Kirk-Othmer Encyclopedia of Chemical Technology.

INSULATION, ELECTRIC

The U.S. Department of Commerce Bureau of Census reports that in 1990 the total value of insulated wire and cable shipments was more than $10.5 billion. These shipments have grown more than 165% compared to 1983 and more than 225% compared to 1977.

Relative sizes of the principal market segments of insulated wires and cables have changed dramatically since 1977: the electronic wires segment has grown by 430%, power wires and cables have grown by 288%, and building wires and cables by 283%. Some other segments have shown smaller increases and even decreases; most notably, in 1990 telephone cables were only 93% of the 1977 shipments. Table 1 compares the values of various segments of insulated wire and cable sales in 1977 and 1990 (1, 2).

Almost all of the industry segments mentioned represent wires and cables that conduct electricity using currents of relatively high voltage and amperage but low frequency for power cables, or currents of high frequencies but low voltage and amperage for telephone and electronic wires. One segment of the insulated wire industry that was not mentioned in the 1977 Bureau of Census report but which has grown dramatically is fiber optic cables. It has been predicted that by the year 2000 fiber optic cables will become the largest segment of the industry, mostly at the expense of the telephone and electronic communication wires. These cables do not conduct electricity, but rather use light as the vehicle for communicating data (see Fiber optics).

Each segment of the insulated wire and cable industry has its own set of standards, and cables are built to conform to specifications provided by a large variety of technical associations such as The Institute of Electrical & Electronic Engineers (IEEE), The Insulated Cable Engineers Association, (ICEA), National Electrical Manufacturers Association (NEMA), Underwriters Laboratories (UL), Rural Electrification Administration of the U.S. Department of Agriculture (REA), Association of Edison Illumination Companies (AEIC), Military Specifications of the Department of Defense (MIL), American Society for Testing and Materials (ASTM), National Electrical Code (NEC), etc.

1. Designs and Materials

1.1. Data Communication Wires

Electronic cables such as data communication wires employ three basic designs: coaxial, twisted pair, and fiber optics (3, 4) (Fig. 1). Coaxial cables are so named because the axis of curvature of its outer conductor is concentric to its inner central wire. The metal braiding wrapped around the insulated center wire acts as the return current conductor in addition to shielding the wire from various interferences.

The twists of twisted pair cable act as a shield against radio frequency interference (RFI), and electromagnetic interference (EMI), and against the cross talk interference that a wire exerts on nearby wires; the more twist the less interference. Telephone wires can use large numbers of pairs. In most cases the pairs are not shielded with braiding or foil, as shown in Figure **1b** for data communication wire. Data communication wires

Table 1. Insulated Wires and Cables Sales

	1977		1990	
Market	Sales, 10^6 $	% of total	Sales, 10^6 $	% of total
electronic wires	474.1	10.0	2,039.2	19.0
telephone cables	1,619.8	34.2	1,514.8	14.2
power cables	695.4	14.7	2,005.4	18.8
control and signal wires	125.2	2.7	251.0	2.4
building wires	875.4	18.5	2,477.8	23.2
automotive wires	191.6	4.0	366.4	3.4
appliance wires	169.7	3.6	296.7	2.8
other equipment wires	293.5	6.2	436.1	4.1
line and extension cord	290.5	6.1	534.6	5.0
fiber optics cables	negligible		758.1	7.1
Total insulated wire	*4,735.2*	*100*	*10,680.1*	*100*

