1974

Electrical cable design and applications

Robert William Buente

Recommended Citation

Buente, Robert William, "Electrical cable design and applications" (1974). *Masters Theses*. 3445.
https://scholarsmine.mst.edu/masters_theses/3445

ELECTRICAL CABLE DESIGN AND APPLICATIONS

BY

ROBERT WILLIAM BUENTE, 1945-

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI - ROLLA

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

1974

Approved by

Herbert A. Crosby (Advisor) David Cunningham

Alan Schwartz

ABSTRACT

The materials available for constructing various electrical cables are discussed, along with remarks pertaining to the attributes and limitations of each. The installation and maintenance considerations are discussed in detail. Electrical considerations involved with designing a cable system are outlined with references to their specific application. Special cable constructions, their applications, and their typical modes of installation are reviewed. The conclusion explains an overall cable system design approach along with miscellaneous information.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

Figures Page

LIST OF TABLES

I. INTRODUCTION

A. Basic Cable Construction and History

As long as there has been electricity, there has been a need for cable to convey this power. In the late 1800's 10,000 volt concentric cables of Ferranti were installed in London, and early proved the success of underground power transmission(1). Prior to this time insulated cable designs were limited to the manufacturing of telephone and telegraph cables for communication purposes. Paper insulation was the primary type used during the early underground cable years. Most often the paper insulated cables were lead or steel sheathed for mechanical and environmental protection.

The demand for higher and higher rated voltages for underground cables originates from both technical and economic considerations. The transmission of power for a given voltage from a large generating station by an insulated cable is limited by the amount of current it can safely carry without overloading the insulation. This problem has resulted in reducing the current by raising the transmission voltage, allowing a smaller amount of conductor current for a given amount of power.

It appears that the cost of a cable system is largely proportional to the amount of conductor metal employed and therefore to some extent inversely proportional to the voltage. It must be kept in mind however, that the saving is not directly proportional to the voltage, as the higher voltage involves increased thickness of dielectric, and protective jacketing materials which partially offset the saving due to reducing the size of the conductor.

The basic construction of a cable involves many processes and materials. A brief explanation of the various types of construction for cables will be helpful in the understanding of the subject of this paper. Table I shows the three basic cable constructions.

Table I. Basic Cable Constructions

Low Voltage 600-2000v	Non-shielded 2001-5000v	Shielded 5000v and above
1. Conductor	1. Conductor	1. Conductor
2. Phase-coded insulation	2. Strand shielding	2. Strand shielding
3. Assembly tape and fillers	3. Phase-coded insulation	3. Insulation
4. Jacket Sheath	4. Assembly tape and fillers	4. Insulation Shielding-Phase Identification
	5. Jacket, Sheath or Armor	5. Metallic Insulation Shielding
		6. Assembly tape and fillers
		7. Jacket, Sheath or Armor

Natural rubber, varnish cambric, butyl rubber, polyethylene, styrene-butadiene rubber, cross linked polyethylene, and ethylene propylene have largely replaced oil impregnated paper insulation. The thermoplastics and thermosetting materials have likewise increased in use for jacketing materials.

Electrical cables are extremely critical to the distribution and control of power, and in recent years many innovations have been introduced in cable design. Improved dielectrics have resulted in better performance in addition to, in many cases, reduced costs.

In researching this subject it was alarming to note the sparse amount of articles and books written on the overall subject of cable. There is an endless number of books and articles written on specific cable subject areas. It is for this reason that the need for a paper on the overall topic of electrical cable seemed apparent. This paper attempts to take from these sources the salient points and combine them in a logical presentation.

It is the explicit intent of this paper to provide a good reference for people interested in cable and its design. So often an engineer must be involved with many specialties, and it is impossible to be an expert in everyone.

There are many descriptive words in the cable industry as defined by the various associations that issue industry standards. The principal bodies that issue these standards, codes, or approved listings applying to the materials, are as follows: American Society for Testing and Metals (ASTM), Underwriters Laboratories, Inc. (U/L), Insulated Power Cable Engineers Association (IPCEA), Institute of Electrical and Electronic Engineers (IEEE), Edison Electric Institute (EEI), Association of Edison Illuminating Companies (AEIC), National Electrical Manufacturers Association (NEMA), and The National Fire Protection Association that issues the National Electric Code (NEC).

B. Conductors

The definition of conductor as used in the wire and cable industry is: A wire or combination of wires not insulated from one another, suitable for carrying a single electric current(4).

Copper and Aluminum are the two basic types of conductors used in the transmission and distribution of electrical power. Hollow tubes, copperweld, square and rectangular bars, aluminum conductor steel reinforced (ACSR), and other special designs for particular requirements comprise the list of conductors, but the most extensive use of conductors is in the form of round solid wires.

Copper is the most widely used metal for conductors, due to its outstanding electrical conductivity and versatility. Because copper is malleable and ductile it can readily be worked cold by any process involving rolling or wire drawing.

The acceptance of aluminum conductors is also expanding rapidly due to its excellent conductivity, availability, light weight, ease of handling, and reasonable price. Table II shows the conductivity of various metals, with aluminum equal to 62% of that of copper.

Table II. Relative Electrical Conductivity of Metals

Metal	Relative Conductivity
Silver	106
Copper	100
Aluminum	62
Magnesium	38.4
Iron	12.4

The specific gravity of aluminum is 2.7 compared to 8.9 for copper. This weight differential is a favorable plus for aluminum conductors but it also follows that the overall diameter of an aluminum conductor must be about 25% greater than that of a copper conductor, in order to carry the copper equivalent current. From this fact it then can be stated that the greater diameter of aluminum necessitates a greater volume of insulation needed, for the same voltage rating of the cable.

The controversy in the use of copper versus aluminum as a conductor continues but a few more comparative facts will help in determining the most suitable conductor metal for a particular application.

Aluminum oxidizes readily in air, which results in the formation of a hard inert oxide coat on the surface of the conductor, which is impermeable and protective in character. This oxide film is a good insulator and it must be removed during splicing and termination of the conductor.

Due to its larger volume the aluminum conductor can store about 16% more heat than a copper conductor of equal resistance, which for a given temperature rise allows it to carry somewhat larger short-circuit currents than copper. In this same frame work of thinking, it must be mentioned that the melting point of aluminum is much lower than that of copper and will therefore burn off at correspondingly lower temperature when short circuits occur.

The thermal linear expansion coefficient of aluminum is considerably larger than that of copper, indicating that aluminum conductors will elongate somewhat more than copper with a given temperature rise.

The tensil strength of aluminum is also lower than that of copper. For example the breaking strengths of a #12 AWG aluminum conductor is equal to that of a #14 AWG copper conductor.

The flexibility of annealed copper and that of an EC grade aluminum conductor are comparable, however, the fatigue resistance of copper is far greater. This is important where continuous flexibility is necessary.

Table III gives a comparison of equivalent conductor sizes based on equal voltage drop.

Table III. Ampacity Ratings

Copper Conductors			Aluminum Conductors		
Size AWG or MCM	Voltage Drop per phase per amp per 1000ft	Current	Size AWG or MCM	Voltage Drop per phase per amp per 1000ft	Current
14	4.67	15	12	4.75	17
12	3.00	20	10	3.02	25
10	1.86	30	8	1.90	38
8	1.21	45	6	1.21	55
6	0.793	65	4	0.790	71
4	0.514	85	2	0.509	97
2	0.341	115	1/0	0.336	126
1/0	0.232	150	3/0	0.228	168
2/0	0.193	175	4/0	0.190	193
3/0	0.163	200	250 MCM	0.169	214
4/0	0.138	230	350 MCM	0.134	260
250 MCM	0.126	255	400 MCM	0.124	282
350 MCM	0.104	310	500 MCM	0.108	319
400 MCM	0.097	335	600 MCM	0.098	353
500 MCM	0.088	380	750 MCM	0.089	399
600 MCM	0.083	420	900 MCM	0.082	437
750 MCM	0.075	475	1000 MCM	0.080	458

The ampacities shown in Table III are based on three single conductors in a magnetic conduit, 80% power factor, 75°C copper temperature and corresponding current carrying capacities at 30°C ambient(5). Any change in one or more of these parameters would change the current rating of the conductors. This table was provided for a comparison of copper conductor size to aluminum conductor size. This comparison yields the rule of thumb, that an aluminum conductor be about two AWG sizes larger than copper for equal conductivity.

The prior discussion of copper versus aluminum involved the use of wire sizes. In the United States, the American Wire Gage (AWG) is used for classifying wire size. The American Wire Gage, also known as the Brown & Sharpe Gage, was devised in 1857 by J.R. Brown(4). This term is usually abbreviated AWG. These gage numbers follow a mathematical law upon which this page was founded.

The gage is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometrical progression(4). Each gage size larger represents an increase of 20% in area and roughly a 10% increase in diameter. The diameter of No. 0000 is 0.460 in. and No. 36 is 0.0050 in. There are 38 sizes between these two. The ratio of any diameter to the diameter of the next greater size is 1.123. Thus the ratio of one size wire to the Nth larger size is 1.123^n times the diameter of the known smaller size.

The wire sizes beyond No. 0000 are expressed in circular mil area. The definition of circular mil is: A unit of area equal to the area of a circle one thousandth of an inch in diameter(4). The 4/0 size of wire possesses a cross-sectional area of 211,600 circular mils. Therefore the next wire size is 250,000 circular mils and is abbreviated 250MCM. The wire sizes then proceed with 250MCM all the way to 2500MCM in conventional steps.

With the wire sizes properly defined the next consideration is that of conductor stranding.

There are various types of strandings such as concentric rope, bunch, compact, segmental, annular and combinations of each. The most often used stranding is concentric.

The reason for stranding is to increase flexibility. The concentric stranded conductor consists of a geometric arrangement laying six wires around one, then twelve wires around six, followed by eighteen and etc. The diameter over the Nth layer in inches (where d = diameter of each wire in inches), is $(1 + 2n)d$.

Bunched stranding consists of twisting a group of wires of any given number together, all at once, in a bunching machine.

Rope stranding consists of twisted groups of stranded conductors. Each group may be bunched or concentrically stranded.

Concentric, bunched and rope stranding are the three basic types.

Most conventional power and control cables employ a class B or class C stranding.

Class B stranding is a designation by the American Society for Testing and Metals (ASTM). As the letter designation progresses, the stranding becomes finer. Class B stranding is the simplest form of concentric stranding used. Class C is a finer concentric stranding than Class B.

When copper wires are twisted together, as in a concentric stranding process, a circle drawn through the centers of the wires of a layer is known as the pitch circle and its diameter as the pitch diameter for the layer(6). The length of lay of the wires in a stranded conductor is usually expressed as a multiple of the pitch diameter. The shorter the length of lay, the tighter and more flexible the conductor, but the ohmic resistance increases due to the greater length of wire used in the stranding process.

The lay of a strand is the lateral direction in which the individual wires run over the top of a cable as they recede from the eye. Right-hand lay recedes in a clockwise rotation and the left-hand lay is just the opposite.

Many cables are now being designed using a concentric stranding but compacting the strands. This provides the same circular mil area with a smaller overall diameter and thus reduced materials cost. Table IV shows the comparison of diameters of a Class B concentric stranded regular round, compact, and solid conductors.

Table IV. Conductor Diameters

Size (AWG)	Regular	Compact	Solid
2	.292	.266	.257
1	.332	.299	.289
1/0	.373	.336	.324
4/0	.528	.475	.460

The compacting of conductors can be done to bunch and shape conductors, as well as the concentric stranded conductor.

Shaped conductors are usually used in cables rated at 5 KV and above where shaping results in reducing cable dimensions, weight, and cost.

The segmental conductor arrangement is single conductors composed of either three or four segments which are electrically separated. Each strand of the individual sections is transposed between the inner and outer positions in order to maintain its concentric lay in its respective segment. This construction reduces the skin effect ratio, and is used mainly where high current carrying capacity must be combined with a small diameter.

The ohmic resistance of a solid straight conductor is directly proportional to its length (L) but varies inversely as the sectional area (A)(6).

$$\text{Resistance} = \rho \frac{L}{A} \text{ ohms}$$

The DC ohmic resistance for a copper annealed conductor is given by:

$$R = \frac{0.008144}{\text{copper area}} \ (\text{in}^2) \quad \text{ohms/1000 ft. at } 20^{\circ}\text{C}$$

It should be mentioned that the heating effect produced by load current increases the resistance value above the standard at 20°C.

Alternating currents in a conductor create induced effects and cause eddy-current losses which result in an increased heating of the conductor. "Skin Effect" is the tendancy for the current to travel near the circumference of a conductor instead of spreading itself uniformly over the total cross-section, thereby increasing the conductor resistance(6). When other conductors are present in the immediate vicinity, a further increase in the conductor resistance is experienced from the uneven current distribution caused by the other current carrying conductors. This is called the "Proximity Effect" and usually is quite small. This effect increases with conductor diameter and is at a maximum when the insulated conductors are in contact. Therefore, the correction in resistance for this effect is usually only necessary for cables of cross-sectional area above 0.40 in^2.

Conductor resistance and reactance are discussed in another section of this paper.

Quite often the strands of a copper conductor are coated to decrease the oxidation of the conductor. This oxidation and other corrosive actions are accelerated by the presence of heat and moisture. With sulfur cured insulations used years ago the conductor was coated to prevent interaction between it and the insulating material. The most often used coating for power cable conductors is tin or lead while nickel and silver is used only in specific constructions, such as high temperature wires. The thickness of the coating does not appreciably affect the conductor diameter and adds about a 4% increase in the resistance on sizes 24 and larger.

Power cables with a voltage rating above 2 KV usually have a semiconducting material placed between the conductor and the insulation. This semiconducting material is usually abbreviated and referred to as "semicon". This semiconducting material is placed at the interface to control or eliminate voltage stresses on voids which could exist between the conductor and insulation. This semiconducting material is made by adding carbon black to regular insulating compound, thus giving the conducting property. It may be in the form of a helically applied tape or an extruded covering.

It has been realized that satisfactory performance of a high voltage extruded type cable depends greatly on both the semiconducting conductor and insulation shields. In order to avoid corona discharges between these shields and the insulation, both shields must be in intimate contact with the insulation. Extruded strand and insulation shields are superior to tape shields in that they provide practically void-free contact with the insulation.

C. Insulating and Jacketing Materials

Many materials can be used both as insulations and jackets, depending on, voltage rating, temperature rating, chemical and physical requirements, etc. Therefore this section will deal with all types of materials and indicate the various applications each has along with their attributes and limitations.

Over the last fifty years, the materials available for use as insulation and jackets for wire and cable constructions have vastly increased. This section will present the characteristics of only the most prominent types of those materials.

There are two fundamental types of insulations and jackets under which there are many various specific types. The first fundamental type is thermoplastic materials and the second is thermosetting materials.

"Thermoplastic" is the term applied to those materials which soften and enter the plastic state with the application of heat. "Thermosetting" is the term applied to those materials which require a curing process to create the molecular bonds. This curing process is commonly referred to as "Vulcanization" of the material. Primarily, vulcanizing allows a material to maintain its dielectric properties and structural stability at higher temperatures and thus allows the entire cable system to carry higher currents without deformation of the insulation.

It must be remembered that the basic polymer, in both thermoplastic and thermosetting materials, is extensively compounded to impart specific properties pertinent to the cable application. The additives to the elastomer may include one or more of the following: fillers, plasticizers, vulcanizing agents, extrusion aids, accelerators, antioxidants, and antiozonants, just to mention a few.

