7.57	11.3	24.9	37.1
10	9.56	14.22	31.43	46.77
9	12.04	17.92	39.62	58.95
8	15.20	22.62	49.98	74.38
7	19.16	28.52	63.03	93.80
6	24.15	35.94	79.44	118.2
5	30.45	45.32	100.2	149.0
4	38.41	57.17	126.3	188.0
3	48.43	72.08	159.3	237.1
2	61.07	90.89	200.9	298.9
1	77.03	114.6	253.3	377.0
1/0	97.15	144.6	319.5	475.5
2/0	122.5	182.3	402.8	599.5

3/0	154.4	229.8	507.8	755.8
4/0	194.7	289.8	640.5	953.2
250	230.1	342.4	…	…
300	276.1	410.9	…	…
350	322.1	479.4	…	…
400	368.2	547.9	…	…
450	414.4	616.3	…	…
500	460.2	648.8	…	…

Table 25-8

Concentric Stranded Class B Aluminum and Copper Conductors

Conductor Size. AWG or kcmil	Number of Strands	Approximate Diameter of Each Strand		Approximate Outside Diameler		Approximate Weight			
						Aluminum		Copper	
		mils	mm	Inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
22	7	9.6	0.244	0.029	0.737	…	…	1.975	2.941
20	7	12.1	0.307	0.036	0.914	…	…	3.154	4.705
19	7	13.6	0.345	0.041	1.04	…	…	3.974	5.922
18	7	15.2	0.386	0.046	1.17	…	…	5.015	7.462
17	7	17.2	0.437	0.052	1.32	…	…	6.324	9.429
16	7	19.2	0.488	0.058	1 .47	…	…	7.974	11.86
15	7	21.6	0.549	…	…	…	…	9.959	14.98
14	7	24.2	0.615	…	…	…	…	12.68	18.88
13	7	27.2	0.691	…	…	…	…	16.01	23.82
12	7	30.5	0.775	…	…	6.13	9.12	20.16	30.00
11	7	34.3	0.871	…	…	7.72	11.5	25.49	37.80
10	7	38.5	0.978	…	…	9.73	14.5	32.06	47.71
9	7	43.2	1.10	…	…	12.3	18.3	40.42	60.14
8	7	48.6	1.23	…	…	15.3	23.1	51.0	75.9
7	7	54.5	1.39	…	…	19.5	29.1	64.2	95.7

6	7	61.2	1.56	…	…	24.6	36.7	80.9	121
5	7	68.8	1.75	…	…	31.1	46.2	102	152
4	7	77.2	1.96	…	…	39.2	58.3	129	192
3	7	86.7	2.20	…	…	49.4	73.5	162	242
2	7	97.4	2.47	…	…	62.3	92.7	205	305
1	19	66.4	1.69	…	…	78.6	117	259	385
1/0	19	74.5	1.89	…	…	99.1	147	326	485
2/0	19	83.7	2.13	…	…	125	186	411	611
3/0	19	94.0	2.39	…	…	157	234	518	771
4/0	19	105.5	2.68	…	…	199	296	653	972
250	37	82.2	2.09	…	…	235	349	772	1150
300	37	90.0	2.29	…	…	282	419	925	1380
350	37	97.3	2.47	…	…	329	489	1080	1610
400	37	104.0	2.64	…	…	376	559	1236	1840
450	37	110.3	2.80	…	…	422	629	1390	2070
500	37	116.2	2.95	…	…	469	699	1542	2300
550	61	95.0	2.41	…	…	517	768	1700	1850
600	61	99.2	2.52	…	…	563	838	1850	2760
650	61	103.2	2.62	…	…	610	908	2006	2990
700	61	107.1	2.72	…	…	657	978	2160	3220
750	61	110.9	2.82	…	…	704	1050	2316	3450
800	61	114.5	2.91	…	…	751	1120	2469	3680
900	61	121.5	3.09	…		845	1260	2780	4140
1000	61	128.0	3.25	…	…	939	1400	3086	4590
1100	91	109.9	2.79	…	…	1032	1540	3394	3050
1200	91	114.8	2.92	…	…	1126	1680	3703	5510
1250	91	117.2	2.98	…	…	1173	1750	3859	5740
1300	91	119.5	3.04	…	…	1220	1820	4012	5970
1400	91	124.0	3.15	…	…	1313	1960	4320	6430
1500	91	128.4	3.26	…	…	1408	2100	4632	6890
1600	127	112.2	2.85	…	…	1501	2240	4936	7350
1700	127	115.7	2.94	…	…	1596	2370	5249	7810