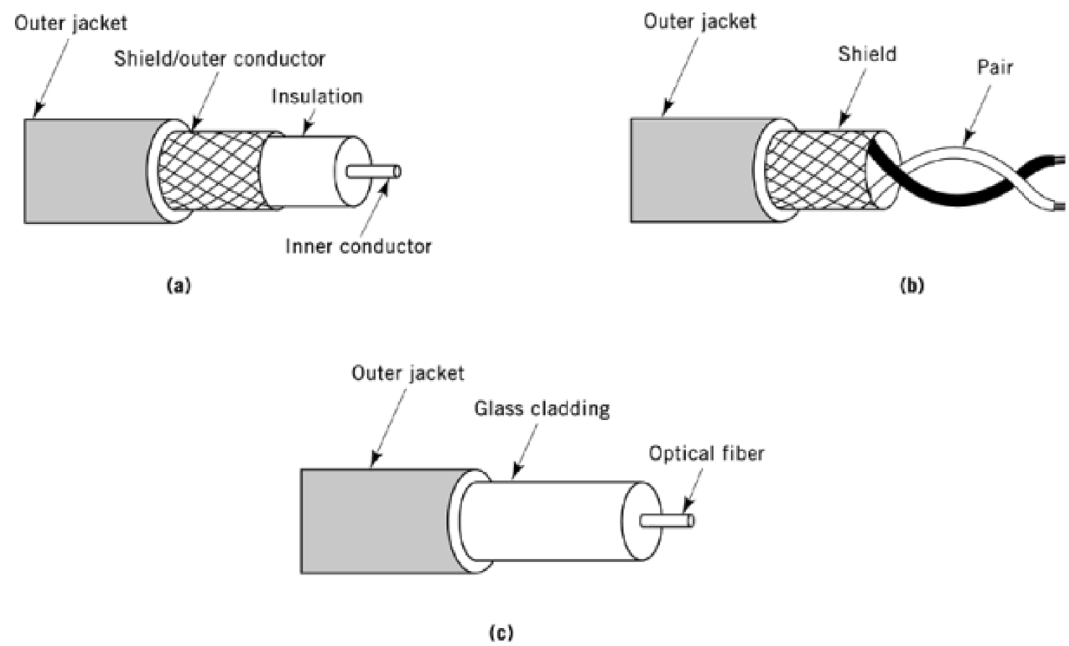

Fig. 1. Cable designs: (**a**) coaxial cable; (**b**) twisted pair cable can be unshielded, as in regular telephone wiring, or shielded (as shown here) with braiding or foil; (**c**) fiber optics cable.

work at very high current frequency (GHz), and can transmit a very large quantity of digital data, as opposed to modulated currents at low frequency that convey lower amounts of data used by the telephone wires.

Fiber optic transmission works differently from copper cable transmission. Instead of metal wire conducting an electrical charge, hair-thin glass or plastic fibers conduct light that is sent by rapid flashing on and off (digitally). The light can travel in more than one beam (multimode) or in one monomode beam, by bouncing off the inner walls of the hollow fiber (3). The coating layer cladding helps reflect light down the fiber.

Cables are available in a variety of constructions and materials, in order to meet the requirements of industry specifications and the physical environment. For indoor usage, such as for Local Area Networks (LAN), the codes require that the cables should pass very strict fire and smoke release specifications. In these cases, highly flame retardant and low smoke materials are used, based on halogenated polymers such as fluorinated ethylene–propylene polymers (like PTFE or FEP) or poly(vinyl chloride) (PVC). For outdoor usage, where fire retardancy is not an issue, polyethylene can be used at a lower cost.

1.2. Building Wires

These wires conduct electricity at relatively low voltages (eg, 110 V and 220 V). Typically they contain a metallic conductor (copper or aluminum) that is insulated with polymeric compounds based on polyethylene or PVC which are applied over a conductor using an extruder.

1.3. Magnet Wires

These wires are used principally in the electrical and electronics industries for coils, inductors, transformers, armatures, solenoids, etc. Typically the manufacturing process takes the metallic conductors through a liquid bath (or sometimes a powderized fluidized bed) of varnishes and enamels based on special resins, such as polyesters, polyurethanes, poly(vinyl formal), or polyimides followed by a heating process that drives off the solvents and cures these resins in a hard nonmelting thermosetting layer. Magnet wires may be classified according to NEMA thermal ratings based on extrapolations of their thermal lives measured in laboratory conditions.

1.4. Specialty Wires

Several categories of specialty wires employ special designs and materials, custom made to fit particular applications and/or specifications (5–8) (Fig. 2).

Appliance wires require a higher temperature rating (105°C or higher). Therefore, the insulation is made of fluorinated thermoplastics, such as poly-tetrafluoroethylene (PTFE) or fluorinated ethylene–propylene (FEP).

Cross-linked polyethylene-based compounds that contain flame-retardant components and compounds based on PVC cross-linked by radiation have also received high temperature rating. They find use not only in appliance wires but also in manufacturing under-the-hood *automotive wires.*

Instrumentation wires contain multiple pairs of conductors, each insulated with flame-retardant PVC and with an overall flame-retardant PVC jacket (5). For *distribution wires*, polyethylene or ethylene–propylene rubber are the polymers of choice (Fig. 2**c**). A typical design for *aerial self-supporting wires*, that employs PE and PVC, is shown in Figure 2**d**.

1.4.1. Military Application and Aerospace Wires

Depending on the specific application, a variety of polymers can be considered: PVC, polyamides, PTFE, etc (Fig. 3). Navy shipboard specifications require cables with flame retardancy, low smoke emission during fire, and containing no halogen.

1.4.2. Railroad/Transit Cables

These are single and multiconductor cables, rated 300 to 2000 V. The cables are designed for railroad and transit applications including vital circuits, track circuits, train control, third rail feeders, or apparatus wiring. Installation may be in wet as well as dry locations, in subway tunnels, or directly buried in the earth. Their insulation can be based on ethylene–propylene rubber (EPR) and is specially compounded to be flame retardant; the jacket can also be flame retardant with low smoke emission during fire. Specifications require that during fires the transit cables should exhibit low smoke emission, low toxicity, low corrosivity; some specifications do not allow the use of halogenated materials in cable composition. The issue of halogen-free cables has been under discussion in the 1990s, especially for cables placed in closed environments, such as underground public