Thus the finished compounds may contain as little as 20% of the actual elastomer to perhaps as much as 90% elastomer, depending on cost and desired properties.

It is obvious that an infinite number of combinations of compounds exist which display different electrical, mechanical, and chemical properties. Since this article is not intended to be a treatise on compounding of elastomers, it will be confined to only the most prominent types of those materials.

The first group to be discussed are thermoplastic materials.

1. Thermoplastic Materials

a. Polyvinylchloride

This material is most often referred to as "PVC". There are many variations of PVC compounds with the operating temperature rating ranging from 60°C to 105°C maximum. Only just in the last year have additives been developed to create a new PVC rated at 125°C operating temperature. Historically PVC has been used as an insulation, only on low voltage cables. Its most common application has been as a jacketing material.

PVC has very good mechanical characteristics and is fairly resistant to oils, paraffinic hydrocarbons, and mineral acids. PVC does experience swelling in ketones, chlorinated hydrocarbons and esters. PVC can be made to be "flame retardant" but in general has poor stability in the presence of heat and flame. The dielectric properties of PVC vary with the different types of compounds but as mentioned before are not considered for primary insulations requiring a low loss dielectric material.

b. Low-Density Polyethylene

Low-density polyethylene generally has a maximum operating temperature of 75°C. It is flammable but can be compounded so as to be "flame retardant" at the sacrifice of some physical and electrical properties(12). The mechanical properties of this material are poor and usually a nylon or other jacketing material is used as an outer covering to improve its abrasion and cut-through resistance. The electrical properties of low-density polyethylene are outstanding as it is a low loss material. Low-density polyethylene is the type of high molecular weight polyethylene most often used for insulating conductors when polyethylene is the desired material.

c. High-Density Polyethylene

High-density polyethylene possesses much better mechanical properties with better abrasion and cut-through resistance, than its low-density counterpart. Their chemical and electrical properties are similar. Both are outstanding in the presence of oils, paraffinic hydrocarbons, acids, alcohols, ketones, fixed alkalies, and esters. Only in a halogenated hydrocarbon environment do they have lesser resistance. High-density polyethylene is a little more stable in the presence of heat and can have a maximum operating temperature of 90°C. High-density polyethylene is the high molecular weight polyethylene most often used for jacketing when polyethylene is the desired material. In isolated cases high-density polyethylene is used as insulating material, as in the case of telephone cable insulation.

d. Polypropylene

The chemical and electrical properties of polypropylene are similar to those of the polyethylenes. Its melting point is higher than either of the polyethylenes and generally is rated at 90°C. The main difference between polypropylene is that it is harder and stiffer than high-density polyethylene and for that reason its abrasion and cut-through resistance is superior. Its primary use is as a jacket material, or as an insulation for the ground check conductor for mining cable, where mechanical strength is a necessity. Like the polyethylenes it is flammable but can be made "flame retardant".

e. Nylon

Where polyethylenes, and polypropylene were of the "polyolefin" family, nylon is from the polyamide resins. Nylon generally is rated at 90°C for continuous service. It is most often used as a jacketing material due to its excellent mechanical characteristics. It is widely used as a protective jacket over polyvinylchloride insulations in control cable constructions. Nylon is just as flammable as the polyethylenes, when applied in the thin wall jackets as is most often done, even though characteristically nylon is slower burning than most plastics.

2. Thermosetting Materials

The second group of insulation and jacketing materials to consider are the thermosetting elastomers. Thermosetting means that the material cannot be reformed or melted. As stated in the preface of this section, these materials are subjected to a heating cycle which causes them to "vulcanize" into their final state.

a. Natural Rubber

The physical and electrical properties of natural rubber are excellent. Natural rubber has a maximum operating temperature of 75°C, and exhibits good resistance to water but does not have good resistance to liquid fuels and oils. Its heat aging, resistance to oxidation and ozone resistance is poor when compared to those qualities in the synthetic elastomers.

Natural rubber has been used as an insulation for power cables, portable cords, control cable and some types of building wire. The use of natural rubber as an insulation material has become almost obsolete due to the outstanding synthetic insulations developed in recent years. Table V further outlines the properties of this material and offers a good comparison in relation to the other thermosetting insulating materials.

b. Styrene-Butadine Rubber

The most common ratio is approximately 75/25 butadine/styrene, with a normal maximum operating temperature rating of 75°C. Compounds can be prepared to allow a maximum operating temperature of 90°C. The electrical properties of SBR are better than those of natural rubber, but is somewhat inferior in mechanical properties. SBR is used for the same applications as natural rubber and is further outlined in Table V.

c. Chloroprene Rubber

The elastomers of this variety are most commonly known by DuPont's name of "neoprene". The electrical properties of neoprene are poorer than natural rubber, SBR, and butyl rubber. The real strong point of neoprene is its oil resistance, flame resistance, ozone resistance, weathering properties, and outstanding mechanical toughness. For these reasons, neoprene is seldom used as an insulation and most often used as a jacketing material. Neoprene can be formulated

Table V. Typical Properties of Elastomeric Compositions

Base Polymer	Natural	SBR	Neoprene	Butyl	Silicone	Silicone Fluor'ated	Hypalon	EPR	Fluoro-carbon
Specific Gravity	1.3-1.7	1.15- 1.55	1.40- 1.65	1.15- 1.50	1.10- 1.55	1.40- 1.80	1.35- 1.70	1.25- 1.45	1.90- 2.00
Ultimate Tensile Strength, psi	1500- 4000	800- 2500	1200- 2700	500- 1500	500- 1500	500- 1500	1200- 2200	1000- 2500	1000- 2000
Ultimate Elongation, %	300- 700	350- 650	300- 700	300- 800	100- 600	100- 250	300- 600	350- 600	200- 400
Rated Max Use Temp, °C	75	90	90	90	200	200	90	90	200
Rated Min Use Temp, °C	-55	-55	-55	-55	-100	-55	-55	-55	-30
Volume Resistivity ohm-cm	10^{13}- 10^{15}	10^{12}- 10^{15}	10^{11}- 10^{13}	10^{13}- 10^{16}	10^{13}- 10^{16}	10^{12}- 10^{14}	10^{12}- 10^{14}	10^{13}- 10^{16}	10^{12}- 10^{14}

Table V. (Continued)

Base Polymer	Natural	SBR	Neoprene	Butyl	Silicone	Silicone Fluor'ated	Hypalon	EPR	Fluorocarbon
Dielectric Constant, 1kHz	3.3-5	3.5-5	5-7	3.2-5	2.9-3.5	6-7.5	9-11	3.2-5	7-9
Dissipation Factor 1kHz	0.01-.035	.006-.035	0.02-0.05	.008-.035	.002-0.02	0.03-0.06	0.05-0.08	.007-0.035	0.02-0.05
Resistance to:									
Water Absorption	great	great	good	great	good	good	good	good	good
Oil & Gasoline	poor	poor	good	poor	poor	good	good	poor	great
Chlorinated Hydrocarbon	poor	poor	poor	poor	poor	good	poor	poor	great
Weathering	poor	poor	good	great	great	great	great	great	great

Table V. (Continued)

Base Polymer	Natural	SBR	Neoprene	Butyl	Silicone	Silicone Fluor'ated	Hypalon	EPR	Fluoro-carbon
Ozone	poor	fair	good	great	great	great	great	great	great
Flame	poor	poor	good	poor	fair	fair	good	poor	good
Radiation	fair	fair	poor	poor	good	good	fair	fair	fair

to permit a maximum operating temperature of 90°C. Further data on neoprene is presented in Table V.

d. Butyl Rubber

Butyl elastomers are copolymers of isobutylene and small amounts of isoprene(12). Some compounds have excellent electrical properties and have been used as insulating material on high voltage cable rated as high as 35 KV. The mechanical properties of butyl are not as good as neoprene or natural rubber and therefore butyl has limited use as a jacketing material and is most often used as an insulating material with a maximum operating temperature of 90°C. Further descriptive information is given in Table V.

e. Silicone Rubber

The silicone elastomers have the widest thermal operating temperature range of the elastomers, ranging from -100°C to 200°C. Fluorinated silicone differs from the standard silicone in that it is more oil resistant. All silicones are flammable but contain the unique property that a nonconductive ash remains after burning, thereby inhibiting further propagation of flame travel. The practice of using silicone as an insulating material covered by a glass or asbestos braid, provides a good insulator for high ambient temperature locations.

While the electrical properties of the silicones are very good, their mechanical properties are not exceptional. The abrasion and cut-through resistance of silicone is inferior to many of the other elastomers. Silicones are used primarily as insulating materials and can be used as high voltage insulation when temperature requirements rule out the use of other insulations. Both standard silicone and fluorinated silicone are further described in Table V.

f. Chlorosulfonated Polyethylene

These elastomers are more commonly known by DuPont's trade name of "Hypalon". These compounds are characterized by their excellent resistance to ozone, common oils, liquid fuels, weathering, flame and corona.

Hypalon has good physical characteristics and in appearance resembles neoprene. Hypalong has adequate electrical properties to allow it to be used as low voltage insulation but is most commonly used as a jacketing material. Hypalon can be colored more readily than neoprene and therefore is used in place of neoprene when coloring is required. Further properties of Hypalon are outlined in Table V.

g. Ethylene Propylene Rubber

These elastomers are copolymers of ethylene and propylene or more recently, terpolymers of ethylene, propylene, and a diene. The latter offers vulcanization with more conventional curing systems(12). Compounds made from these elastomers offer outstanding electrical properties and have a maximum operating temperature rating of 90°C. The mechanical properties of EPR are good but due to its outstanding electrical properties it is most often used an an insulating material. High voltage power cables can be insulated with EPR up to and including 69 KV. Further descriptive properties of EPR are outlined in Table V.

ASTM refers to ethylene propylene as the M family where both EPM, a copolymer, and EPDM, a diene-monomer are used as an insulating material.

h. Cross-Linked Polyolefins

"Cross-linked" describes the process of tieing together individual polymer molecules into a network structure. This cross-linking process can be effected by two means: (1) by irradiation and (2) chemical means.

In 1954 General Electric offered an irrathene-irradiated polyethylene developed by the electron irradiation of special polyethylene films. The source of this radiation was a modified resonant-transformer electron-beam generator. This process was very costly even in view of the advantages of cross-linking. This cross-linked polyethylene insulating material is commonly referred to as "XLP".

It was not until the advent of peroxide cross-linking techniques that the XLP, as we know it today, became a major source for low, medium, and high voltage insulation.

The electrical properties of the cross-linked polyolefins are greatly improved along with increased flow resistance at elevated temperatures. Maximum operating temperatures of XLP insulations are normally $90^{\circ}C$. In general only the polyethylene resins have been successfully cross-linked commercially.

XLP is most commonly used as an insulating material but can serve as both insulation and jacketing in low and medium voltage applications. XLP has been used as high voltage insulation up to 69 KV.

One criticism of XLP has been its susceptibility to "treeing". "Treeing" is the term used to describe the minute branching which develops within the insulation, where it is under electrical stress and a combination of voids, contaminants, or moisture exist in the insulation. The branches extend generally in the direction of the conductor and shield. If the treeing continues it is only a matter of time before electrical breakdown of the dielectric occurs. Except in the cases where paper insulation is still necessary, EPR and XLP are the two primary high voltage insulations.

3. Films

Film can be defined as sheeting less than 10 mils in thickness(12). The application of films is usually in the form of a tape wrapping followed by an operation to hold the wrap in place. Heat sealing is the most often used form of sealing the films.

Cellulostics, polyesters, fluorocarbons and polymide are the most commonly used films.

The use of films permits the incorporation of the film properties with that of the primary insulation thereby reducing the insulation wall thickness. Most films possess a specific mechanical or electrical property that is desired in the construction of a cable for specific applications.

4. Fibers

The primary use of fibers in the wire and cable industry is in the form of reinforcements, filters, and protective coverings providing improved overall mechanical characteristics.

Cotton, rayon, nylon, polyester, glass, asbestos and fiber combinations are the most often used fibers in the wire and cable industry. Fibers, like films, provide a specific electrical or mechanical property to the final product that is desirable in its application.

5. Paper Insulation

In the early 1900's almost all high voltage cable was insulated by impregnated paper. Although in some applications paper insulated cables are still used, this type of insulation has been replaced through the years by the rubber, butyl, and more recently EPR and XLP compounds.

Paper when dried at high temperature easily soaks up impregnating materials. It is the impregnating material, containing organic mineral oils, resin and grease, that gives the paper insulation its superior dielectric strength. This impregnation material must possess a high electric strength, it must be as dry as possible, and flow easily, especially at low temperatures.

In making paper cable the paper is cut into narrow strips and wound spirally around the conductor. It is important that the layers not be compacted so as to keep the cable flexible and allow room for the impregnating material.

Since moisture and mechanical damage are two problem areas for paper insulation, lead sheaths are the most common type of sheaths applied over paper insulation. It is important to note that even a small amount of moisture present in a paper impregnated insulation can decrease its dielectric strength significantly. Therefore in underground paper cables the lead sheath provides outstanding protection for the insulation. Many people are of the opinion that if the lead sheath is not penetrated through to the insulation, either by mechanical or chemical damage, and the cable is not electrically overloaded, the cable has an almost infinite life span.

6. Varnish Cambric (VC)

Varnish Cambric (VC) insulation is a cloth which consists of a closely woven cotton sheeting both sides of which have been coated with an asphalt base and a linseed oil varnish. It is the varnish film that acts as the dielectric. This insulation is helically applied in tape form.

Varnish cambric insulated cables were introduced in the early 1900's shortly after the high voltage paper insulated cables. Varnish cambric is not affected by moisture or oil migration, where a difference in elevation is involved, as much as paper insulation and originally was used at higher voltages than paper and in vertical riser installations. In the early years of rubber dielectrics, varnish cambric was rated at 85°C as compared to 60°C or 70°C for rubber and thus allowed for greater ampacity ratings.

Due to its high power factor and greater dielectric loss, varnish cambric insulation is not recommended for voltages above 15 KV. With the development of many solid dielectrics VC insulation is seldom used except for some industrial and commercial power cables having a lead or inter-locked armor sheath.

D. Shielding

Semiconducting strand shielding has already been discussed. This section deals with insulation shielding. Shielding of an electric power cable is the practice of confining the electric field to the insulation of the conductor or conductors(7). The combination of strand semiconducting material, insulation semiconducting material, and a metallic shield make this confinement possible.

The insulation semiconducting material is constructed similar to that of the strand semiconducting material as described in Section I-B and is applied over the insulation. It is referred to as the insulation "semicon". Like the strand screen, the insulation semicon layer is made by adding carbon black to regular insulating compound. The insulation semiconducting shield is applied to eliminate air spaces between the insulation and the metallic shield and to maintain the surface at an equipotential voltage. Voids at this interface, under voltage stress, can result in "corona" as described later.

The insulation semiconducting material may be applied in the form of semiconducting tape or an extruded layer. Only in the voltages above 35 KV does it become important to consider using an extruded insulation semicon.