1750	127	117.4	2.98	…	…	1643	2440	5403	8040
1800	127	119.1	3.02	…	…	1691	2510	5562	8270
1900	127	122.3	3.11	…	…	1783	2650	5865	8730
2000	127	125.5	3.19	…	…	1877	2790	6176	9190

Table 25-9

Concentric Stranded Class C and D Aluminum and Copper Conductors

Conductor Size, AWG or kcmil	Class C			Class D		
	Number of Strands	Approximate Diameter of Each Strand		Number of strands	Approximate Diameter of Each Strand	
		mils	mm		mils	mm
22	…	…	…	…	…	…
20	…	…	…	…	…	…
19	…	…	…	…	…	…
18	…	…	…	…	…	…
17	…	…	…	…	…	…
16	…	…	…	…	…	…
15	…	…	…	…	…	…
14	19	14.7	0.373	37	10.5	0.267
13	19	16.5	0.419	37	11.8	0.300
12	19	18.5	0.470	37	13.3	0.338
11	19	20.8	0.528	37	14.9	0.378
10	19	23.4	0.594	37	16.7	0.424
9	19	26.2	0.665	37	18.8	0.478
8	19	29.5	0.749	37	21.1	0.536
7	19	33.1	0.841	37	23.7	0.602
6	19	37.2	0.945	37	26.6	0.676
5	19	41.7	1.06	37	29.9	0.759
4	19	46.9	1.19	37	33.6	0.853
3	19	52.6	1.34	37	37.7	0.958
2	19	59.1	1.50	37	42.4	1.08

1	**37**	**47.6**	**1.21**	**61**	**37.0**	**0.940**
1/0	**37**	**53.4**	**1.36**	**61**	**41.6**	**1.06**
2/0	**37**	**60.0**	**1.52**	**61**	**46.7**	**1.19**
3/0	**37**	**67.3**	**1.71**	**61**	**52.4**	**1.33**
4/0	**37**	**75.6**	**1.92**	**61**	**58.9**	**1.50**
250	**61**	**64.0**	**1.63**	**91**	**52.4**	**1.33**
300	**61**	**70.1**	**1.78**	**91**	**57.4**	**1.46**
350	**61**	**75.7**	**1.92**	**91**	**62.0**	**1.57**
400	**61**	**81.0**	**2.06**	**91**	**66.3**	**1.68**
450	**61**	**85.9**	**2.18**	**91**	**70.3**	**1.79**
500	**61**	**90.5**	**2.30**	**91**	**74.1**	**1.88**
550	**91**	**77.7**	**1.97**	**127**	**65.8**	**1.67**
600	**91**	**81.2**	**2.06**	**127**	**68.7**	**1.74**
650	**91**	**84.5**	**2.15**	**127**	**71.5**	**1.82**
700	**91**	**87.7**	**2.23**	**127**	**74.2**	**1.88**
750	**91**	**90.8**	**2.31**	**127**	**76.8**	**1.95**
800	**91**	**93.8**	**2.38**	**127**	**79.4**	**2.02**
900	**91**	**99.4**	**2.53**	**127**	**84.2**	**2.14**
1000	**91**	**104.8**	**2.66**	**127**	**88.7**	**2.25**
1100	**127**	**93.1**	**2.36**	**169**	**80.7**	**2.05**
1200	**127**	**97.2**	**2.47**	**169**	**84.3**	**2.14**
1250	**127**	**99.2**	**2.52**	**169**	**86.0**	**2.18**
1300	**127**	**101.2**	**2.57**	**169**	**87.7**	**2.23**
1400	**127**	**105.0**	**2.67**	**169**	**91.0**	**2.31**
1500	**127**	**108.7**	**2.76**	**169**	**94.2**	**2.39**
1600	**169**	**97.3**	**2.47**	**217**	**85.9**	**2.18**
1700	**169**	**100.3**	**2.55**	**217**	**88.5**	**2.25**
1750	**169**	**101.8**	**2.59**	**217**	**89.8**	**2.28**
1800	**169**	**103.2**	**2.62**	**217**	**91.1**	**2.31**
1900	**169**	**106.0**	**2.69**	**217**	**93.6**	**2.38**
2000	**169**	**108.8**	**2.76**	**217**	**96.0**	**2.44**