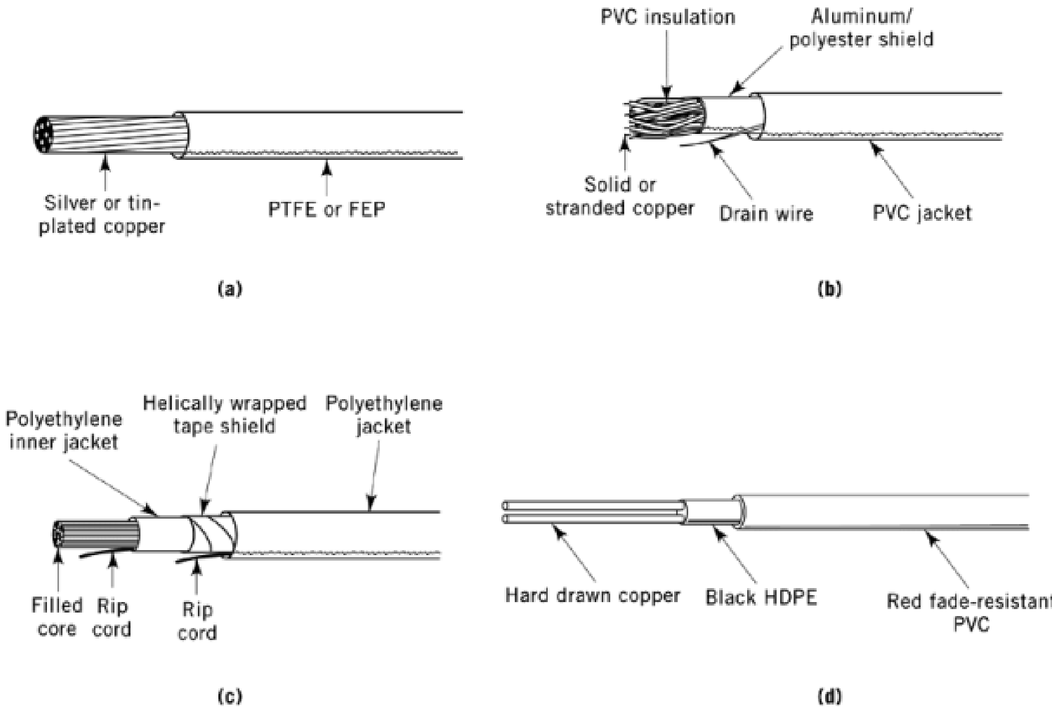

Fig. 2. Specialty wires: (**a**) appliance wires; (**b**) instrumentation wires; (**c**) distribution wires; and (**d**) aerial self-supporting wires.

transportation (transit, railways), buildings which house large numbers of people (eg, department stores, hospitals, offices, hotels), buildings which house valuable installations (eg, telephone and computer centers, power stations, television and radio stations), and military installations (eg, Navy ships, submarines). When fires occur in enclosed spaces, the halogenated compounds can decompose and release toxic and corrosive chemicals such as hydrochloric acid, which are harmful to health and corrosive to important and expensive equipment.

Control and signal cables are made up of fine copper wire strands of plain electrolytic copper wire with PVC or EPR-based insulation and an outer jacket of special PVC or ethylene copolymers.

1.4.3. Electric Submersible Oil Well Pump Cable

These cables are rated up to 5 kV and are designed for highly corrosive oil wells that besides oil also contain brine and other harsh chemicals as well as gases under high pressure and high temperatures (6). Insulations can be based on polypropylene for low temperature wells or on ethylene–propylene rubber which is compounded with special ingredients in order to resist the environments of high temperature wells (Fig. 4).

1.5. Power Cables

These high voltage cables have the most complicated designs. Depending on the voltages used (138,000+ V), the power cables can contain many layers, each one made of specially developed materials, with very specific characteristics (9). Figure 5 shows a typical 5-35 kV distribution power cable (9), such as the URD (Underground Residential Distribution) power cable. Typical conductors are aluminum or copper, mostly stranded or solid. At special request filled strands based on organic compounds are used. The conductor shield is bonded to