There are many reasons for employing an insulation shield system. Some of these are:

a) Safety
b) Distribute symmetrical voltage stress within the dielectric
c) Protect the cable from induced potentials
d) Reduce radio interference
e) Provide a positive path for short circuit current to follow to ground

By using an insulation shield and grounding it, the electric field is indeed confined to the dielectric. Where there is no metallic shielding or covering over the insulation, the electric field is between the conductor and the nearest ground point. Thus the possibility of shock becomes greater. It is also possible and likely that a non-shielded power cable will generate a surface discharge and convert the air into ozone which may be destructive to the cable jacket and insulation. This ionization of the air is commonly referred to as "corona". It is for these two reasons that IPCEA recommends that non-metallic covered power cables operating above 2000 volts for single conductor cables, and 5000 volts for assembled conductors with a common overall jacket, have a metallic shield. Above 5 KV all power conductors must be shielded. Using an insulation semiconducting shield, a strand semiconducting shield and a metallic insulation shield, the voltage stress is distributed symmetrically within the dielectric. This eliminates excess voltage stress in a particular portion of the dielectric and enhances the life of the insulation.

For certain applications it is desirable to shield against all possible induced potentials and it is a fact that shielded cables are effected less than non-shielded cables in the presence of an external magnetic field. In power cables but more importantly in control cables, shielding helps prevent voltage pick-up by the conductor when transient currents tend to induce voltage into a circuit by virtue of surges on the adjacent power transmission lines. Another source of interference on control cables comes from the sparking and arcing of switch or relay contacts in the power transmission circuits. These low-level signal cables can usually be sufficiently protected by shielding.

Finally a common use of shielding is to provide a positive path for current to follow to ground if a fault occurs in the cable insulation. Under this fault condition, the short circuit capacity of the shield must be adequate to conduct the fault current prior to protective interrupt, without damage to the peripheral equipment. There are many types of insulation shields and various ways to apply them. Some of the more popular types of shielding are:

a) Non-magnetic tapes-usually copper
b) Concentric wires-usually copper
c) Lead sheaths and other metallic non-magnetic outer coverings
d) Corrugated non-magnetic sheaths
e) Non-magnetic braids

The most often used shield in a power cable is a copper tape helically wrapped around the core. The thickness and number of tapes is determined by the fault current magnitude and duration. Usually these copper tapes range from .003" to .005" thick. Where unusually high fault currents may exist, a combination of copper tape and concentric wires can provide the cross-sectional area of copper required.

Concentric wires are used in shielding as mentioned before, but more often are found in the underground residential distribution (URD) cables. In the URD cables the concentric wires provide a shield as well as act as a conductor and in the case of a single phase operation, must have the same ampacity as the insulated conductor.

Lead sheaths and other metallic non-magnetic outer coverings usually provide a good shielding system if the ampacity rating of the sheath is sufficient to carry predicted fault currents.

Corrugated non-magnetic shields usually have been confined to control and telephone cable constructions. The corrugated shield is usually longitudinally applied and has greater flexibility, greater resistance to crushing, less possibility of gouging into the insulation, and improved electrical conductive properties when compared to the traditional helically wrapped tape shields. It is for these reasons that much support is being gained for corrugated longitudinally applied shields in other areas such as power cable shields.

Finally, a most popular type of shielding is that of a woven braid. This braid which can be copper, or a copper-nylon combination consists of many ends of fine wire to give 85% to 96% surface coverage. Probably the greatest attribute of a shielding braid is that it is the most flexible type of shield available. A braid is used almost exclusively in the construction of portable shielded mining cables.

The material used in insulation shields is most often copper. Aluminum is another metal used as in an aluminum/mylar tape. Bronze is another type of metal used along with some bimetallic constructions; but where conductivity is important, the copper insulation shield is the one used.

E. Jackets and Outer Sheaths

Contained in the section on insulation was references to the types of materials most often used in outer jacketing of cables. Other than the plastic and thermosetting materials used in the jacketing of cables, there is a category containing metallic sheaths.

Probably the oldest type of sheath known is the lead sheath. Almost all power cables in the early 1900's were insulated with paper and sheathed in lead. Lead provides an outstanding jacket for a cable with almost the ultimate in protection for the cable core. The disadvantages of lead are: expense, flexibility, and splicing and termination time required.

Another metallic jacket gaining popularity is the inter-locked armor sheath. The inter-locked armor is a helically wrapped inter-locking armor applied over the cable core. The armor material is usually steel, aluminum, or copper.

Another type of sheath is the continuously corrugated metallic sheath. The advantage of this construction is that it provides a completely impervious sheath like the lead and unlike the inter-locked armor construction. The materials used in these sheaths is also copper, aluminum, or steel.

Almost all of these metallic sheaths can have a PVC or polyethylene jacket applied over their exterior, for added corrosion resistance and ease of pulling.

II. TECHNICAL CONSIDERATIONS

A. A-C/D-C Resistance

The formula for the ohmic resistance of a solid conductor was given in Section I-B. Conductor D-C resistance values are usually listed in ohms per 1000 feet at 20°C. Due to the "Skin Effects" and "Proximity Effects" created by alternating currents, it is necessary to have an A-C/D-C resistance ratio for converting known D-C values into A-C values. Table VI shows this relationship.

Table VI, assumes standard concentric stranding in all stranded conductors. Values in columns A & B include skin effect only, whereas values in columns C & D include skin effect, proximity effect and all other A-C inductive losses. A-C/D-C resistance ratios for frequencies other than 60 hz can be derived from using a combination of formulas and graphs. These formulas and graphs will not be shown in this article but can be found in electrical engineers handbooks.

B. Inductance

There are two types of inductance associated with a conductor carrying an alternating current. The inductance within the conductor is termed the series or internal inductance and designated by (L_i). The inductance in the space between one or more conductors is termed external

Table VI. A-C/D-C Resistance Ratios for Insulated Aluminum and Copper Conductors at 50 Cycles and 65°C

Conductor Size	A	B	C	C
(AWG or MCM)	Aluminum	Copper	Aluminum	Copper
up to 3	1.000	1.000	1.00	1.00
2	1.000	1.000	1.00	1.01
1	1.000	1.000	1.00	1.01
1/0	1.000	1.000	1.00	1.02
2/0	1.001	1.000	1.00	1.03
3/0	1.001	1.000	1.01	1.04
4/0	1.001	1.000	1.01	1.05
250	1.002	1.005	1.02	1.06
300	1.003	1.006	1.02	1.07
350	1.004	1.009	1.03	1.08
400	1.005	1.011	1.04	1.10
500	1.007	1.018	1.06	1.13
600	1.010	1.025	1.08	1.16
700	1.013	1.034	1.11	1.19
750	1.015	1.039	1.12	1.21
800	1.017	1.044	1.14	1.22
1000	1.026	1.067	1.19	1.30
1250	1.040	1.102	1.27	1.41
1500	1.058	1.142	1.36	1.53
1750	1.079	1.185	1.46	1.67
2000	1.100	1.233	1.56	1.82

Table VI. (Continued)

Use Columns A & B for the following:

1. Single or multi-conductor non-metallic sheathed cables in air or in non-metallic conduit.
2. Single conductor non-magnetic metallic-sheathed cables installed with sheaths insulated in air or in separate non-metallic conduits.

Use Columns C & D for the following:

1. Multi-conductor non-magnetic metallic-sheathed cables.
2. Multi-conductor non-metallic sheathed cables in non-magnetic metal conduit.
3. Two or more single conductor non-metallic sheathed cables in same non-magnetic metallic conduit.

inductance (L_e). The total inductance (L) is the sum total of these two values.

$$L = L_e + L_i$$

L_e is a function of the geometry of the circuit and given by the equation:(25)

L_e = .1404 [log(b/a)] x 10^{-3} henries to neutral/MFT
b = spacing between centers of conductors (in.)
a = radius of conductors (in.)

L_i is a function of the diameter of the conductor and the operating frequency. Conductors under 1.5" in diameter, which incorporates almost all of them, can use the constant value of .015 x 10^{-3} henries to neutral/MFT., L_i.

The inductance of multi-conductor cable depends principally on the thickness of the insulation in as much as they are normally in a concentric configuration which places each conductor in contact with an adjacent conductor.

Mutual inductance is discussed in Section II-L, concerning shield and sheath losses.

The inductance of two-conductor concentric or coaxial cables consists of three inductance values and is the sum total of the three.

$$L = L_e + L_i + L_o$$

L_e and L_i are as described previously, but L_o is the value of internal inductance of the outer conductor. This value of L_o is usually negligible for all non-magnetic materials and may be ignored. Only when magnetic conductors are used or extreme accuracy is needed must one consider the value L_o as being significant enough to include in the total inductance calculation.

C. Capacitance

The electrostatic capacitance of an insulated conductor is given by:(25)

$$C = \frac{.00736\ (SIC)}{\log\ (D/d)} \quad \text{in farads/MFT}$$

where SIC = dielectric constant (specific inductive capacity) of insulating material

D = Outside diameter of the insulation (in)

d = Diameter of conductor (in.)

The SIC of an insulating material is the ratio of the capacitance of a capacitor insulated with that material, to the capacitance of the same capacitor insulated with a vacuum(25). The capacitance of a multi-conductor cable can be approximated in terms of C_1 and C_2 where;

C_1 = Capacitance of one conductor relative to the other

C_2 = Capacitance between all conductors and overall sheath

Mutual capacitance is usually associated with twisted pairs as used in communication and instrumentation cables. This value is usually between 30 and 50 percent of the values of one conductors capacitance to ground and can be approximated by:

$$C_m = \frac{.00221\ (SIC)}{\log\ (D/d)}\ \text{uf/MFT}$$

D = o.d. of cable (in.)

d = o.d. of conductor (in.)

The capacitance of a coaxial cable is defined by its relationship between the inner and outer conductors.

$$C_m = \frac{.00736\ (SIC)}{\log\ D/d}\ \text{uf/MFT}$$

where: D = I.D. of outer conductor

d = O.D. of inner conductor

Table VII lists some typical values of SIC.

Table VII. Typical Values of SIC

Material	SIC
PVC	5.0--8.0
Oil Base, Butyl and EPM	3.5
Polyethylene	2.3

D. Reactance

Reactance is the sum of inductive reactance and capacitive reactance, and is usually given in ohms/MFT.

$$X = X_l + X_c = wL - \frac{1}{wC}$$

Where L and C are the inductance and capacitance as described in the previous two sections.

The inductance reactance is given by the formula below:

$$X_l = 2\pi f\ [.1404 \log (s/r) + .0153] \times 10^{-3}$$

where X_l = Reactance ---ohms/MFT
r = Radius of conductor (in.)
f = Frequency (hz)
s = Spacing between the centers (in.)
where s = $3\sqrt{AxBxC}$

The above reactance is the inductive reactance of a conductor and pertinent when calculating the voltage drop of a feeder. In this calculation the capacitive reactance is negligible. The only effect that the capacitance of an insulated conductor has is on the charging current. The subject of charging current is discussed in a later section.

It must also be stated at this point that the above reactance is for a single insulated conductor. There are correction factors for single conductors in conduit. Non-magnetic conduit increases the reactance 20% for single conductor random lay cables. Magnetic conduit increases the reactance 50% for random lay cables. There are slight correction factors for multi-conductor cables as listed in Table VIII. There is no increase in reactance for multi-conductor cables installed in non-magnetic conduits but when they are installed in magnetic conduits, the correction factor for round conductors with magnetic binders must be used, as listed in Table VIII.

Table VIII. Corrections for Multiconductor Cables(19)

Conductor Size MCM	Non-Magnetic Binder		Magnetic Binder	
	Round	Sector	Round	Sector
Up to	Multiplying Factor			
250	1.000	.975	1.149	1.230
300	1.000	.970	1.145	1.225
350	1.000	.965	1.140	1.220
400	1.000	.960	1.134	1.216
500	1.000	.950	1.122	1.208
600	1.000	.940	1.111	1.199
700	1.000	.930	1.100	1.191
750	1.000	.925	1.095	1.186

E. Voltage Regulation

The formula for voltage drop of a feeder is:(19)

$v = 100\ (V_s - V_1)/V_1$ where,

v = Voltage drop in percent

V_1 = Voltage across the load

$$V_s = \sqrt{(V_1 \cos\theta + RI)^2 + (V_1 \sin\theta + XI)^2}$$

θ = is the angle by which the load current lags the voltage across the load

$\cos \theta$ = Power factor of load

R = Total A-C resistance of feeder

X = Total reactance of feeder

I = Total load current

The above formulas apply for single phase lines where resistance and reactance are loop values and voltage is the voltage between lines.

For a 3-phase circuit use voltage to neutral and resistance and reactance of each conductor to neutral. This will results in the voltage drop to neutral. By multiplying the voltage drop to neutral by $\sqrt{3}$, voltage drop line-to-line may be obtained.

F. D-C Insulation Resistance

Measuring the D-C insulation resistance, following installation of a cable, can be a maintenance aid. This is often done by using a megohmmeter or the voltage-ammeter method. By doing this after installation, possible weaknesses may be detected by subsequent measurements, and their comparison to previous measurements. It is also helpful in fault location to know the normal insulation resistance of a cable. The formula for calculating the D-C resistance of an insulation is:

$R = K \log (D/d)$ where,

R = D-C insulation resistance (megohms/mft at 60°F)

K = Insulation resistance constant (megohms/mft at 60°F)

D = Average O.D. of the insulated conductor (mils)

d = Average O.D. of the bare conductor (mils)

Table IX. Typical Values for Insulation Resistance Constant

Polyethylene	50,000
PVC	2,000
Rubber	2,000
Butyl	20,000
EP	20,000

G. Dielectric Loss

Most of the energy which flows into the insulation in the form of charging current is returned to the system as the voltage alternates. There is however, a small portion of energy loss in the dielectric. This dielectric loss is the heat dissipated in the insulation, that is generated due to the resistance of the dielectric. In general, at 60 hz/second this can be ignored except at voltages of 69 KV and above. The formula for calculating the dielectric power loss is:

$PL = I_c \times PF \times E$ where,

PL = Power Loss (watts)

PF = Power factor of the insulation

I_c = Charging current in phase with the capacitive element

E = Impressed voltage

The power factor of the dielectric is determined by the molecular make-up of the insulating compound. From the formula for power loss in a dielectric, it is apparent that a low power factor is the most desirable.

H. Charging Currents

Cable is like any other capacitor, when it is subjected to an alternating voltage, a charging current is proportional to the capacitance of the insulation. Because of this, a low dielectric constant (SIC) is the most desirable to lower the charging current. The charging current I_c of a single conductor insulated power cable can be obtained from the formula below:

$I_c = 2\pi FCE \times 10^{-13}$ milliamperes/MFT, where,

C = Capacitance--picofarads/ft

E = Voltage to neutral--kilo--volts

F = Frequency

I. Absorption Current

Absorption current is caused by various polarizations and accumulation of electrical charge which can be released after the removal of the applied voltage. If insufficient discharge time is allowed, the effect of the absorption current would be to build up a possibly dangerous voltage when the short circuit is removed.

J. Leakage Current

The leakage or conduction current is the third and most important component comprising the total current flow in a conductor. In a high voltage D-C test the leakage current can be determined by $I_l = E/R$, where,

E = Voltage
R = Insulation Resistance
I_l = Leakage Current

With the application of a D-C voltage, the charging current and absorption current decrease almost to zero within a short time interval. In high voltage D-C testing the leakage current is observed closely, hoping for it to reach a constant value after a short time interval. Constantly increasing leakage current with respect to time with a constant voltage applied usually indicates faulty insulation, splice or terminations. This will be discussed in a later section concerning high voltage testing.