NOTE: The weights of Class C and Class D conductors are the same as for the equivalent Class B conductor

Table 25-10

Rope-Lay Aluminum and Copper Conductors, Class G

Conductor Size, AWG or kcmil	Number of Strands	Suggested Construction	Approximate Diameter of Each Strand		Approximate Outside Diameter		Approximate Weight			
							Aluminum		Copper	
			mils	mm	inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
14	49	7×7	9.2	0.23	0.083	2.11	…	…	12.8	19.1
12	49	7×7	11.6	0.29	0.104	2.64	…	…	20.3	30.3
10	49	7×7	14.6	0.37	0.131	3.33	…	…	32.3	48.2
9	49	7×7	16.4	0.42	0.148	3.76	…	…	40.8	60.7
8	49	7×7	18.4	0.47	0.166	4.22	…	…	51	76.6
7	49	7×7	20.6	0.52	0.185	4.70	20	29.4	65	96.6
6	49	7×7	23.1	0.59	0.208	5.28	25	37.0	82	122
5	49	7×7	26.0	0.66	0.234	5.94	31	46.7	103	154
4	49	7×7	29.2	0.74	0.263	6.68	40	58.9	130	194
3	49	7×7	32.8	0.83	0.295	7.49	50	74.2	164	244
2	49	7×7	36.8	0.93	0.331	8.41	63	93.6	207	308
1	133	19×7	25.1	0.64	0.377	9.58	80	119	264	392
1/0	133	19×7	28.2	0.72	0.423	10.7	102	150	334	495
2/0	133	19×7	31.6	0.80	0.474	12.0	127	190	419	623
3/0	133	19×7	35.5	0.90	0.533	13.5	161	239	529	786
4/0	133	19×7	39.9	1.01	0.599	15.2	203	301	668	991
250	259	37×7	31.1	0.79	0.653	16.6	242	358	795	1175
300	259	37×7	34.0	0.86	0.714	18.1	287	429	945	1410
350	259	37×7	36.8	0.93	0.773	19.6	337	501	1110	1650
400	259	37×7	39.3	1.00	0.825	21.0	385	573	1265	1885
450	259	37×7	41.7	1.06	0.876	22.3	433	644	1425	2120
500	259	37×7	43.9	1.12	0.922	23.4	482	716	1585	2355
550	427	61×7	35.9	0.91	0.969	24.6	532	791	1750	2600
600	427	61×7	37.5	0.95	1.013	25.7	581	863	1910	2840

650	**427**	**61×7**	**39.0**	**0.99**	**1.053**	**26.7**	**629**	**935**	**2070**	**3075**
700	**427**	**61×7**	**40.5**	**1.03**	**1.094**	**27.8**	**678**	**1005**	**2230**	**3310**
750	**427**	**61×7**	**41.9**	**1.06**	**1.131**	**28.7**	**725**	**1080**	**2385**	**3545**
800	**427**	**61×7**	**43.3**	**1.10**	**1.169**	**29.7**	**774**	**1150**	**2545**	**3785**
900	**427**	**61×7**	**45.9**	**1.17**	**1.239**	**31.5**	**869**	**1295**	**2860**	**4255**
1000	**427**	**61×7**	**48.4**	**1.23**	**1.307**	**33.2**	**967**	**1440**	**3180**	**4730**
1100	**427**	**61×7**	**50.8**	**1.29**	**1.372**	**34.8**	**1064**	**1580**	**3500**	**5205**
1200	**427**	**61×7**	**53.0**	**1.35**	**1.431**	**36.3**	**1158**	**1725**	**3810**	**5675**
1250	**427**	**61×7**	**54.1**	**1.37**	**1.461**	**37.1**	**1208**	**1800**	**3975**	**5910**
1300	**427**	**61×7**	**55.2**	**1.40**	**1.490**	**37.8**	**1257**	**1870**	**4135**	**6150**
1400	**427**	**61×7**	**57.3**	**1.46**	**1.547**	**39.3**	**1356**	**2015**	**4460**	**6620**
1500	**427**	**61×7**	**59.3**	**1.51**	**1.601**	**40.7**	**1452**	**2155**	**4775**	**7095**
1600	**703**	**37×19**	**47.7**	**1.21**	**1.670**	**42.4**	**1560**	**2325**	**5130**	**7640**
1700	**703**	**37×19**	**49.2**	**1.25**	**1.722**	**43.7**	**1660**	**2470**	**5460**	**8115**
1750	**703**	**37×19**	**49.9**	**1.27**	**1.747**	**44.4**	**1709**	**2540**	**5620**	**8355**
1800	**703**	**37×19**	**50.6**	**1.29**	**1.771**	**45.0**	**1756**	**2615**	**5775**	**8595**
1900	**703**	**37×19**	**52.0**	**1.32**	**1.820**	**46.2**	**1854**	**2760**	**6100**	**9070**
2000	**703**	**37×19**	**53.3**	**1.35**	**1.866**	**47.4**	**1950**	**2905**	**6415**	**9550**