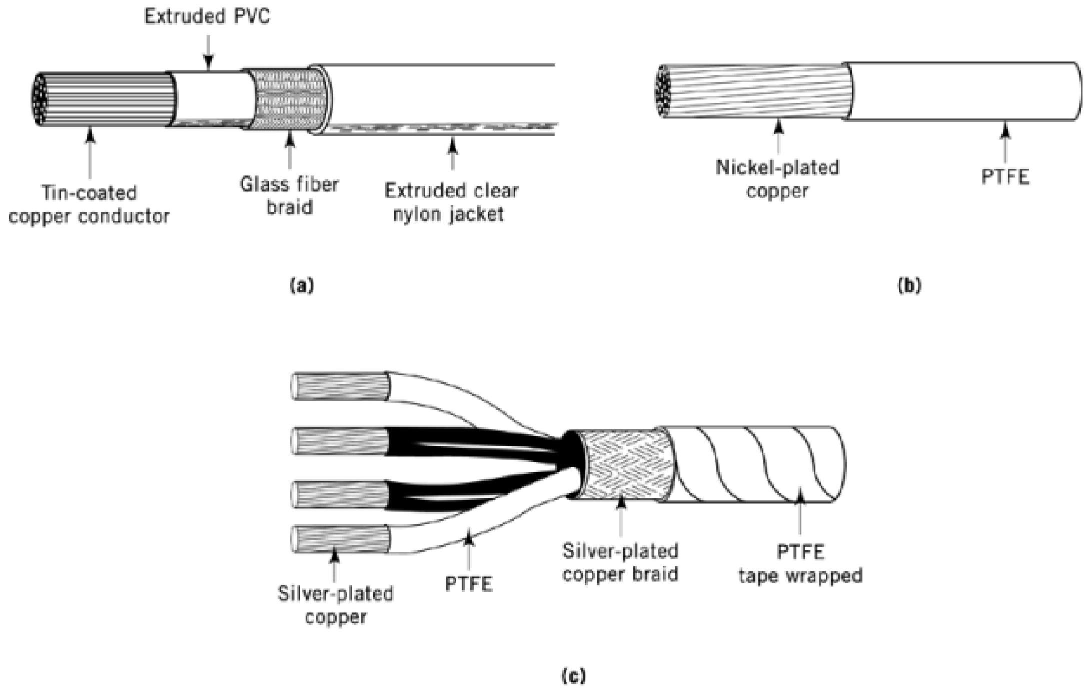

Fig. 3. Military application and aerospace wires.

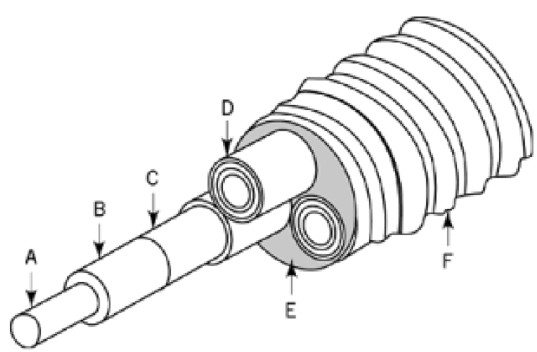

Fig. 4. Submersible oil well pump cable. A, Solid copper conductor; B, EPR-based insulation; C, chemical barrier; D, lead sheath; E, filler; F, galvanized steel armor.

the insulation. Conventional conductor shields are semiconductive and contain an ethylene-based copolymer and large amounts of carbon black. Some companies promote stress-relieving layers based on high dielectric constant (high permittivity) materials. Conventional insulations may employ either cross-linked polyethylene (XLPE), tree retardant cross-linked polyethylene (TRXLPE), or EPR-based compounds. Conventional design for the insulation shield uses semiconductive compounds based on carbon black loaded ethylene-based copolymers that are thermosetting in nature and are bonded, but also strippable from the insulation layer. Concentric copper neutral wire is used for returned current. The jacketing layer can be based on thermoplastic polymers, such as polyethylene, PVC, or thermosetting compounds based on polymers like chloroprene, chlorosulfonated

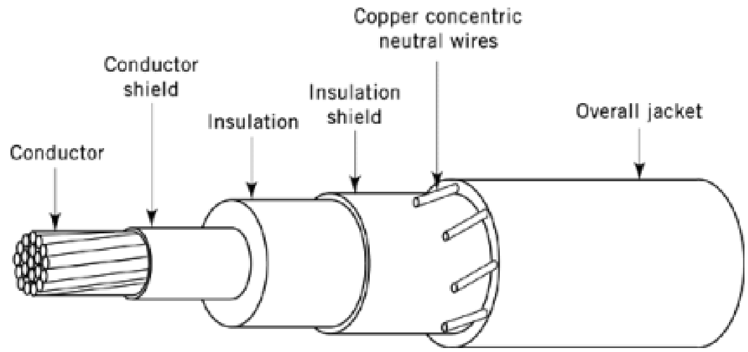

Fig. 5. Distribution power cable.

polyethylene, nitrile, chlorinated polyethylene, etc; it can be insulating or conductive. Some power cables have a metal shield at special request.

Most of the polymeric-based layers are applied using extrusion technology; the main equipment is the extruding coating line .

2. Properties and Test Specifications

Each segment of the insulated wire and cable industry has its own set of standards, some of which are quite complicated because of requirements imposed by specific applications and/or environments. The most complex specifications are typically imposed on power cables and telecommunication wires.

The most important electrical properties of insulation are dielectric strength, insulation resistance, dielectric constant, and power factor. Corona resistance, although not strictly an electrical property, is usually considered also (10).

2.1. Dielectric Strength

The dielectric strength of a material is the electric stress required to puncture a sample of known thickness and is expressed in terms of volts per thickness units, eg, $\mathrm{V}/\mu\mathrm{m}$. The dielectric strengt of an insulating material is influenced by the rate of rise of the applied voltage, and the total length of time the voltage is applied. A slow rate of rise usually causes the material to puncture at a lower voltage than does a rapid rate of rise. Similarly a material may withstand a relatively high voltage for a short time, but is punctured by prolonged exposure to a considerably lower voltage.