K. Total Current

The total current flow caused by the application of a voltage across an insulation material is made up of three components: (1) charging current, (2) absorption current, and (3) leakage current. All of these have been discussed in detail in the previous sections.

L. Shield/Sheath Losses

When a shielded cable is installed, the metallic shield must be solidly connected to ground. For the most effective operation and maximum safety, the shield should be grounded at both ends and at each splice. All grounding connections should be made in a way so as to provide the lowest resistance path to ground. No matter how well the shield is attached to ground, metallic shields or sheaths grounded at more than one point will create current flow in the shield or sheath due to induced voltage. This current flow will cause heating in the shield or sheath and thus reduce the overall current rating of the cable. The value of circulating current flowing depends on the mutual inductance of other cables, the currents in these conductors, and the resistance of the shield or sheath.

The current rating should be corrected by the factor determined by the following formula:

$$F = \sqrt{\frac{R_C}{R_C + R_O}}$$ where,

F = Current rating correction factor

R_C = A-C resistance of conductor, including all skin and proximity effects (ohms/mft at operating temperature)

R_O = Increment of increased resistance due to heating of shield (ohms/mft)

For tape or tubed shields or sheaths, and cables in a triangular configuration, R_o is calculated as follows:

$$R_o = \frac{X_m^2 \quad R_s}{X_m^2 + R_s^2} \quad \text{ohms/MFT, where,}$$

$$X_m = .053\log S/R_m \text{ ohms/MFT}$$

$$R_s = \frac{\rho}{8R_m t} \times 10^{-3} \quad \text{ohms/MFT}$$

ρ = Resistivity of shield or sheath (ohms/circular mil ft)

R_m = Mean radius of shield or sheath (in.)

t = Thickness of shield or sheath (in.)

s = Spacing between conductors

Table X. Typical Values of Shield/Sheath Resistivity

Overlapped tinned copper tape.....	30 ohms/cir mil ft
Overlapped monel tape...........	2500 ohms/cir mil ft
Overlapped Ambrac tape...........	350 ohms/cir mil ft
Lead sheath.....................	150 ohms/cir mil ft
Aluminum sheath..................	20 ohms/cir mil ft
Aluminum Interlocked Armor........	28 ohms/cir mil ft
Galvanized Steel Armor Wire......	102 ohms/cir mil ft

Where shield or sheath losses become prohibitive, it is possible to ground the sheath or shield at one point only, thus cutting down on circulating currents. There then becomes a new problem which is the voltage build-up in the sheath or shield. This voltage build-up is due to the mutual inductance to other cables, the current in the other cables, and the distance to the ground point. This voltage build-up can become unsafe and the value of 25 volts is used as the maximum permissible voltage build-up. With this value in mind the following table lists the maximum allowable continuous lengths for single copper conductor cables having their shields or sheaths grounded at one point.

Table XI. Maximum Allowable Continuous Lengths for Single Copper Conductor Cables Having Their Shields or Sheaths Grounded at One Point

Size Conductor	One Cable Per Duct	Three Cables Per Duct
1/0	1250	9550
2/0	865	3000
350	710	2260
500	580	1870
750	510	1500
1000	450	----
2000	340	----

III. INSTALLATION AND MAINTENANCE CONSIDERATIONS

A. Ampacity Rating

There are many factors that determine the ampacity rating of a cable. The voltage, whether it is A-C or D-C, along with frequency if A-C, and the load factor, are all circuit factors that should be known to determine ampacity. The conductor type, size and number in the same cable, along with the kind of insulation, shielding and jacket material, also effect the ampacity rating. One should also know the type of installation he is to place this cable. Ambient temperature of earth, number of ducts, spacing of ducts, material of ducts are all important factors when considering a duct installation.

All these factors mentioned above contribute to the overall ampacity rating of a specific cable, and should be known before going to an ampacity table to determine the rating of a cable and its conductor. Probably the best recognized source of information for determining the ampacity rating of a cable is the National Electrical Code (NEC), Section 310, Tables 310-12 thru 310-15 on Pages 70-113 thru 70-120. These tables cover ampacities for cables having a voltage rating up to and including 600 volts. For circuits having a voltage rating above 600 volts, the best source for determining the ampacity of a conductor is the AIEE-IPCEA "Power Cable Ampacities" joint publication

S-135-1 and P-46-426.

Since it is assumed that both of these sources should be readily available to the reader, the tables mentioned will not be included in this treatise.

The ampacities listed in the NEC and AIEE-IPCEA tables are based on the maximum operating temperature. There are three classifications of conductor temperature. These are listed below and are a result of a study of the Insulated Power Cable Engineers Association (IPCEA) and are recognized throughout the industry.

> Maximum Conductor Temperature--Operating---The highest conductor temperature attained by any part of the cable line under operating current load(30).
>
> Maximum Conductor Temperature--Emergency Overload The highest conductor temperature attained by any part of the cable line during emergency overload of specified time, magnitude, and frequency of application(30).
>
> Maximum Conductor Temperature--Short Circuit The highest conductor temperature attained by any part of the cable line during a short circuit of specified time and magnitude(30).

The operating temperature of an insulation is a function of the ambient temperature, the I^2R losses, dielectric losses, and losses due to induced voltages in the cables metallic covering or its metal surroundings such as conduit.

It is imperative to the cable life that the insulation not be heated above the determined maximum operating temperature for long periods of time.

It should be noted that even though the "Power Cable Ampacities" publication by AIEE-IPCEA might not be as accessible as the NEC, certainly the more reliable sources of ampacity tables for the above 600 volt cable class are usually taken from this publication. Also make certain that all correction factors and notes accompanying these tables are considered in the final determined value of ampacity.

B. Conduit Sizing

The NEC in Chapter 10 Table I outlines the following allowable percent of conduit and tubing fill:

Table XII. Percent Allowable Internal Area Fill of Conduit or Tubing

No. of Conductors	1	2	3	4	over 4
All conductors except lead covered	53	31	40	40	40
Lead covered	55	30	40	38	35

When these figures are converted to percent of internal diameter of the conduit or tubing, Table XIII results.

Table XIII. Allowable % Internal Diameter Fill of Conduit or Tubing

No. of Conductors	1	2	3	4	over 4
All conductors except lead covered	72.8	39.3	36.5	31.6	---
Lead covered	74.2	38.7	36.5	30.8	---

Table XIV outlines the maximum allowable diameter (in inches) of individual cables of the same size in a given size conduit.

Table XIV. Maximum Allowable Diameter (in inches) of Individual Cables of the Same Size in a Given Size of Conduit

Nominal Size of Conduit	Number of Cables Having the Same O.D.			
	1	2	3	4
1/2	0.453	0.244	0.227	0.197
3/4	0.600	0.324	0.301	0.260
1	0.763	0.421	0.383	0.332
1 1/4	1.010	0.542	0.504	0.436
1 1/2	1.173	0.633	0.588	0.509
2	1.505	0.812	0.754	0.653
2 1/2	1.797	0.970	0.901	0.780
3	2.234	1.206	1.128	0.970
3 1/2	2.234	2.306	1.128	0.970
4	2.930	1.583	1.470	1.273
5	3.675	1.984	1.844	1.595
6	4.416	2.385	2.215	1.916

To determine the size of conduit required for a group of cables having different outside diameters the following procedure and formulas can be used.

First determine the equivalent diameter "D" by using the following formula:(19)

$$D = \sqrt{\frac{n_1 d_1^2 + n_2 d_2^2 + \cdots\cdots\cdots\cdots n_m d_m^2}{n_1 + n_2 + \cdots\cdots n_m}} \quad \text{where,}$$

n_1 = Number of cables having diameters d_1

n_2 = Number of cables having diameters d_2

n_m = Number of cables having diameters d_m

After determining the value of "D" then use the Table XIV, to determine the size of conduit required for m amount of cables.

To determine the size of conduit required for any number (m) cables in excess of four, multiply the diameter of one cable by $\sqrt{m/4}$. This will yield the equivalent diameter for four such cables. Then use the column for four cables to obtain the correct conduit size required.

C. Pulling Tensions

The definition of pulling tension is that force required to pull a cable into a duct. Rule-of-thumb is that the maximum stress on a cable shall not exceed .008 times the circular mil area of the conductor.

The pulling tension in a given duct section having no bends may be calculated by the following formula.

$T = L\ w\ f$ where,

T = Total pulling tension (lbs.)

L = Length of the duct run in ft.

w = Weight of cable in #/ft.

f = Coefficient of friction = 0.5

For duct runs having a curved section the following formula applies:

$T = T_2 + T_1 e^{fa}$ where,

T_2 = Tension for a straight section at pulling end

T_1 = Tension for a straight section at feeding end

f = Coefficient of friction = 0.5

e = Naperian logarithim base = 2.718

a = Angle of bend in radians (1 radian = 57.3 degrees)

From this formula it is easy to see that the minimum tension is obtained if the feeding end of the cable is nearest to the bend.

Although conduits are generally filled according to code, which allows only a maximum of 53% fill, it is still wise to aid yourself during the pulling process. A soap or lubricant solution applied to the cable surface will ease the friction during the pulling process. Always feed the cable straight into the conduit. When coming into a junction box where sharp angles are involved, allow a slack to develop rather than feeding from one duct abruptly into the other. It is always wise to swab and clean the duct before beginning the pulling process.

D. Bending Radii

Minimum recommended values of bending radii to which cables may be bent during installation are given by the table below. These values are expressed in terms of the outside diameter of the cable in question.

Table XV.(19) Non-Metallic Sheathed Non-Shielded Cables Bending Radii Relationships

Insulation Thickness	Overall Diameter 1.000 & Less	Overall Diameter 1.001 to 2.000	Overall Diameter 2.001 & Over
10/64 and less	4	5	6
11/64 to 20/64	5	6	7
21/64 and over	---	7	8

Power Cables with Metallic Shielding or Armor

Wire shielded, Tape shielded, and Armored

Cables....................................12 times

Interlocked Armor non-shielded................7 times

Control and Portable Cables

Control cables 19/c and larger................8 times

Portable cables 0-5 KV........................6 times

5 KV and above................8 times

It must be remembered that these values are minimum bending radii that must be adhered to during both installation and the permanent installed state. These values are not the only criteria that must be followed during installation. One must be careful not to exceed the maximum allowable sidewall pressure. Sidewall pressure is the radial force exerted on the insulation and sheath of a cable at a bend point when the cable is under tension(25). The normally accepted value of maximum allowable sidewall pressure is 300 pounds per foot.

E. Direct Burial

Regardless of the type of sheath being installed, care should be taken during the installation. Keep stones and sharp objects away from the immediate area of the cable where possible. Soft fill should be used around the cable which not only keeps the sheath intact but also improves the heat dissiaption. Allow at least 24" between the cable and the surface of the trench. Try to provide a soft bedding for the cable to lay on and do not pull the cable taut as it is laid in the trench; rather, allow it to slacken. If these few helpful hints are followed, many problems with direct burial may be avoided.

F. Sag and Tension

The values of sag and tension are important when considering installation of an aerial cable. The formula for determining the amount of sag is:

$$t = \frac{s^2 w}{8d} \quad \text{where,}$$

t = Horizontal tension in messenger (lbs)

w = Weight of complete cable including messenger (lbs/ft)

d = Sag (ft)

s = Span length (ft)

Normally 50% of the messenger breaking strength is used when calculating for heavy loading and 25% of breaking strength for a normal loading condition.

While it is recognized that the total tension in the messenger is due to both horizontal and vertical components, the vertical component has been neglected as it is negligible. Some typical breaking strengths of messengers are shown in Table XVI along with their weights per foot.

Table XVI. Typical Breaking Strengths of Messengers

Messenger Size	Copperweld WT/FT-Strength	Stainless Steel WT/FT-Strength	Galvanized WT/FT-Strength
5/16"	.204 9,196 Lb.	.208 11,900 Lb.	.205 11,200 Lb.
3/8"	.324 13,890 Lb.	.278 16,200 Lb.	.273 15,400 Lb.
1/2"	.515 20,460 Lb.	.525 27,000 Lb.	.517 26,900 Lb.
9/16"	.649 24,650 Lb.	-- ---	.617 35,000 Lb.

With this table, the tension can be determined. The span length should be known; which then leaves the weight of the complete cable to be determined before the value of sag can be calculated.

The ice and wind loading on a cable must be taken into account when calculating the resultant weight of a cable. The National Electrical Code divides the country into three geographic districts and then designates the loading constants according to district. These values are given in Table XVII (19).

Table XVII. (19) NEC Loading Factors

District	Heavy	Medium	Light
Radial Thickness of Ice (in.)	1/2	1/4	0
Horizontal Wind Pressure (lbs/ft^2)	4	4	9
Temperature (F)	0	15	30
Constant--K (lbs/ft)	0.31	0.22	0.05

The resultant weight is then calculated using the above values and the following formulas (19).

i = Weight of ice loading (lb/ft), $i = 1.24t(D + t)$

t = Thickness of ice (in.)

D = Diameter of cable (in.)

h = Force due to wind (lbs/ft), $h = P(D + 2t)/12$

P = Horizontal wind pressure (lbs/ft^2)

w' = Weight of unloaded cable

w'' = Vertical weight of loaded cable $w'' = w' + i$

w''' = Resultant weight of loaded cable

$w'''' = (w' + i)^2 + h^2 + k^2$

Using the values and formulas on Page 61, most sag calculations can be determined for aerial cables having a messenger.

With the modulus of elasticity and the coefficients of expansion of both the steel and aluminum, ACSR sag and tension may be calculated using the formulas list on Page 61.

G. Splicing

When splicing two cables together the principle objective is to join the conductor ends so that the connection provides conductivity equivalent to that of the conductors. Splicing of cables rated 2000 volts and below usually involves designing adequate mechanical strength in the splice. Crimp type connectors are the type most often used. The process of replacing the insulation with the use of tape has not changed much through the years. Rubber and thermoplastic insulating tapes are used on cables insulated with rubber and thermoplastic respectively. The amount of build-up is usually one and a half to two times the normal insulation thickness. A jacketing tape of neoprene or thermoplastic is usually applied to provide adequate jacketing and mechanical protection. A rubber cement can be applied between the insulation and jacketing materials if adhesion is a problem.

In splices of cables rated above 2000 volts the connector must have a smooth surface with no abrupt changes in shape so as to avoid excessive electrical stresses in the insulation applied over it. Hand applied insulation tape of a type compatible with the cable insulation is wrapped to a thickness so that the cable and splice will withstand test, normal, and emergency operating voltages. In the early years of high voltage cable installations, paper or varnish cambric insulated lead covered cables were the most prevalent. This situation has changed considerably in recent years and also has the splicing materials and techniques.

Shielded cables are used mostly in the voltage range above 2 KV, but there are some installations using non-shielded cables. Non-shielded cables with a neoprene or thermoplastic jacket are spliced in much the same manner as that described for low voltage cables except where a strand semicon is present, wherein it must be replaced by a semicon tape.

It is also a good practice to overlap the factory insulation by about three inches.