NOTE: Rope-lay aluminum Class O conductors are not recommended in sizes 8 AWG and smaller and individual aluminum wires in strande conductors should not be smaller than 24 AWG.

Table 25-11 Rope-Lay Aluminum and Copper Conductors, Class H

Conductor Size, AWG or kcmil	**Number of Strands**	**Suggested Construction**	**Approximate Diameter of Each Strand**		**Approximate Outside Dimeter**		**Approximate Weight**			
							Aluminim		**Copper**	
			mils	**mm**	**inches**	**mm**	**Pounds per 1000 Feet**	**g/m**	**Pounds per 1000 Feet**	**g/m**
8	**133**	**19×7**	**11.1**	**0.28**	**0.167**	**4.24**	**…**	**…**	**52**	**77.4**
7	**133**	**19×7**	**12.5**	**0.32**	**0.188**	**4.78**	**…**	**…**	**65**	**97.5**
6	**133**	**19×7**	**14.0**	**0.36**	**0.210**	**5.33**	**…**	**…**	**82**	**123**
5	**133**	**19×7**	**15.8**	**0.40**	**0.237**	**6.02**	**…**	**…**	**105**	**155**
4	**133**	**19×7**	**17.7**	**0.45**	**0.266**	**6.76**	**…**	**…**	**132**	**196**

3	133	19×7	19.9	0.51	0.299	7.59	…	…	167	247
2	133	19×7	22.3	0.57	0.335	8.51	63	94.5	208	311
2	259	37×7	16.0	0.41	0.336	8.53	…	…	210	312
1	259	37×7	18.0	0.46	0.378	9.60	…	…	266	394
1/0	259	37×7	20.2	0.51	0.424	10.8	102	151	334	497
2/0	259	37×7	22.7	0.58	0.477	12.1	128	190	422	626
3/0	259	37×7	25.5	0.65	0.536	13.6	162	240	533	790
3/0	427	61×7	19.8	0.50	0.535	13.6	…	…	532	794
4/0	259	37×7	28.6	0.73	0.601	15.3	204	303	670	996
4/0	427	61×7	22.3	0.57	0.602	15.3	205	304	675	1000
250	427	61×7	24.2	0.61	0.653	16.6	242	360	795	1180
300	427	61×7	26.5	0.67	0.716	18.2	290	431	953	1420
350	427	61×7	28.6	0.73	0.772	19.6	337	503	1110	1655
400	427	61×7	30.6	0.78	0.826	21.0	386	575	1270	1890
450	427	61×7	32.5	0.83	0.878	22.3	436	647	1435	2130
500	427	61×7	34.2	0.87	0.923	23.4	483	719	1590	2365
550	703	37×19	28.0	0.71	0.980	24.9	538	798	1770	2625
600	703	37×19	29.2	0.74	1.022	26.0	584	871	1920	2865
650	703	37×19	30.4	0.77	1.064	27.0	634	944	2085	3105
700	703	37×19	31.6	0.80	1.106	28.1	686	1015	2255	3340
750	703	37×19	32.7	0.83	1.145	29.1	733	1090	2410	3580
800	703	37×19	33.7	0.86	1.180	30.0	778	1160	2560	3820
900	703	37×19	35.8	0.91	1.253	31.8	880	1305	2895	4295
1000	703	37×19	37.7	0.96	1.320	33.5	974	1450	3205	4775
1100	703	37×19	39.6	1.01	1.386	35.2	1075	1595	3535	5250
1200	703	37×19	41.3	1.05	1.446	36.7	1169	1740	3845	5730
1250	703	37×19	42.2	1.07	1.477	37.5	1221	1815	4015	5970
1300	703	37×19	43.0	1.09	1.505	38.2	1268	1885	4170	6205
1400	703	37×19	44.6	1.13	1.561	39.6	1363	2035	4485	6685
1500	703	37×19	46.2	1.17	1.617	41.1	1464	2180	4815	7160
1600	1159	61×19	37.2	0.94	1.674	42.5	1564	2325	5145	7640
1700	1159	61×19	38.3	0.97	1.724	43.8	1658	2470	5455	8115