Dielectric strength is measured by determining the minimum voltage which will puncture a sample of known thickness placed between electrodes of specified size and shape. Because both the magnitude and duration of the applied voltage influence the results, this property can be measured in three ways.

In the most frequently used test the sample is placed between two electrodes and the voltage is increased from zero at a uniform rate until breakdown occurs. When an insulated wire is available, the voltage can be placed between the inner conductor and a conductive medium, such as an outside metallic shield or even water.

Another test consists of the application of a voltage starting at zero and increasing at a uniform rate up to a predetermined value. The voltage is held at this value for a specified time. The voltage and time vary with the type of product and with the kind of information desired. This test is useful for determining whether or not a given product or assembly has a sufficient high dielectric strength. It is nondestructive and the voltage applied is determined more by service conditions than by the actual dielectric strength of the insulating material. Since failures are caused by manufacturing defects, impurities, or damage, this test is used extensively for quality control.

A third test consists of an instantaneous application of the full test voltage; higher voltages are impressed on the insulation than in previous tests.

A spark test is used to continuously detect faults in wire insulation during some stage of its manufacture. This test employs a chamber which contains either a bath of metallic spheres or a chain curtain suspended from the top of the chamber. The wire is run through the chamber and high voltage is applied between the beads or curtain and the insulated conductor. The voltage is held just under the maximum stress the insulation can withstand, so that any foreign material, thin spot, or other defect will cause a spark to pass through the insulation.

In actual practice, mechanical and electrical design factors usually require the cables to have layers of a certain thickness such that the electrical stress is far below the dielectric breakdown point.

2.2. Resistivity/Conductivity

The resistivity or specific resistance of a material is the electric resistance offered by an element of the material having unit length and unit cross-sectional area. The current intensity is proportional to the voltage across its path, and is inversely proportional to resistance. This relationship is expressed by Ohm's law, where $I =$ current in amperes, $E =$ potential in volts, and $R =$ resistance in ohms.

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

The resistance of a segment of the path described above is proportional to its length, inversely proportional to its cross-sectional area, and proportional to a specific property of the material of the segment called resistivity or volume resistivity, ie:

$$R = \rho\frac{L}{A}$$

where $R =$ resistance of the segment, $L =$ length of the segment, $A =$ cross-sectional area of the segment, and $\rho =$ resistivity of the material of the segment. The resistivity of a material is therefore

$$\rho = \frac{RA}{L}$$

The reciprocal of resistivity is conductivity.

There is no perfect conductor, nor is there a perfect insulator, hence every material has some value of resistivity. The range of resistivity values between good conductors and good insulators is tremendous. A conductor such as copper has a resistivity of about $1.7 \times 10^{-6}\Omega{\cdot}\text{cm}$ as compared with the resistivity of an insulator such as polyethylene, which is $\sim 10^{17}\Omega{\cdot}\text{cm}$ or more.

For flat samples such as press cured slabs the resistivity may be computed from the following formula where $\rho =$ resistivity, $R =$ resistance, $A =$ area of the sample (the effective area of the smaller electrode if two electrodes of different sizes are used), and $t =$ thickness of the sample.

$$\rho = \frac{RA}{t}$$

For wire insulation, the relationship between the resistance of the sample and the resistivity of the insulation material is expressed by the following equatisend on, where $R =$ resistance, $\rho =$ resistivity,

L = length of the sample, r_1 = radius of the conductor, and r_2 = radius of the insulation.

$$R = \frac{\rho}{2\pi L} \log_e \frac{r_2}{r_1}$$

This formula may be rearranged for greater convenience, and at the same time D_2/D_1 may be substituted for r_2/r_1 where D_2 is the diameter of the insulation and D_1 is the diameter of the conductor. Also, it is more convenient to use common rather than natural logarithms.

$$\rho = \frac{2\pi RL}{2.3 \log_{10} \frac{D_2}{D_1}}$$

The method of measuring insulation resistance varies with each type of device or product. The insulation resistance of insulated wire is the resistance between the conductor and the outside of the insulation. When the insulation is covered by a metallic sheath or braid the measurement is made between the conductor and the sheath. Insulated wire with no sheath is usually immersed in water and the resistance measured between the conductor and the water after the wire has been immersed for a specified period of time.

For each specific application of a rubber compound as an insulating material, there is a minimum value of resistivity below which it does not function satisfactorily. In addition, insulating compounds are required to withstand the effect of water, moist atmosphere, or heat without their resistivity values falling below a satisfactory level. Insulation resistance measurements frequently serve as useful control tests to detect impurities and manufacturing defects in rubber products.

2.3. Dielectric Constant

Dielectric constant or specific inductive capacity (SIC) is both defined and measured by the ratio of the electric capacity of a condenser having that material as the dielectric to the capacity of the same condenser having air as the dielectric. The dielectric constant of vacuum is unity. Dry air has a constant slightly higher; but for most practical purposes it is considered as unity.