Shielded cables are spliced in much the same manner as low voltage cables except at the point of the shielding and strand semicon. As mentioned before, the strand semicon must be replaced by a tape semicon applied over the cleaned conductor. After the insulation build-up has been completed, the insulation semicon must be replaced with a hand applied tape semicon. A tinned or bare copper mesh braid is usually used to replace the shield in the area of the splice. The hand applied braid shield should be soldered at both ends to the factory shielding. Care must be taken at these points to provide a smooth transition from the uniform cable diameter to the increased diameter of the splice joint to avoid excessive longitudinal stresses in the insulation. The jacket can be replaced with a neoprene or thermoplastic tape which should overlap the factory jacket at least one inch along with a rubber cement applied to provide good adhesion.

Lead covered cables in general are protected at the splicing point by a lead sleeve wiped to the cable sheath and filled with a compound. This sleeve provides a continuous path for fault current. A compatible insulating tape is used such as rubber tape on rubber insulation and varnished cambric tape on varnished-cambric and paper insulations. It is usually a good practice to wrap the tape insulation with two layers of friction tape to prevent damage from the heat of the compound when the joint is filled.

The method of splicing multi-conductor cables is the same as that for a single conductor cable.

In splicing a portable cable or cord extra care must be taken to maintain, throughout the splice, the flexibility originally designed in the cable. There are two types of splices used on portable cables and cords; one is termed a temporary splice and the other is termed a permanent splice. The temporary splices are usually made in the field and employs a connector, insulating tapes, cement, shielding braid if needed, and jacketing tapes. The amount of temporary splices is usually determined by the governing body of the industry. It must be mentioned that within the last couple years there has been many new temporary splice kits marketed employing various types of jacketing sleeves. Some splice kits employ heat shrinkable tubing, while others use zipper or pre-stretched tubings. Almost all kits contain connectors, sleeves, tapes, spacing inserts termed spiders, and outer sleeves. Since most of the portable cables and cords are used in the mines, all kits must be approved by the United States Bureau of Mines.

A permanent splice is usually made in a cable repair shop operated either by the company or an independent source. This splice usually employs a soldered strand connection or in the case of a rope stranding can be rewoven without the use of solder or connector. In the case of multi-conductor cables the splices are stepped and placed at alternate positions within the splice to insure flexibility. The insulation is replaced by wrapping alternate layers of cured and non-cured tapes. The shield and semicons are replaced in an identical manner as that used for power cables previously described. The jacket is replaced by a non-cured vulcanizer jacketing tape. The entire assembly is then inserted into a heated die and cured by heat until the insulation and jacketing tapes flow into their respective materials that they have been applied to and become one homogenous mass.

There are many variations to the basic types of splices described; in addition to there being specific dimensions and instructions that must be followed with respect to the voltage and individual requirements of a splice. There will be no attempt here to include all the instructions that must be followed during the many types of splicing encountered. Most manufacturers include instructions in their splice kits as do many manufacturers of cables. One point that should be remembered is that tapes most often are applied in half-lapped layers with sufficient tension applied to obtain good homogenous insulation without over-stretching the tape.

In the case of aluminum conductors the splicing technique is identical to that of a copper conductor except for the connection procedure. The splicing of aluminum cables has always been difficult. The conductor has a tendency to creep and oxidize. When aluminum is exposed to air, a thin film of high dielectric strength forms. This film must be completely removed before aluminum conductors can be satisfactorily joined. The method of autogenous welding appears to be the best method of connection, but due to simplicity pressure connection is usually preferred.

When copper and aluminum conductors are to be joined, special techniques must be used to prevent direct contact. If the two metals touch, any moisture present would initiate severe electrolytic corrosion of the aluminum.

One point should be remembered, as the operating voltage of the cable to be spliced increases, the care and cleanliness required to make that splice should also increase.

H. Terminations

There are three categories of terminations: 1) Low voltage (600 v to 5000 v) non-shielded and non-lead sheathed cables, 2) Low and medium voltage (600 v to 15,000 v) leaded and shielded cables, 3) Medium and high voltage (15,000 v to 69,000 v) leaded and shielded cables.

The termination of a low voltage non-shielded and non-lead sheathed cable is generally a simple matter. The primary objectives are mechanical support, electrical connection and physical protection of the cable insulation. In exposed locations, the insulation is penciled and wrapped with suitable insulating and protective tapes overlapping the connector. The cable should not be supported or touch a grounded surface anywhere within the minimum leakage distance. This distance is 5 inches for 600 volt non-shielded cables and 8 inches for cables rated to 5000 volts.

The termination of low and medium voltage cables

(600 volts to 15,000 volts) leaded and shielded cables is more complicated, because of the shield or lead sheath. As mentioned in the section on shielding, it is very important to ground the shield. Within this class of terminations are three distinct groups: non-pothead type termination, compartment-type termination, and pothead-type terminations.

The non-pothead type termination usually involves a shielded non-leaded cable. The rubber or plastic insulated cables may be terminated indoors or outdoors with some modification in their construction. The termination of the shielding of a cable results in a considerable change of the dielectric field resulting in the combination of radial and longitudinal stress in the area of termination.

This concentrated stress is a result of the shield being at ground potential and the insulation surface being at a voltage above ground. It is due to this area of concentrated stress that a stress relief cone must be constructed. This stress cone is constructed by increasing the insulation thickness at the termination gradually by applying insulating tape and forming the shape of a cone. The cable shield is then carried up the cone surface and terminated at a point of greater insulation thickness that that of the cable.

The voltage gradient at the end of the conductor and shield terminus is extremely non-linear. This cone shaped build-up provides a gradual transition from the grounded shield to the insulation. The stress cone design factors for a given voltage have been adopted, based on field experience and many laboratory tests.

Table XVIII.(33) Dimensions Normally Used in Terminating

Creepage Distance	5 KV	8 KV	15 KV	25 KV
Dry Location "A" (inches)	10	10	15	25
"A" Wet Location	10	14	20	33
Stress Relief Cone Thickness	2 times factory applied insulation thickness			
Length of Cone Base "C"	10 times cone thickness "b"			

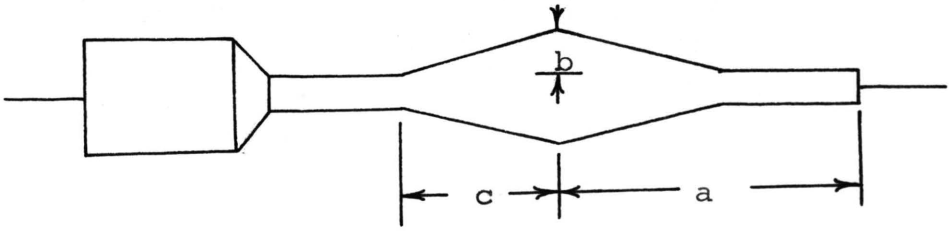

Figure 1. Stress Cone Design

It must be remembered that the stress relief cone does not completely eliminate the stress but does reduce it to a value to allow for trouble-free cable operation.

Additional insulation tape and jacketing tape are usually applied to provide added dielectric strength to the area that is subjected to water, direct, and other likely outdoor contaminats.

Compartment-type terminations may be used on almost any type of cable. The stress relief cones are constructed in the same manner as described in the previous section. It is generally recommended that stress relief cones be constructed on all leaded and non-leaded cables having a shielding tape over the insulation. Many compartments are filled with insulating compounds which allow for shorter creepage and spacing distances. Often times the sheath on a single conductor lead sheathed cable can be "belled" to form an effective stress relief cone when filling compound is used. Stress relief cones are generally not used on "belted" multi-conductor leaded cables. It is only necessary to leave an inch of the belt insulation beyond the "belled" end of the lead sheath.

Pothead-type terminations can be used on almost all types of high voltage cables. The cables are prepared in like manner to that described in the section on compartment-type terminations. The pothead is filled with high dielectric strength compounds to allow for reduction of length required to terminate the cable. The pothead also provides physical protection and support of the cable insulation and conductors. The pothead-type of termination is recommended for most outdoor terminations of shielded cables, especially in contaminated, industrial, or extreme weather atmospheres.

Medium and high-voltage (15,000 volts to 69,000 volts) leaded and shielded cables require similar techniques as described in the section on low and medium-voltage terminations; but extra care and attention must be given to electrical and physical requirements due to the more severe electrical stresses brought about by the higher voltages. Almost all outdoor terminations in this voltage category are terminated in potheads. Those not terminated in potheads should follow the same procedures as described in the previous sections, incorporating the larger creepage, cone thickness, and cone length due to the higher potentials.

It is interesting to note that mathematical calculation of the ideal contour of the stress relief cone construction will result in a log-log curve. It is questionable how much additional relief is gained by this calculation and, since it is time consuming, straight shield tapers made up of two or more slopes are recommended in applying the insulation in the field.

Exact materials and instructions, like the splice kits, appear in most termination kits. Therefore no special mention of detailed terminating will be discussed in this paper.

I. High Potential Proof Testing

Basically a high potential dielectric test is a deliberate application of a pre-determined over-voltage to determine if the insulation contains defects that might affect voltage breakdown of the insulation. This type of test many times finds mechanical weaknesses along with impurities that may later lead to chemical deterioration, cracks, and voids.

In most cases the high voltage test consists of the application of higher than normal operating voltage for a specific time, between mutually insulated circuits, or between an insulated circuit and a nearby grounded surface.

The invention of the "Kenetron" rectifier tube in the 1930's led to the rapid development of direct current high voltage supplies. During the 1930's and 1940's alternating current was predominantly used while D-C became more popular where field mobility was required. As a rule alternating current is used for insulation resistance tests. The D-C test can give more information than is normally obtainable with alternating current. The high capacitive currents frequently associated with alternating currents are not present to interfere with the determination of actual leakage currents.

As mentioned previously, the total current caused by the application of a high potential direct current across an insulation material is made up of three components: 1) charging currents, 2) absorption currents, and 3) leakage currents. Both the charging and absorption currents usually become negligible after a short period of time and therefore the leakage current is the quantity measured after the circuit stabilizes. The leakage current is that value of current that flows through the volume of insulation, or over leakage surfaces such as terminations.

While there are many ways to perform a D-C high potential test, there are three basic tests that are the most significant: 1) Leakage current vs Voltage, 2) Leakage current vs Time, and 3) Go/no-go Test.

The leakage current vs voltage test is made by raising the test voltage in discrete steps, waiting for the leakage current to stabilize at each step, and then plotting that value as a function of the test voltage. As long as the plot remains linear, the test may continue. When the value of leakage current rises at a faster rate than the voltage, it is usually an indication that breakdown is near.

The increased potential breaks down the dielectric and provides a more formidable path to ground. Surges in the applied voltage therefore could bring about a fault condition.

The leakage current vs time test is a plot of initial peak value obtained at the time of application of the voltage step and its decay with time. If the leakage current decreases with time, the insulation is considered to be good. If however, the leakage current increases with time, the insulation is faulty and the test should be discontinued.

For the Go/no-go test, the voltage is slowly raised to the predetermined test value with the rate of rise determined by the time required to keep the charging current below the capabilities of the test set. When the final test voltage is reached, it is held for a predetermined length of time or until the leakage current stabilizes. As long as the leakage current stabilizes and reaches a steady state value, the equipment is considered to have passed the test. Failure of the current to reach a steady state value or in fact having the leakage current increase with time indicates the failure of the cable to pass the test.

The dielectric strength of an insulation material is the breakdown voltage divided by the sample thickness, usually expressed in volts per mil. The breakdown voltage of a solid insulation generally increases at a less than linear rate for increasing thickness of material. As a result, the dielectric strength is higher for a thin sample than a thick sample. Dielectric strength is also reduced by elevated temperatures or frequency.

Dielectric strength is strongly dependent upon time and is much higher for a short time of application than for a long term test.

The use of a high voltage proof test is functional both as a check after installation and just before final energizing of equipment to insure that no damage or incorrect methods were used during the installation of the cable. The proof test also is an aid in preventive maintenance to indicate possible weak spots or trouble areas. D-C voltage has no harmful or cumulative effect on the insulation as long as the voltage applied does not exceed the breakdown strength of the insulation. Applied D-C proof test voltages are a function of the insulation thickness, and given in volts/mil. These values are usually furnished by the cable manufacturer and should be obtained from him.

In general the D-C proof test voltage should be at least equal to 3 times the A-C peak voltage of the phase-to-ground circuit voltage.

In summary, high voltage D-C proof testing is a very necessary test both at time of installation and as a maintenance aid. Frequency of proof testing is left to the individual to decide, with the importance of the circuit usually determining the frequency of testing. Remember that the trend of a leakage curve is more important than its magnitude. Temperature and moisture changes can make a perfectly good cable yield different magnitudes of leakage current from one day to the next. Always consult the cable manufacturer for recommended values and duration of proof test voltages.

J. Fault Location

Faults in power cables occur because of damage to the conductor, insulation, or both. Usually one or more of the following situations exist when a cable experiences a fault: 1) High series resistance fault, 2) An open conductor, 3) A grounded conductor, 4) A conductor to conductor fault. An open circuit or resistive conductor are both classified as series faults and can be detected by measuring any change from the normal conductor resistance.

The larger percentage of faults are classified as shunt faults and include the phase-to-phase, and the grounded circuit conditions. These too can be detected by measuring any change from normal conductor resistance.

There are many different types of fault locating equipment, methods, and techniques. In general there are two distinct methods of fault location: 1) Terminal measurement, and 2) Tracer signal. The use of a megohmeter can usually classify the fault as either series or shunt and therefore is a good test to begin with.

1. Insulation Resistance Ratio

The distance to an open in the conductor from a particular terminal can be found by comparing the insulation resistance to the open, to that of the insulation resistance of a known length of unfaulted cable. This can be effected using a wheatstone bridge or a megohmeter. That is the ratio of the known insulation resistance R_1, to that of the insulation resistance to the open circuit R_2, multiplied by the length of unfaulted cable d_1, will yield the length to the open circuit d_2:

$$d_2 = \frac{R_1}{R_2} (d_1)$$

This method depends upon the fact that the cable or conductor has a uniform insulation resistance per unit length.

2. Voltage Drop Method

This method is useful in determining the location of shunt faults. The distance to a shorted or grounded section can be found from measuring the voltage drop of the conductors when a constant current is applied and the distance between terminals is known. A constant current should be applied to one terminal of a loop formed by connecting the faulted conductor to a good conductor at the opposite terminal and then measuring the voltage with a sensitive voltmeter. In the case of a short circuit:

$$d_1 = \frac{V_1}{2V_1} (d_2), \quad \text{where,}$$

d_1 = Distance to the fault

d_2 = Length of known conductor

V_1 = Voltage between shorted conductors

In the case of a grounded conductor:

$$d_1 = \frac{V_1}{V_2} (d_2), \quad \text{where,}$$

d_1 = Distance to the fault

d_2 = Length of known conductor

V_1 = Voltage between one terminal of the grounded conductor with respect to ground

$V_2 = V_1$ + voltage between the other terminal with respect to ground

3. Resistance Loop Balance

The distance of a short circuit or a ground fault from a terminal can be determined by comparing the resistance of the faulted section to a resistance of a known loop made by joining the faulted conductor to a good conductor at the opposite terminal. This is known as the Murray loop method and can be effected by using a Murray loop bridge:

$d_1 = \frac{X}{S}\ (d_2)$, where,

d_1 = Distance of shunt fault

d_2 = Total distance of loop including joing cable

X = Resistance required to balance bridge

S = Total resistance of bridge

Where larger resistances are present in the smaller conductors, a known resistance is inserted in the loop and this method is known as the Varley loop method.