1750	**1159**	**61×19**	**38.9**	**0.99**	**1.751**	**44.5**	**1710**	**2540**	**5625**	**8355**
1800	**1159**	**61×19**	**39.4**	**1.00**	**1.773**	**45.0**	**1754**	**2615**	**5770**	**8595**
1900	**1159**	**61×19**	**40.5**	**1.03**	**1.823**	**46.3**	**1854**	**2760**	**6100**	**9070**
2000	**1159**	**61×19**	**41.5**	**1.05**	**1.868**	**47.4**	**1946**	**2905**	**6400**	**9550**

NOTE: Individual aluminum wires in stranded conductors should not be smaller than 24 AWG.

Table 25-12

Aluminum and Copper Conductors, Class I

Each Individual Strand 24 AWG, 0.0201 Inch (0.511 mm)

Conductor Size, AWO or kcmil	Suggested Construction	Approximate Number of Strands	Approximate Outside Diameter		Approximate Weight			
					Aluminum		Copper	
			inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
10	**1×26**	**26**	**0.125**	**3.18**	**…**	**…**	**32.5**	**48.3**
9	**1×33**	**33**	**0.138**	**3.51**	**…**	**…**	**41**	**61.3**
8	**1×41**	**41**	**0.156**	**3.96**	**16**	**23.1**	**51**	**76.1**
7	**1×52**	**52**	**0.185**	**4.70**	**20**	**29.3**	**65**	**96.5**
6	**7×9**	**63**	**0.207**	**5.26**	**24**	**36.3**	**80**	**119**
5	**7×12**	**84**	**0.235**	**5.97**	**32**	**48.3**	**105**	**159**
4	**7×15**	**105**	**0.263**	**6.68**	**41**	**60.4**	**134**	**199**
3	**7×19**	**133**	**0.291**	**7.39**	**51**	**76.5**	**169**	**252**
2	**7×23**	**161**	**0.319**	**8.10**	**62**	**92.7**	**205**	**305**
ī	**7×30**	**210**	**0.367**	**9.32**	**81**	**121**	**267**	**397**
1/0	**19×14**	**266**	**0.441**	**11.2**	**104**	**155**	**342**	**508**
2/0	**19×18**	**342**	**0.500**	**12.7**	**133**	**199**	**439**	**654**
3/0	**19×22**	**418**	**0.549**	**13.9**	**163**	**243**	**537**	**799**
4/0	**19×28**	**532**	**0.613**	**15.6**	**208**	**309**	**683**	**1015**
250	**7×7×13**	**637**	**0.682**	**17.3**	**251**	**374**	**825**	**1230**
300	**7×7×15**	**735**	**0.737**	**18.7**	**290**	**431**	**955**	**1420**