Two parallel plates of conducting material separated by an insulation material, called the dielectric, constitutes an electrical condenser. The two plates may be electrically charged by connecting them to a source of direct current potential. The amount of electrical energy that can be stored in this manner is called the capacitance of the condenser, and is a function of the voltage, area of the plates, thickness of the dielectric, and the characteristic property of the dielectric material called dielectric constant.

The capacitance of a condenser in terms of its physical dimensions and the dielectric constant of the insulation is given by the following equation, where C = capacitance in microfarads, K = dielectric constant of the insulation, A = area of plates in square centimeters, and t = thickness of the insulation in centimeters.

$$C = 0.088 \frac{KA}{t}$$

If an alternating current potentialis applied to an electrical condenser, each reversal of the potential results in a reversal of the charge stored in the condenser. There is, therefore, an alternating current apparently flowing through the condenser proportional to the capacitance of the condenser, hence proportional to the dielectric constant of the insulation material forming the dielectric of the condenser.

The dielectric constant of the insulation of a wire is measured by immersing a known length of wire in a conducting medium such as water or mercury. The dielectric constant vs capacitance relationship for a wire is given by the following formula, where C = capacitance, L = length of wire, K = dielectric constant of the insulation, r_2 = radius of insulation, and r_1 = radius of conductor. The most commonly used length of sample for this test is ∼6 m (20 ft) immersed length.

$$C = \frac{LK}{18 \times 10^5 \log_e \frac{r_2}{r_1}}$$

Typical dielectric constant values for raw materials are 2.6–3.0 for natural rubber insulation, approximately 2.2 for polyethylene, and approximately 2.4 for ethylene–propylene rubber.

For most commercial voltages and frequencies used in power distribution, the capacitance effects are negligible. At relatively high voltages the current due to capacitance may reach sufficient value to affect the circuit, and insulation for such an application is designed for a moderately low dielectric constant.

The dielectric constant of a compound is increased by small amounts of absorbed water; hence wire insulation for communications generally must have a dielectric constant as stable as possible in the presence of water or moisture.

For telecommunication wires, where higher frequencies are used, there are some other critical properties that are related to the dielectric constant; for example, mutual capacitance, defined as the capacitance between two wires of a pair. In voice communication, mutual capacitance shifts the phase of the transmitted analogue signal. Since voice frequencies vary over a narrow range, phase shifts are usually not objectionable. In high frequency digital transmission, however, metal capacitance rounds or distorts the square wave shape of the signal, causing error in data transmission. The larger capacitance, the higher the distortion and error rate.

For coaxial cables, the following electrical properties related to the dielectric constant of the core material and the dimensions determine the quality of the signal: impedance, capacitance, attenuation, crosstalk, and time delay and velocity of propagation.

2.3.1. Impedance

Impedance defines the relationship of voltage and current in a coaxial cable. The electrical requirements of the hardware dictate the impedance values for the interconnecting cables. Most coaxial cables are designed to match the impedances required by electronic hardware.

2.3.2. Capacitance

This property is dependent on the dimensions of the inner and outer conductors and the dielectric constant of the core. Most computer systems have a maximum allowable capacitance for interconnecting cables. For these systems, the lower the capacitance of the core material, the longer the cable that can be used.

2.3.3. Attenuation

Attenuation refers to the reduction in amplitude or height of a transmitted signal. In voice communication, attenuation simply means that the conversation is not as loud. Attenuation of a digital signal reduces the height of the square wave so that the receiving equipment must be sensitive enough to distinguish the signal's on and off states and the difference between an adjacent signal. If the receiver has to look too closely, it can be deceived by noise pulses, causing errors in the data.

Because the FCC limits the strength of the transmitted signal, increasing the strength of the original signal is not an acceptable solution. Therefore, low attenuation is essential for high quality, error-free signal transmission, particularly over long cable runs.

2.3.4. Combined Effect of Capacitance and Attenuation

When capacitance is high, the signal never reaches the 1 state before it starts declining to 0 again. This yields a signal in which the 1 and 0 states are nearly indistinguishable by the receiver and an error results. Since capacitance and attenuation are always present in telephone cables, for error-free transmissions the communications wire must have the lowest capacitance and attenuation possible.

2.3.5. Crosstalk

This is a measure of the signal induced in a quiet pair by an excited pair. The excited signal could be voice, digital data, ringing, or noise. Crosstalk is expressed as a decibel (dB) loss, so the smaller the number, the less the crosstalk. Crosstalk becomes important when transmitting digital signals at high speeds.

The relationship of the dielectric constant of the cable insulation to crosstalk can be measured by testing two cables for crosstalk with the same dimension, but different insulation materials. The cable with the lower dielectric constant has less capacitance unbalance, thus resulting in lower crosstalk than the cable with the higher dielectric constant.

2.3.6. Time Delay and Velocity of Propagation

Time delay is directly proportional to the square root of the dielectric constant and describes the time that it takes for a signal to travel through a cable. The lower the dielectric constant, the less time required for a signal to travel through a cable.

Velocity of propagation is the speed of transmission in a cable as compared to the speed of transmission in air and is therefore expressed as a percentage. Since the velocity of propagation is inversely proportional to the square root of the dielectric constant of the core, a lower dielectric constant results in higher transmission speed (3).