4. Burn Down Process

When the fault resistance is sufficiently high, some faults will never be detected by low voltage methods. It may be necessary to overcome this problem by application of sufficient voltage to burn down the insulation at its weakest point, being careful to not over stress the good insulation. This process carbonizes the insulation until the resistance is reduced so as to enable one to use one of the previously described tests. As one might assume, this is only necessary on shunt faults. The high voltage, high current D-C supply is connected between the faulted conductor and solidly grounded shield or sheath. Careful use of this method must be employed.

5. Capacitance Impulse Method

This method has been used for many years by both utilities and mining companies. This method uses a series of high voltage surges transmitted along the faulted cable until they reach the fault and discharge to the return path. The fault may be detected by detector circuitry or using one's four senses when scanning the length of cable in question. The risk to good insulation is nil in this method and it has gained popularity due to the impulse generator being so light and portable to carry during field testing. The generator is connected between the faulted conductor and the solidly grounded sheath or shield.

6. A-C Methods

This A-C method is particularly useful on locating faults on non-shielded cable. An A-C audio frequency is transmitted along the faulted conductor and is returned at the fault via the solidly grounded shield or sheath. The applied signal can be measured by sensing the electromagnetic field using an electromagnetic field detector, or using a voltage gradient detector and probes. The fault resistance should not exceed 50Kohms for electromagnetic detection and not over 500Kohms for earth gradient detection.

7. D-C Tracer Method

In this method a modulated D-C signal is employed. The D-C generator is connected between the faulted conductor and the solidly grounded shield or sheath. Although there is no audio sound with D-C, these tracing signals offer the advantage that they can reveal the magnitude and direction of the signal. The detection of the fault can be done with the same instruments as described in the previous A-C method. With this method, unshielded direct buried cables having faults, can be detected better using the voltage gradient detector and earth probes.

IV. SPECIFIC CABLE CONSTRUCTIONS AND THEIR APPLICATIONS

The basic designs for all types of cables were discussed in section one. This section will concentrate on specific designs and their applications. The four groups to be discussed are power, control, mining, and miscellaneous cables.

A. Power Cables

There are many different types of cable that fall under this category. Presently the voltage range of insulated power cables is from 600 volts to 69kvolts, and 35 KV to 500 KV for pipe type cables and ACSR. Almost all of the insulated cables included in this section can be constructed using both aluminum and copper conductors.

The following symbols apply to the common 600 volt cables used for power transmission in the building wire category.

T = Thermoplastic
R = Rubber or thermosetting
X = XLP insulation
H = Heat resistant
W = Water resistant
N = Nylon

Probably the simplest form of a 600 volt power cable is the TW and THW. These cables have simple extruded PVC that serves as both the insulation and the jacket. The difference between the two is merely that the THW has a thicker PVC insulation/jacket, and the THW is rated 75°C where the TW is generally rated at 60°C. Both the THW and TW are usually installed in conduits and trays for general purpose power circuits. The THHN-THWN is a 600 volt cable having a 90°C temperature rating. This cable incorporates a PVC insulation with a thin nylon jacket applied over the insulation. In addition to having a higher temperature rating, THHN-THWN has excellent chemical and weather resistance. This cable is usually installed in conduit or trays and is used as a building and industrial wire where hydrocarbon contaminants might be present. XHHW is also a 90°C rated 600 volt power cable having a cross-linked polyethylene material serving as both the insulation and jacket. This cable is recommended for general applications and is usually installed in duct or tray.

The RHH-RHW-USE rated cables are 600 volt cables which can be used in a direct burial application. Cross-linked polyethylene can be used and is identical to the XHHW except that the insulation/jacket wall thickness is greater. There are other constructions having this rating with one having a low voltage insulation and a neoprene jacket. Depending on the type of insulation used, the cable may be rated either 75°C or 90°C. All RHH-RHW-USE cables as stated before are most often used on 600 volt circuits that require the cable to be direct buried.

The next category of power cables is the 5 KV non-shielded cables. Most cables above 600 volts have either an ethylene propylene (EP) or cross-linked polyethylene (XLP) insulation. At 5 KV and above a conductor semiconducting material is applied between the conductor and its insulation. Since there is no shielding, an insulation semicon is not needed. The EP insulated 5 KV non-shielded cable usually has a PVC jacket applied over it, while an XLP insulated non-shielded 5 KV cable has only the XLP to serve as both the insulation and jacket. The Insulated Power Conductors Association (IPCEA), does not recognize the use of non-shielded cables above 2 KV unless they are assembled as a three conductor cable and have an overall covering, such as PVC or metal. This edict has caused a decrease in the use of 5 KV non-shielded power cables. The 5 KV non-shielded cable is usually installed in a conduit or duct and is not recommended for direct burial.

The next category is 5 KV shielded cables. Again, the XLP and EP insulations are the most often used in this category. The EP insulated cable usually has a copper tape shield of .003" or greater thickness, helically applied and contains both a strand and insulation semicon. The XLP insulated cables usually have a wire shielding which is also recognized by the IPCEA as an acceptable method of shielding.

This wire shielding consists of small copper wires concentrically wrapped around the insulation semicon and held in place by a nylon tape. The reason for using a wire shielding on cables insulated with XLP is that the coefficient of expansion indicates considerable increase of the O.D. as the ambient rises. Both EP and XLP shielded cables have PVC outer jackets. Unlike the non-shielded 5 KV cables, a shielded 5 KV cable can be direct buried, but most often is installed in a conduit, tray, or duct.

There are cables rated at 15 KV, 25 KV, and 35 KV, that are constructed identical to the 5 KV shielded cables described previously. The only difference in these cables is that each higher voltage range requires a greater insulation thickness. Table XIX outlines the minimum insulation thickness recommended by IPCEA.

Table XIX. IPCEA Recommended Insulation Thicknesses References

Voltage	EP Insulated		XLP Insulated	
	grounded	ungrounded	grounded	ungrounded
5 KV (shielded or non-shielded)	.090	.090	.090 (shielded)	.090
15 KV	.175	.220	.175	.220
25 KV	.260	.345	.260	.345
35 KV	.345	.420	.345	.420
46 KV*	.445	--	.445	--
69 KV*	.650	--	.650	--

Table XIX. (Continued)

*These thicknesses are not covered by the IPCEA. Above 35 KV the manufacturers are on their own to determine the thickness most suitable for a particular voltage.

Another popular construction used primarily by the utilities is the underground residential distribution (URD) cable. This cable is basically a 2/C cable using either a copper or aluminum conductor. The most popular conductor is aluminum but regardless of the insulated conductor used, both normally have copper coated concentric wires. The construction employs a strand semicon between the inner conductor and the insulation. Over the insulation, an extruded semiconducting material is applied. Then the copper coated concentric wires are wrapped around this outer semicon. The number and size are dictated by the size of the inner conductor, in as much as the outer conductor must have the same ampacity rating as the insulated inner conductor. In the case of a three phase system, the outer concentric wires may be 1/3 the inner conductor ampacity rating considering that the three concentric wires of the three phases will be connected together. The URD cable can be used at 600 volts to 35 KV. In this type of cable, high molecular weight polyethylene (HMWP) and XLP are the most popular insulations used. The XLP insulated cables have a 90°C rating where as the HMWP have a 75°C rating. The reason for using these types of insulation is the desire for mechanical strength. URD cables can be installed in ducts but most often are direct buried.

In years past a 69 KV insulated cable was only thought of as being available as a pipe type cable. Recent improvements in dielectrics have caused some manufacturers to produce a 46 KV and 69 KV solid dielectric cable using EP, XLP, or HMWP as the insulation. Due to the popularity of these types of cables, many experiments and tests are being conducted using insulations as described above at voltage levels of 115 KV and 138 KV.

As mentioned in section one, paper impregnated with oil is a very fine insulation and usually has a lead outer sheath. Cables of this type are extremely popular where contaminants that would attack EP, XLP and PVC, are present. These cables are generally used from 5 KV to 35 KV.

A system that is used in the voltage range of 35 KV thru 161 KV is oil-filled cables. The insulation used is paper and the conductor copper. This type of cable has oil channels in the interstices of a three conductor cable and in the center of a single conductor cable to allow for longitudinal and lateral flow of the oil. The sheath is usually lead and the oil is kept at a pressure of 15 psi with the use of reservoirs that allow for temperature fluctuation.

A cable of similar design is the gas-filled cable. This resembles the oil-filled cables in appearance except the oil is replaced by nitrogen gas kept at a pressure of 15 psi. This type of cable is usually a three conductor and one of the three tubes in the interstices is solid to allow the gas to flow through the entire length of cable and alleviate drops in pressure should the other tubes become clogged with impregnant. The strength of the outer sheath determines the pressure that the nitrogen can be kept. A pressure of 15 psi will handle voltages from 15 KV to 46 KV but a pressure of 40 psi must be maintained to handle voltages of 69 KV. The gas pressure is maintained by the integrity of the outer sheath.

While the use of oil-filled cables has been very successful, they have been superseded by pipe type cables. Pipe type cables are three copper conductors, paper insulated, shielded, and enclosed in a steel pipe. The three conductors are shielded with non-magnetic tape and have copper skid wires wrapped around each conductor to separate them and provide an easier means of pulling the cables into the pipe. The pipe is usually coated with a mastic coating to prevent corrosion.

The principle of pipe type cable is the same as that of an oil filled, which is elimination of ionization by eliminating all gas. The pipe type cable is usually installed for voltages of 69 KV to 500 KV. The oil static cable system is more economic than the oil-filled cables and can be constructed to handle higher voltages. The mass impregnation process of an oil static system allows a reduction of manholes and joints when compared to an oil filled cable system. This plus the fact that the oil static system has no lead sheath, thus it is lighter, allows it to be installed in lengths of a mile or more. The pipe is of sufficient size to allow snakelike movement within the conductors during load cycling. The pressure of 200 psi is maintained by a terminal pumping station which operates responsively to oil pressure changes in the pipe.

Another type of pipe cable is a gas filled system. This system has nitrogen gas instead of oil as the pressure medium and requires no terminal reservoirs or pumping equipment. The tightness of the pipe is relied upon to maintain the pressure. There are two types of cables used in this system: sheathed and non-sheathed. The sheathed conductors are termed "gas compression cables". In the United States, this type of cable is more widely used, and has a polyethylene sheath enclosed by two bronze tapes. The other type of gas system is non-sheathed or "high pressure gas filled cable". It operates on the principle that insulation containing gas will not ionize permanently if the gas is kept under pressure. The construction of the individual conductors is the same as that of a gas filled cable. The gas pressure of this system is 200 psi for both the sheathed and non-sheathed types.

A consideration when designing pipe type cables is the component losses in the pipe material. These losses are in the form of hysteresis and eddy currents flowing in the pipe wall. Due to the extra strength of the magnetic field when cables are installed in a steel pipe, the losses in the component parts are increased further than those inherent in an identical installation in a non-metallic pipe or air.

The magnetic pipe is a major contribution to the increased A-C resistance of a pipe cable system. The multiplying factors applicable for operation in pipe have been empirically determined and depend on the arrangement of the conductors in the pipe. The two types of cable configurations most often used are, close triangular and cradled. It is assumed that the cradle arrangement is more representative of field installations even though losses of this configuration are greater than those derived assuming a close triangular configuration. It should be noted that segmental conductors are used on the larger size conductors to reduce the skin effect ratio.

The overall losses are due to many components. Dielectric, conductor, shield, and pipe losses all contribute to the overall total losses of a pipe type cable system. The multiplying factors are, as stated before, empirically derived and are A-C/D-C resistance ratios that can become as high as 1.75 for conductor sizes of 2500 MCM in pipe of about 7.5" inside diameter.

Other types of cables in the power cable classification include 600 v to 15 KV cables having sheaths of aluminum, copper, and steel. The ALS 600 v cable is an aluminum sheath cable that is used in much the same applications as thin walled conduit, but already has the advantage of having the conductors contained in the aluminum sheath. Another type of cable construction used for many years is the interlocked armor cable which employs an aluminum or steel interlocking armor as the sheath. The interlocked armor type cable is used primarily in a tray or tray and conduit installation. The most recent type of cable sheath developed is a continuous corrugated outer sheath which uses an aluminum, copper, or steel completely impervious sheath. Both the interlocked armor and continuous corrugated sheaths are used from 600 v to 25 KV. The continuous corrugated impervious sheath is the only type that may be direct buried.

Another extremely popular type of cable used in power transmission is the aluminum cable steel reinforced termed ACSR. The ACSR conductors are generally used for high voltage power transmission lines. The current carrying capacity, tensil strength, and O.D. can be varied by varying the proportions of steel and aluminum in the conductor. Stranded copper, copperweld, and hollow copper conductors are also used in power transmission but the weight, cost, and flexibility yields the ACSR stranded conductor as the most popular. It is for this reason that the ACSR cable will be thoroughly discussed.

The current rating of an overhead line is obtained by equating the heat developed in the conductor, by the current plus the heat absorbed from the sun, to the heat lost by radiation and convection(38). The factors that can effect this current rating are, air temperatur, wind velocity, maximum permissible temperature rise of the conductor, and the thermal emissivity and thermal absorption of the conductor.

In the calculation of sag and tension of ACSR cable, the modulus of elasticity and coefficient of expansion of both the steel and aluminum must be considered. These combined values are generally available from most manufacturers of ACSR cables. With these values the strength of the ACSR can be determined and the same formulas and considerations listed in the section on tension and sag, described previously may be used.

Generally there is electro-chemical action between the galvanized steel core and the aluminum wires. The present practice is to coat the steel wire and inner wires of aluminum to protect against this bi-metal action and corrosion.

During the pulling process, running blocks are fastened to the cross arms through which the conductor and leads are pulled. AFter completion of the stringing operation the cable must be tensioned properly. The tensioning is most often done with a winch. If the cable is not pre-stressed, the cable can be pulled to the calculated sag. If the cable is pre-stressed the cable is then pulled to the pre-determined tension. After this has been done, the insulator clamps are fitted.

Transmission line towers are usually built to handle more than one circuit since they are a considerable part of the line cost. Special towers are built and inserted in the support chain to allow the conductors of each circuit to be transposed. This phase rotation reduces the inductive interference on telephone lines paralleling the transmission lines. The distance between transposition varies but is usually about 15 to 20 miles. Support towers must be solidly grounded to drain off the induced voltages produced by electrically charged clouds drifting over the transmission line. Two overhead ground wires placed approximately over each conductor on the tower help transmit this lightning type surge.

In the case of polyphase circuits, the sum of the currents in the conductors must, at any given instant, be equal to zero. In the case of a three phase circuit the current flowing out through any one wire, can be considered as returning along the two remaining conductors. Using this criteria the induced EMF in any conductor may be calculated by:

$$e = 0.004545 x f x \left[-I_1 \log \frac{D_1}{R} - I_2 \log \frac{D_2}{R} \cdots - I_n \log \frac{D_n}{R} \right]$$

where, e = Induced voltage (volts/mile)

I = The conductor current (AMPS)

D = The distance between the two conductors in question (inches)

R = The radius of the conductor effect (inches)

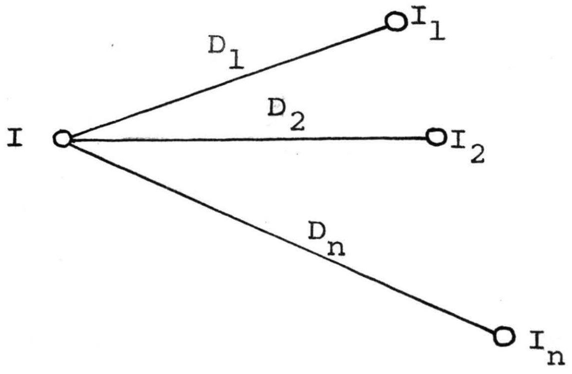

Figure 2. Circuit Induction Relationships

With an unsymmetrical arrangement of conductors, the unbalancing effect is due to the mutual induction between loops formed by pairs of wires. It is for this reason that transposition is so important. Where circuits are neither transposed or in an equilateral triangle configuration, this dis-symmetry must be included in computing the reactance.