350	**7×7×18**	**882**	**0.800**	**20.3**	**348**	**517**	**1145**	**1700**
400	**7×7×20**	**980**	**0.831**	**21.1**	**386**	**575**	**1270**	**1890**
450	**7×7×23**	**1127**	**0.894**	**22.7**	**444**	**661**	**1460**	**2175**
500	**7×7×25**	**1225**	**0.941**	**23.9**	**483**	**719**	**1590**	**2365**
550	**7×7×28**	**1372**	**0.980**	**24.9**	**541**	**805**	**1780**	**2645**
600	**7×7×30**	**1470**	**1.027**	**26.1**	**579**	**862**	**1905**	**2835**
650	**19×7×12**	**1596**	**1.152**	**29.3**	**635**	**945**	**2090**	**3110**
700	**19×7×13**	**1729**	**1.194**	**30.3**	**687**	**1025**	**2260**	**3365**
750	**19×7×14**	**1862**	**1.235**	**31.4**	**740**	**1100**	**2435**	**3625**
800	**19×7×15**	**1995**	**1.290**	**32.8**	**793**	**1180**	**2610**	**3885**
900	**19×7×17**	**2261**	**1.372**	**34.8**	**901**	**1340**	**2965**	**4405**
1000	**19×7×19**	**2527**	**1.427**	**36.2**	**1005**	**1495**	**3305**	**4920**
1100	**19×7×21**	**2793**	**1.495**	**38.0**	**1111**	**1655**	**3655**	**5440**
1200	**19×7×22**	**2926**	**1.537**	**39.0**	**1164**	**1730**	**3830**	**5700**
1250	**19×7×23**	**3059**	**1.564**	**39.7**	**1216**	**1810**	**4000**	**5955**
1300	**19×7×24**	**3192**	**1.605**	**40.8**	**1269**	**1890**	**4175**	**6215**
1400	**19×7×26**	**3458**	**1.674**	**42.5**	**1386**	**2045**	**4560**	**6735**
1500	**19×7×28**	**3724**	**1.715**	**43.6**	**1482**	**2205**	**4875**	**7250**
1600	**19×7×30**	**3990**	**1.797**	**45.6**	**1587**	**2360**	**5220**	**7770**
1700	**19×7×32**	**4256**	**1.852**	**47.0**	**1693**	**2520**	**5570**	**8290**
1750	**19×7×33**	**4389**	**1.880**	**47.8**	**1746**	**2600**	**5745**	**8545**
1800	**19×7×34**	**4522**	**1.921**	**48.8**	**1800**	**2675**	**5920**	**8805**
1900	**19×7×36**	**4788**	**1.976**	**50.2**	**1905**	**2835**	**6265**	**9325**
2000	**19×7×37**	**4921**	**2.003**	**50.9**	**1958**	**2915**	**6440**	**9585**

NOTE: Aluminum Class 1 conductors are not recommended in sizes 8 AWG and smaller.

Table 25-13

Copper Conductors, Class K

Each Individual Strand 30 AWG, 0.0100 Inch (0.254 mm)

Conductor Size, AWG or kcmil	Suggested Construction	Approximate Number of Strands	Approximate Outside Diameter		Approximate Weight	
			Inches	mm	Pounds per 1000 Feet	g/m
20	1×10	10	0.038	0.97	3.2	4.59
18	1×16	16	0.048	1.22	5.0	7.35
16	1×26	26	0.060	1.52	8.0	11.9
14	1×41	41	0.078	1.98	12.8	18.8
12	1×65	65	0.101	2.57	20.3	29.9
10	1×104	104	0.126	3.20	32.5	47.8
9	7×19	133	0.150	3.81	42	62.3
8	7×24	168	0.157	3.99	53	78.7
7	7×30	210	0.179	4.55	66	98.4
6	7×38	266	0.210	5.33	84	125
5	7×48	336	0.235	5.97	106	157
4	7×60	420	0.272	6.91	132	197
3	19×28	532	0.304	7.72	169	252
2	19×35	665	0.338	8.59	211	315
1	19×44	836	0.397	10. 1	266	395
1/0	19×56	1064	0.451	11.5	338	503
2/0	7×7×27	1323	0.470	11.9	425	632
3/0	7×7×34	1666	0.533	13.5	535	795
4/0	7×7×43	2107	0.627	15.9	676	1005
250	7×7×51	2499	0.682	17.3	802	1195
300	7×7×61	2989	0.768	19.5	960	1425
350	19×7×26	3458	0.809	20.5	1120	1665
400	19×7×30	3990	0.878	22.3	1290	1925
450	19×7×34	4522	0.933	23.7	1465	2180

500	19×7×38	5054	0.988	25.1	1635	2435
550	19×7×41	5453	1.056	26.8	1765	2630
600	19×7×45	5985	1.125	28.6	1940	2885
650	19×7×49	6517	1.166	29.6	2110	3140
700	19×7×52	6916	1.207	30.7	2240	3335
750	19×7×57	7581	1.276	32.4	2455	3655
800	19×7×60	7980	1.305	33.1	2585	3845
900	37×7×35	9065	1.323	33.6	2935	4370
1000	37×7×39	10101	1.419	36.0	3270	4870

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