2.4. Power Factor

The amount of energy given up by the condenser during discharge is measured. The power factor is the ratio of this loss to the energy required to charge the condenser and may be expressed as a decimal fraction or a percent of the charging energy. The equipment for measuring power factor is the same as for measuring dielectric constant, and usually the two are determined simultaneously.

The power factor of a sample is determined from the capacitance and resistance values by means of the following relationship, where P = power factor, G = conductance in mhos (reciprocal ohms), $W = 2\pi \times \text{frequency}$, and C = capacitance.

$$P = \frac{G}{WC}$$

Typical power factors for an EPR-based compound employed for 5–35 kV power cable is approximately 0.03–0.05% when measured at room temperature and about 1.0–1.4% measured at 90°C.

Power factor, like the dielectric constant, is a property that represents a power loss that takes place when a wire insulation becomes the dielectric of a condenser because of a surrounding sheath or other conducting medium.

Power factor losses under certain conditions cause a temperature rise in the insulation that may result in failure or reduced life of the insulation. In communication wiring the power factor of the insulation plays an important role. Here the actual power loss can represent an appreciable portion of the total energy in the circuit. In addition, this loss disturbs the circuit characteristics of the equipment at both ends of the line.

2.5. Corona Resistance

Corona resistance is the ability of material to withstand the effect of electrical discharge. Corona discharge is a flow of electrical energy from a conductor at high potential to the surrounding air. If the cable has an insulating covering, the corona discharge takes place at the outer surface of the insulation. If there are voids or air spaces between the conductor and its insulation, corona discharge (sometimes named partial discharge) will probably take place at these points. The discharge is accompanied by a faint glow and a noise, and can convert oxygen to ozone and ionize gases.

The insulation on the conductor is therefore exposed to a considerable concentration of ozone and subjected to chemical reactions and mechanical erosion from the impingement of ions. This causes deleterious effects and shortens the life of the cable.

There are several methods to determine and compare the resistance to partial discharges. Some tests are done on finished cables, such as the U-bend test, and others are done on laboratory samples molded from the insulation, that are subjected to partial discharges created by sharp objects, such as needles under high voltages. The tests compare either the energy required or the length of time required to erode or fail (short circuit) samples of similar thickness.

3. Electrical and Water Treeing

Treeing is an electrical prebreakdown phenomenon. This type of damage progresses through a dielectric section under electrical stress so that, if visible, its path looks something like a tree. Treeing can occur and progress slowly by periodic partial discharge, it may occur slowly in the presence of moisture without partial discharge, or it may happen rapidly as the result of an impulse voltage. Although generally associated with a-c or impulse voltages, treeing has been observed with high d-c voltage stresses in wet experimental conditions. Treeing may or may not be followed by complete electrical breakdown of the dielectric section in which it occurs. In solid organic dielectrics it is the most likely mechanism of electrical failures which do not occur catastrophically, but rather appear to be the result of a more lengthy process.

Generally, trees occur under the relatively high voltages associated with power cables (11–13). Trees can be classified in three classes: electrical, water, and electrochemical.

Electrical trees consist of visible permanent hollow channels, resulting from decomposition of the material, and show up clearly in polyethylene and other translucent solid dielectrics when examined with an optical microscope. Fresh, unstained water trees appear diffuse and temporary. Water trees consist of very fine paths along which moisture has penetrated under the action of a voltage gradient. Considerable force is required to effect this penetration which starts at a surface imperfection or stress concentration and must rupture but not decompose the internal structure as it progresses. When the voltage force and source of water are removed, most of the injected water diffuses away and evaporates, and the tree disappears. This disappearance indicates that channels or paths close up, because if they did not, their appearance would be enhanced rather than diminished when the water is replaced by air which has a greater refractive index difference with respect to polyethylene.

Electrical and water trees can grow from the interface of electrode and insulation into the insulation or they can grow from internal voids and contaminant particles radially outward, parallel to the field, and toward the electrodes. These latter are called bow tie trees. Trees which start their growth at surfaces with an unlimited supply of air or water can grow completely through a dielectric section to bridge the electrodes. These are called vented trees. Trees which start at an internal void or inclusion are called nonvented trees and rarely grow very large.

Electrochemical treeing is applied in those cases of water treeing in which the water contains solute ions which move under the action of an electric field and are detected within the insulation layer, or at an electrode surface after having passed through the insulation. They are not encountered as often as the first two classes, for example, trees formed in a cable exposed to a hydrogen sulfide environment called sulfide trees.

3.1. Test Methods for Electrical and Water Treeing

3.1.1. Laboratory Samples

In order to test resistance against electrical treeing, the concept of the standard defect is used in the needle test and modifications thereof. Since trees initiate and grow at sites of stress concentration rather than in perfectly uniform fields, the needle test provides a reproducible and highly divergent electrical field when the specimens are prepared with precision. In this test, the needles have very sharp and well-defined tips and are inserted in sample materials at defined depths; the samples are electrically stressed under certain voltages for periods of time. After stressing, the specimens are carefully examined with a $100\times$ microscope to determine evidence of trees at the needle tip. There are also several laboratory methods to test resistance to water treeing formation. For opaque specimens, such as filled EPR-based compounds, there are special techniques that include special staining chemicals that color electrical and even water tree paths and make them visible (11).