In the early days of high voltage transmission corona was assumed to be detrimental due to the energy loss associated with it. In recent years, the radio interference (RI) aspect of corona has become more important. At a given voltage, corona is determined by conductor diameter, line configuration, type of conductor, conductor surface, and the weather. Therefore in areas where RI must be considered, the evaluation of the RI must be extensively explored. This could be a limiting factor in the choice of the voltage and system to be used.

B. Control and Instrumentation Cables

1. Control Cable

Almost all systems contain control circuits which control the operation of processes and equipment. The entire performance of a plant is contingent upon the reliability of the control system and its cable.

The basic design of a control cable consists of a conductor, insulation, and jacket. There are two categories of these cables: thermoplastic and thermosetting. The sizes of the conductor range from size 22 AWG through size 9 AWG of annealed copper. To insure flexibility the conductor is class B or class C stranded.

The thermosetting control cables can be insulated with SBR, Butyl, XLP, EPR, and silicone. SBR insulation has a maximum operating temperature of $75^{\circ}C$, where as silicone is used for extremely high temperatures and has a maximum rating of $200^{\circ}C$. The butyl, XLP, and EPR compounds usually are rated at $90^{\circ}C$.

The most popular thermosetting insulations are XLP and EPR with voltage ratings of 2 KV maximum.

and polyvinylchloride are the most often used jacketing materials. Unlike the thermoplastic insulations, EPR and XLP can be used with or without individual conductor jacketing. Silicone requires a glass or asbestos braid jacketing over the individual conductors to insure its electrical properties at the extremely high operating temperatures that it is designed to be operated. One of the most reliable control cable designs incorporates a class B stranding, an EPR insulation, a neoprene jacket over the individual conductors and a neoprene jacket overall. The flame resistance, oil resistance, abrasion resistance, and overall mechanical and thermal stability lends this design as a most reliable one. This design is used often for control circuits in power plants and other critical circuitry.

The thermoplastic insulations most often used are polyvinylchloride and polyethylene. As stated in the section describing insulations, PVC can be formulated to carry an operating temperature of $105^{o}C$, while polyethylene has a maximum operating temperature of $90^{o}C$. Polyethylene most often has a PVC or nylon jacket to enhance the operation of the cable in the presence of chemical contaminants and heat. PVC can be used as an insulation and covered with a thin nylon jacket to improve the cables physical and mechanical properties.

As with the thermosetting materials, the outer jacket is applied to protect the inner assembly from mechanical and chemical damage. The two most popular thermoplastic constructions are: 1) Class B stranded conductor, a polyethylene insulation, a thin nylon jacket over the individual conductors and a PVC jacket overall, 2) A class B stranded conductor, a polyethylene insulation, a PVC jacket over the individual conductors, and a PVC jacket overall.

Both thermosetting and thermoplastic insulated control cables are often jacketed with a metallic material. Lead, interlocked armor, and impervious corrugated sheaths can all be used where extra chemical, mechanical and flame resistance are required.

During recent years there has been increased interest in flame retardant control cables because of the close grouping in trays. A flame resistant control cable is one that will retard the propogation of flame along the cable and maintain the integrity of the electrical circuit as long as possible in the presence of flame. It is common knowledge that most thermoplastic materials are flammable and do not qualify as a flame resistant control cable. Probably the most common flame retardant material used in control cable construction is neoprene. It is for this reason, that using a good insulation such as EP, then jacketing the individual conductors with neoprene, along with an overall jacket of neoprene, constitutes the most flame resistant control cable now being manufactured.

2. Instrumentation Cables

Where control cables usually have a minimum rating of 600 volts, an instrumentation cable usually has a maximum voltage rating of 300 volts. Instrumentation cables are usually used on low voltage circuits involving supervisory control monitoring, or information conveyance such as communication, telmetering, temperature, pressure, flow, etc. With the continuing growth of computers, computer cables are extremely important and also fall into this category.

Since these cables are used on low voltage circuits, less importance is paid to the electrical properties of the cable and more attention is paid to the physical properties. The two important design factors to be considered in this type of cable are the mechanical requirements, and the shielding from other cables of the important signals carried in them. The conductor size ranges from a 22 AWG to a 16 AWG annealed copper conductor. A stranded conductor is used where flexibility is an important factor, but many times in this cable a solid conductor is used with the two conductors twisted together as a pair. A thermoplastic insulation is almost exclusively used in this type of cable with polyethylene and PVC being the most common. The individual conductors are not usually individually jacketed. The shielding required can range from a copper corrugated shield used for mechanical protection and magnetic shielding, to individually shielded twisted pairs with a drain wire and an overall shield over the core. The type of shield used over the individual pairs is usually an aluminum/mylar tape. The outer shield can be as light as aluminum/mylar or as sturdy as a corrugated bronze or copper. The most often used outer jackets are polyethylene and PVC. The individually shielded pairs that include a drain wire are constructed in a manner so as to provide the ultimate in protection from induced voltages from surrounding power cables and/or high voltage contact movements. The shield and drain wire construction can bleed off to ground the high induced voltages that often are present in an industrial environment. When instrumentation cable is to be installed in tray or direct buried, a double jacket should be used with a corrugated armor installed between the two jackets which allows for mechanical protection.

There are two types of noise associated with instrumentation cables. The flow of currents in adjacent cables which in turn produces a magnetic field, can produce a magnetic noise that interferes with the signal conveyed in an instrumentation cable. The voltage applied to the conductor gives rise to an electrostatic field in the surrounding medium. If a second conductor is within this field, it will be affected by that of the space it occupies. Where two conductors are present in this field they occupy different positions in the field and current will flow from one to the other if paths are provided.

The effects of these two phenomena upon a communication or instrumentation circuit is to cause currents to flow through connected equipment in proportion to the difference in electric potential between them. It is for this reason that shielding which is grounded is used to neutralize this field and lower the voltage induced in other circuits. As with a telephone cable, most instrumentation cable twists the two conductors for a circuit into a pair so that each conductor can be subjected as equally as possible to the two types of noise.

C. Mining Cable

Almost all portable equipment used in the mining of coal is powered by electricity. It is for this reason that mining cable must be designed to provide reliable service and be able to withstand the hazards present in the mining operation.

Because of the portable nature of mining equipment, the cable for this use must be designed with flexibility in mind. To aid with this requirement, class G and class H stranded conductors are usually used, employing more strands of smaller diameter. These strands are usually coated with a tin or zinc to aid the corrosion resistance of the strands. Thermosetting insulations such as SBR, EP, and XLP are the most commonly used insulations. SBR is used mainly for low voltage cables and has a temperature rating of 75°C. EP is used both at low voltage and at high voltages. It posseses good electrical qualities, a 90°C rating, and a better flexibility than XLP which is the other high voltage insulation normally used. XLP has good electrical characteristics, a 90°C rating, and is the most mechanically rugged insulation available. The shielding on most mining cables is a braid type using small copper wires to form the braid. The outer jacket can be hypalon, neoprene, or nitrile-butadiene/polyvinyl-chloride (NBR/PVC). Neoprene has excellent physical and chemical properties in addition to being quite flame resistant. Neoprene probably is the best overall jacket for mining cables, but cannot be colored. There has been an increased interest in colored mining cable jackets. Color coding the cables according to voltage for ease of identification, and increased light reflection during night mining, are the two basic reasons for coloring the outer jackets. Hypalon as well as NBR/PVC can be colored quite readily.

There are two methods to cure a thermosetting material. One way is to pass the jacket through a long temperature regulated tube after extrusion. At the end of the tube the jacket is cured and this process is known as continuously vulcanizing (CV) the jacket. The other method most often used in jacketing these cables is a lead cured method. This is done by extruding a lead sheath over the freshly extruded jacket and then reeling it up and putting the reel in a heat regulated vault. After a pre-determined time, the reel is taken out of the vault and the lead is stripped from the jacket. It is thought that this lead curing controls the cure by keeping the jacket compressed during the curing process thus resulting in a more dense uniform jacket than the CV cured jacket.

There are two basic types of coal mining: underground and strip. The underground mines employ high voltage cables connecting from their outside substations to their underground rectifiers where they convert to D-C for many of their operations. The cables used for the transmission of this high voltage can be done by using an SHD-GC flexible construction as described before or using a Mine Power Feeder Cable (MPF). The Mine Power Feeder Cable is constructed much like a three conductor power cable. It employs a class B stranding, EP or XLP insulation, a copper tape shield and a neoprene or PVE outer jacket. In an underground mine, the power cable is often supported on hooks and not moved often, thus not requiring the flexibility that a strip mining power cable would require, and hence the MPF cable was developed.

After the A-C power has been rectified in an underground operation many flat type G and W cables are used on the shuttle cars. The 600 volt A-C cables termed G-GC, are usually used on the machines actually cutting, drilling, and loading the coal. These can be a flat or round cable depending on what the machine reel requirements are. The term G-GC refers to a three conductor cable having two ground wires and a ground monitor wire cabled with the power conductors. The subject of ground monitoring will be discussed later.

The surface mine usually employs all A-C equipment and uses SHD-GC type cables for its power distribution of 5 KV and above. The term SHD-GC refers to a three conductor cable having individually shielded power conductors, two ground wires and a ground check. The strip mine usually has shovels, drag lines, and drills which use this type of SHD-GC cables.

In 1969 the Federal Coal Mine Health and Safety Act was passed containing several regulations that apply to electrical cable. In this act it was decided that high, medium and low voltage resistance grounded systems should have a fail safe ground check circuit to monitor continuously the grounding circuit. It was due to this decree that cables were designed to include an insulated ground monitor wire of size no smaller than #8 AWG.

The inclusion of this ground monitor wire in the 600 volt cables disturbed the electrical balance of the three ground wire construction formerly used. The ground wires are no longer equally effected by induced voltages from the power conductors and it now is possible to have potential differences exist between grounded equipment. It has been proven that a potential hazard can exist if this potential difference, between equipment that comes in contact with one another, can cause a spark in the gaseous atmosphere of an underground mine. This is presently very much a problem, with many solutions being offered, and the Bureau is somewhat uncertain as to which path to follow. In time there will be cable designed and/or peripheral equipment that will alleviate this problem and insure good grounding and good ground monitoring.

D. Miscellaneous Cables

Another electrical cable that is installed in the millions of feet per year is telephone cable. Like power cable, telephone cable years ago had paper insulated conductors and an overall sheath of lead. Paper insulated telephone cable is still used with both lead and steel coverings with a polyethylene jacket usually applied over the metallic sheaths. This type is still manufactured but the demand for this construction has diminished and the thermoplastic insulated telephone cables have become the most commonly used. There are two basic types--aerial and direct burial--with many variations in the construction of these two types.

Basically an aerial cable has soft bare solid copper conductors in sizes 19, 22, 24, and 26, that are insulated with a thermoplastic insulation. The conductors are twisted in pairs in the same manner as the low level instrumentation cable. As mentioned, this lets each conductor for a circuit be effected equally by noise. The shield can be corrugated copper, aluminum, coated aluminum, or steel. The shields are corrugated to add strength, and flexibility to the construction of the cable. The aluminum is usually .008" thick and the copper is .005" thick. The aluminum offers a weight and significant cost reduction when compared to copper. The coated aluminum is usually .008" thick and coated with an ethylene copolymer that offers good moisture resistance. The coated aluminum shield is slightly higher in price than the bare aluminum shield. The steel shield has an aluminum inner shield of .008" thickness and the steel is .006" thick and offers outstanding mechanical protection. All types of aerial cable are usually jacketed with high molecular weight polyethylene. Another feature that may be included in the construction of aerial cable is a stranded galvanized steel messenger. This messenger is encompassed by the jacket and forms a figure 8 type construction.

The direct burial telephone cables are constructed in the same manner as the aerial cables except that an inner jacket of high molecular weight polyethylene is applied between the core and shield as well as over the shield, forming a double jacketed cable. The copper, aluminum, aluminum coated, and steel corrugated shields are also available in the same thickness as the aerial cables.

In the past couple of years, there has been a new innovation in the telephone cable industry--polyethylene/ petroleum jelly inserted in the core of the cable during its construction. It is the intent that this jelly filling will almost completely eliminate the problem of moisture being present between the conductors. Although this cable is extremely messy to splice and terminate, there have been good results where this filled cable has been installed.

The Rural Electrical Association (REA) is a government bureau that offers loans to many of the independent telephone companies. They also have specifications that must be adhered to when installing cable on an REA funded project. REA has recently requested mostly filled cables on projects involving their support. The large telephone companies usually manufacture their own cable where as independent telephone companies are servied by independent cable manufacturers.

The effects of noise in telephone circuits are very similar to those experienced with instrumentation circuits as previously described. One thing that is not a problem in instrumentation circuits but is very prevalent in communication circuits is cross talk. Cross talk is the induction in a telephone circuit from an adjacent telephone circuit; whereas, noise is the induction in a telephone circuit from a power circuit.

Another widely used type of cable is that used by the railroad industry. They use track wire, line wire, case wire, and signal cable. Track wire has a solid coated conductor in sizes 9 AWG, 8 AWG, and 6 AWG. It is usually insulated with a good 600 volt insulation and covered with a neoprene or polyethylene jacket. This wire is used in track circuits and signal operations. It can be installed in tray, ducts, or direct buried. Line wire is a hard drawn bare conductor that ranges in size #12, 10, 8 and 6, with stranded conductors offered in the larger sizes. Line wire is usually jacketed with polyethylene of minimal thickness and used in signal and power circuits installed on insulators. This construction is similar to the weatherproofed type cable used so often in aerial type installtions.

Case wire is a relay and control circuit wire used in apparatus wiring applications. It uses a stranded conductor and is insulated with a good 600 volt insulation and usually jacketed with neoprene or polyethylene.

Signal cable is an extremely critical cable in as much as the reliability of the cable is essential to the knowledge of the train engineers. A false signal could jeopardize the lives of those on the train. Almost all signal cables are direct buried and thus must be mechanically rugged. Probably the most durable construction is the "CMPF" construction. "CMPF"--corrugated metal polyethylene finish employs solid coated conductors ranging in size from #14 AWG thru #6 AWG. Almost any number of conductors can be assembled in this type of multi-conductor cable; but two conductor thru 37 conductor is the most popular range of conductors. The insulation can be EP, XLP, polyethylene, butyl, or a similar type of insulation. A .005" corrugated bronze armor is then applied over the core of the cable mainly for mechanical protection with a polyethylene jacket overall. Some railroads prefer a flat metal tape rather than the corrugated type and for that reason flat metal polyethylene finish--"FMPF" is available from most cable manufacturers. This cable has the same exact construction as the "CMPF" except that a flat .010" bronze armor is used. It is interesting to note that studies have shown the .005" corrugated bronze tape to be mechanically superior to the .010" flat bronze tape.

In installations where mechanical strength is not as important, non-armored cables are used. Their construction is the same as the "CMPF" and "FMPF" except no armor is used and a jacket of neoprene may be used in place of polyethylene if so desired. These cables may be installed aerially, in duct, or direct buried. Where signal cables are to be installed strictly aerially, a non-armored multi-conductor cable of lesser insulation is available and quite often used. This cable, like the non-armored underground cable described previously, has solid coated conductors ranging in size of #14 AWG thru #9 AWG. The insulation used is the same as all other signal cable and the jacket can be neoprene or polyethylene.

There are two other types of cables used by the railroad industry in their maintenance of locomotives. These two types are "DEL" and "DLO". "DEL" is an extra flexible stranded single conductor cable insulated with 600 volts insulation and jacketed with neoprene. "DEL" is usually used for Diesel-Electric locomotive power circuits. It can be installed in conduits, ducts, cable troughs, or trays. "DLO" is also a single conductor extra flexible stranded cable insulated with hypalon, which serves as the jacket also. "DLO" is used for general purpose low voltage power and control circuits on Diesel Electric locomotives. It too can be installed in conduits, ducts, cable troughs, or trays.

Although railroad communication circuits have become more and more of the wireless variety, those circuits using communication cable employ much the same type of cable as that used in the telephone industry.

V. CONCLUSION

A. System Design Information

Probably the first choice that has to be made when engineering a cable system is the voltage to be used. Many times there is very little choice in as much as only one voltage is available to do the job. This is generally dictated by the length of the circuit involved. Where a choice is available one should look at the overall economic picture. Switchgear, transformers, cable, motor control, labor cost and other significant costs should be evaluated at the voltages available and the most economic one chosen.

The nominal voltage of a system is the value assigned for convient designation of a given voltage class(29). The rated voltage is the voltage for which apparatus and equipment of a voltage class is designed and tested. Table XX outlines some typical voltages.

Table XX. Nominal Voltage/Rated Circuit Voltage Relationships

Nominal Voltage	Rated Circuit Voltage
110	120
220	240
440	480
2300	2400
6900	7200

Table XX. (Continued)

Nominal Voltage	Rated Circuit Voltage
13200	13800
22000	23000
33000	34500
44000	46000
66000	69000
110000	115000
132000	138000
154000	161000
187000	196000
220000	230000
330000	345000

After the voltage has been selected the cable can be chosen. The next most important decision is the type of installation; aerial, duct, conduit, tray, direct burial, etc. This may seem premature, but all of the following cable ingredients are based on the type of installation. The next choice should be what type of insulation should be used. This decision should be based on the requirements needed such as mechanical strength, flexibility, dielectric strength etc. The insulation chosen will determine the maximum operating temperature of the conductor. It is also at this point that the insulation thickness must be chosen. Always chose the cable that will handle the rated circuit voltage phase to phase. If the system is grounded, the 100% insulation level will suffice. If the system is ungrounded, the 133% insulation level must be used.

> <u>100 Per Cent Insulation Level</u>(19)---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 which are ungrounded, 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.
>
> <u>133 Per Cent Insulation Level</u>(19)---This insulation level corresponds to that formerly designated for ungrounded systems. Cables in this category may be applied in those situations where the clearing requirements of the 100 per cent level 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 per cent level category is desirable.

Since the anticipated loads in KVA should be known at this point, the current rating can be calculated. This load current combined with the installation design, and maximum conductor temperature will determine the conductor size to be used, with whatever type of conductor material is chosen. The shielding, if rated above 2 KV, is the next choice to be made. The amount of shielding in power cables is based on the anticipated fault currents. In the case of instrumentation and telephone cables the shield is based on the anticipated noise. Finally the suitable jacket must be chosen. The jacket chosen must best suit the environment the cable will be subjected to; chemicals, mechanical abuse, etc. The above sequence of thoughts along with the economic considerations should help chose the best cable design for a particular set of system requirements.

The above remarks pertain primarily to cables rather than overhead transmission lines. Where there is a choice between overhead lines versus underground cable, the following remarks might be helpful in favor of underground cables.

1) Greater freedom of interruption of service and damage due to weather and other natural hazards.
2) Short circuits and grounds due to flashover; breaking of conductors and insulators; objects falling across the wires always are possible problem areas for overhead lines.
3) Overhead lines always present a possible liability of accident to the public.

4) Underground cables rid the unslightly appearance of conductors and supports in city and rural areas.
5) Underground cables alleviate much of the way-leave encountered with overhead lines.

The above considerations often result in the installation of underground cables in populus districts, despite the fact that overhead line initial cost is cheaper.

Symmetrical component analysis has become an indispensible tool in the analysis of power system performance. The method of analysis using symmetrical components makes possible the prediction of the behavior of a power system during unbalanced short-circuit or unbalanced load conditions. The symmetrical components are a group of associated unbalanced vectors that can be resolved into balanced vectors. The resolved vectors are of equal length and symmetrical with respect to each other. The theory of symmetrical components is a complicated one and will not be discussed further. It should be an area of concern for those engineers who are interested in the behavior of a power system during unbalanced short-circuit or unbalanced load conditions.

B. Ground Conductors

1. Power Cable--Generally in all power cables the grounding conductor is designed for a minimum of 50% of the cross-sectional area of one power conductor.

It does not make any difference in how many ground conductors are used, as the total must be equal to the 50% value.

2. Mining Cable--The United States Bureau of Mines and Federal Law states that the grounding conductor shall be a minimum of 50% of the cross-sectional area of one power conductor. The IPCEA has set up a value of about 80% and this value is followed in most standard types of construction now furnished from manufacturers.

3. Metallic Sheathed Cables--Underwriters Laboratories, Inc., and the National Electrical Code recognizes sheaths as ground wires if the total sheath resistance is less than 2.22 times the power conductor resistance. Beyond this value ground wires must be used equal to the 50% cross-sectional area of one power conductor.

C. Flame Resistance and Testing

Due to many factors over the last few years, flame resistance of insulated cables has created much discussion and interest. It seems that the trend away from metallic sheaths and towards the less expensive plastic jackets has been one reason. Another reason is that there has been an increase in control and instrumentation cables and many of these cables are now carried in open trays. Flame resistance requirements for cables installed in central stations, have become more stringent in recent years. All insulations and jackets are hydrocarbons and as such will burn. Special compounding of the dielectrics offer some degree of flame resistance. Propagation of flame and how long a circuit need be maintained after initiation are two major concerns in this area.

In checking cables for flame resistance, the most common test used is the Vertical Flame Test as described in IPCEA specifications, such as S-61-402, section 6.5.

D. Manufacturers Identification

Almost all cable manufacturers are assigned two thread colors by the Underwriters Laboratories for identification purposes. This type of identification is usually found only in single conductor cables and inserted in the strands.

Another method usually reserved for shielded cable is an identifying tape placed between the shield and the semiconducting tape. This way the tape does not interfere with the bond between the jacket and the core assembly. This tape is usually either yellow or white with black lettering and these colors are common to all companies. This tape usually is marked with the company's name and date of manufacture.

The cables that do not have either of these types of identification, usually are surface printed on the outer jacket. This is considered by UL to be a permanent means of identification. Another method of surface printing would be the embossing on a lead cured neoprene jacket.

BIBLIOGRAPHY

1. Floy, Henry. High Tension Underground Electrical Cables. New York: Electrical Publishing Co., 1909.

2. Dunsheath, P. High Voltage Cables. London: Sir Isaac Pitman and Sons, LTD, 1929.

3. Schwaiger, A. Theory of Dielectrics. New York: John Wiley and Sons, Inc., 1932.

4. Fink, Donald G., and others. Standard Handbook for Electrical Engineering, Tenth Edition. New York: McGraw-Hill Book Co., 1968.

5. Sturdevant, E.G. "Insulated Aluminum Conductors", presented at the Symposium on the Use of Aluminum for Insulated Conductors. New York: American Institute of Electrical Engineers, 1953.

6. Barnes, Cyril. Power Cables. London: Chapman and Hall LTD., 1966.

7. Biskenborn, H.W. "A Historical Review of Aluminum Applications in Insulated Conductors". Presented at the Symposium on the Use of Aluminum for Insulated Conductors, New York: American Institute of Electrical Engineers, 1953.

8. Nelson, C.E., Garrett, K.S. "Design Problems and Operating Experience With Aluminum Distribution Conductors in the Philadelphia Electric Company", Presented at the Conference on the Electrical Utilization of Aluminum. New York: The American Institute of Electrical Engineers, 1955.

9. Carpenter, H.E., Thornton, R.E. "Eight Years With All-Aluminum Distribution System", Presented at the Conference on the Electrical Utilization of Aluminum. New York: The American Institute of Electrical Engineers, 1955.

10. Graham, R.C., Lowe, J.J. "Integral Insulation Shielding for Power Cables--A Simple Solution to a Serious Dilema". A.Z. Publishing Corporation, 1971.

11. Nelson, Roy A. "Modern Wire and Cable Designs", Presented to the Electrical Maintenance Engineers Association. Maine: Simplex Wire and Cable Co., 1970.

BIBLIOGRAPHY (Continued)

12. Engineering Design Handbook--Electrical Wire and Cable. Prepared by International Telephone and Telegraph Corp. Wire and Cable Division. Washington D.C. Headquarters, U.S. Army Material Command, 1969.

13. Javitz, Alex E. "Developments in Polyethylene Insulation", Presented at the Second Symposium on Polyethylene Wire and Cable Insulation. New York: American Institute of Electrical Engineers, 1958.

14. MacKenzie, Kenneth J. "Irrathene Irradiated Polyethylene--A New Insulating Material for Wire and Cable", Presented at the Second Symposium on Polyethylene Wire and Cable Insulation. New York: American Institute of Electrical Engineers, 1958.

15. Sinatra, Robert S. "A Comparison of Medium-Voltage Cable Insulations", IEEE Transactions on Industry Applications, Vol. IS-8, Nov. 5, 1972.

16. Merrell, E.J. "Applications of Polyethylene in the Wire and Cable Industry", Presented at the Second Symposium on Polyethylene Wire and Cable Insulation. New York: American Institute of Electrical Engineers, 1958.

17. Graham, R.C. "Polyethylene for Higher Voltage Cables", Presented at the Second Symposium on Polyethylene Wire and Cable Insulation. New York: American Institute of Electrical Engineers, 1958.

18. Whitehead, J.B. Impregnated Paper Insulation. New York: John Wiley and Sons, Inc., 1935.

19. "Engineering Data for Electrical Cables". New Jersey: The Okonite Co., 1971.

20. Scheide, Alfred, W. "Evaluation of the Shielding Properties of Cable Trays for Use in an Industrial Environment". IEEE Transactions of Industry Applications, Vol. IA-8, No. 6, 1972.

21. Masciarelli, Alberico. "Application of Clad Metal Longitudinally Corrugated Applied to Control Cables". Wire and Wire Products, 1973.

22. Mildner, R.C., Arends, Co, B., Woodland, P.C. "The Short-Circuited Rating of Thin Metal Tape Cable Shields", IEEE Transactions on Power Apparatus and Systems, Vol. Pas-87, No. 3, 1968.

BIBLIOGRAPHY (Continued)

23. National Fire Protection Association, National Electrical Code. Mass: National Fire Protection Association, 1971.

24. Hayt, William H. Engineering Electromagnetics. New York: McGraw-Hill Book Co., Inc., 1958.

25. "The Simplex Manual". Mass: Simplex Wire and Cable Co., 1969.

26. Chapman, C.R. Electromechanical Energy Conversion. New York: Blaisdell Publishing Co., 1965.

27. Brenner, E., Javid, Mansour. Analysis of Electrical Circuits. New York: McGraw-Hill Book Co., Inc., 1959.

28. Halliday, D., Resnick, R. Physics. New York: John Wiley and Sons, Inc., 1963.

29. Westinghouse Electric and Manufacturing Company-Central Station Engineers. Electrical Transmission and Distribution Reference Book, First Edition. Penn: Westinghouse Electric and Manufacturing Co., 1942.

30. Kennedy, N.D., Mitropoulos, J.N., Seamonds, W.L. "Electrical Characteristics of Butyl Insulation", Presented at the AIEE Fall Meeting, New York: AIEE, 1962.

31. DeBaene, E.C., Franke, W.C., Robertson, E.R. "Study of Connections for Use with Large All-Aluminum Conductors", Presented at the Conference on the Electrical Utilization of Aluminum. New York: The American Institute of Electrical Engineers, 1955.

32. Editorial Staff of the Edison Electric Institute Transmission and Distribution Committee, Underground Systems Reference Book. New York: Edison Electric Institute, 1957.

33. Hansen, Ted. "Splicing Techniques for Portable Cables Through 25 KV". Ohio: Anaconda Wire and Cable Co., 1972.

34. Miller, Harold N. Nondestructive High Potential Testing. New York: Haden Book Co., Inc. 1964.

35. Nelson, Roy A. "Overpotential Direct Current Testing of Electrical Cables" Underground Engineer, 1971.

BIBLIOGRAPHY (Continued)

36. Maloney, Charles A. "Locating Cable Faults", IEEE Transactions on Power Apparatus and Systems, Vol. IA-9, 1973.

37. Nelson, Roy A. "Paper Report on Fault Location", Presented at the Fault Location Symposium Underground Distribution Special Technical Conference. Maine: Simplex Wire and Cable Co., 1966.

38. McCombe, John, Haigh, F.R. Overhead Line Practice. London: MacDonald and Co., LTD., 1966.

39. Chu, S.C. "Screening Factor of Pipe-Type Cable Systems". IEEE Transactions on Power Apparatus and Systems, Vol. Pas-88, No. 5, 1969.

40. Skortzki, Bernhardt, G.A. Electric Transmission and Distribution. New York: McGraw-Hill Book Co., Inc. 1954.

41. Still, Alfred. Overhead Electric Power Transmission, New York: McGraw-Hill Book Co., Inc., 1913.

42. Corbett, Laurence, J. Inductive Coordination of Electrical Power and Communication Circuits, California: J.H. Neblett Pressroom LTD., 1936.

43. Nelson, Roy A. "Control Cables for Petroleum and Chemical Plants", Presented at the Petroleum and Chemical Industry Technical Conference. Maine: Simplex Wire and Cable Co., 1969.

44. Nelson, Roy A. "Cable Trends and Design in the Mining Industry", Presented before the Alabama Mining Engineering Group, Maine: Simplex Wire and Cable Co., 1971.

45. Waddicor, H. The Principles of Electric Power Transmission. New York: John Wiley and Sons, Inc., 1935.

46. Myatt, L.J. Symmetrical Components. London: Pergamon Press, 1968.

VITA

Robert William Buente was born on March 15, 1945, in Granite City, Illinois. He received his primary and secondary education in Granite City, Illinois; receiving a High School Diploma from Granite City Senior High School in January of 1964. He received his College education from Bradley University, completing studies and acquiring a Bachelor of Science Degree in Electrical Engineering in June of 1967.

From July of 1967 he was employed with Granite City Steel Co., as a Project Engineer, until November of 1971 when he began as a Sales Representative for The Okonite Co., with whom he is still employed.

Beginning in the Fall of 1968, he began his graduate studies at The St. Louis Graduate Engineering Center of the University of Missouri - Rolla.