3.1.2. Tests on Cable Constructions

The Association of Edison Illumination Companies (AEIC) has approved an accelerated cable life test in which typical underground distribution power cables can be statistically compared based on their resistance to water treeing (number of days to fail). The comparison can be made by varying the type of insulation and/or other cable layers in an environment that contains hot water (90°C) under $8\ \mathrm{V}/\mu$ (200 V/mil) voltage stresses (four times the typical power cables operating voltages).

4. Physical, Mechanical, and Environmental Tests

Typical standard tests performed on insulation and/or jacket compounds measure tensile strength, ultimate elongation, modulus, set, tear, heat distortion, heat shock, cold bend and low temperature brittleness, abrasion resistance, and shear resistance. Depending on the environment in which the cable operates, the following tests may be done: resistance to oil or other chemicals, including water absorption; air aging resistance, measured at various temperatures either as percent retention of the sample initial physical properties or as the ultimate end life for sample to become brittle; oxygen and ozone resistance; radiation resistance when used in nuclear stations; flame resistance, measured as oxygen index or vertical or horizontal flame tests; smoke tests, using various equipment; and flame and smoke emission for the wires used indoors in the plenum areas are determined by the UL910 test.

5. Materials Used in Insulated Wires and Cables

The most widely used insulation compounds are based on PE, PP, silicone rubber, EPR, PVC, and fluoroplastics. Polyethylene (thermoplastic or cross-linkable) is used because it is lightweight, water-resistant, and easy to strip, and has low dielectric constant and power loss. It is used, especially in foamed form, to make computer and TV coaxial cables. Polypropylene has very good abrasion resistance and its heat resistance is better than that of polyethylene. It has low electrical losses but since it is relatively stiff its use is rather limited. Silicone rubber-based compounds are used to produce wires used at high temperatures (due to its good aging properties) and for special fire-resistant application, due to its char formation during fire, such as for Navy shipboard wires. Ethylene–propylene rubber-based compounds have some use in low voltage cables but are much more popular in manufacturing power cables.

Examples of fluoroplastics include polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), ethylene–chlorotrifluoroethylene (ECTFE), ethylene–tetrafluoroethylene (ETFE), poly(vinylidene fluoride) (PVDF), etc (see Fluorine compounds, organic). These polymers have outstanding electrical properties, such as low power loss and dielectric constant, coupled with very good flame resistance and low smoke emission during fire. Therefore, in spite of their relatively high price, they are used extensively in telecommunication wires, especially for production of plenum cables. Plenum areas provide a convenient, economical way to run electrical wires and cables and to interconnect them throughout nonresidential buildings (14). Development of special flame-retardant low smoke compounds, some based on PVC, have provided lower cost competition to the fluoroplastics for indoors application such as plenum cable, Riser Cables, etc.

5.1. Poly(vinyl chloride)

PVC has intrinsic resistance to fires, oils, most chemicals, ozone, and sunlight. Due to its natural stiffness and rigidity, it cannot be used as is but is compounded with various ingredients, especially plasticizers, in order to obtain flexibility as well as other properties. In compounded form, PVC is used either as insulation in areas where its relatively high dielectric constant and dielectric power loss is acceptable (such as wires used for audiotransmission, low voltage building, and portable), or as jacketing for a large variety of cables including power cables. UL specifications define certain temperature rating criteria based on physical aging characteristics of PVC compounds (15). Other UL test criteria for PVC compounds used in wires and cables includes the cold-bend test, deformation test, heat–shock test, vertical flame test, horizontal flame test, tray–cables flame test, smoke emission test, dielectric voltage–withstand, etc.

In a flexible PVC compound, ingredients in the recipe are chosen based on cost and/or their contribution to physical and other properties and performance. Typical ingredients (16, 17) are stabilizers, fillers, plasticizers, colorants, and lubricants.

5.1.1. Plasticizers

Monomeric (mol wt 250–450) plasticizers (qv) are predominantly phthalate, adipate, sebacate, phosphate, or trimellitate esters. Organic phthalate esters like dioctyl phthalate (DOP) are by far the most common plasticizers in flexible PVC. Phthalates are good general-purpose plasticizers which impart good physical and low temperature properties but lack permanence in hot or extractive service conditions and are therefore sometimes called migratory plasticizers. Polymeric plasticizers (mol wt up to 5000 or more) offer an improvement in nonmigratory permanence at a sacrifice in cost, low temperature properties, and processibility; examples are ethylene vinyl acetate or nitrile polymers.

5.1.2. Stabilizers

Heat stabilizers (qv) are included in PVC compounds to counteract the internal generation of hydrogen chloride as well as the external degradative effect of heat. Due to environmental considerations, there is a trend toward decreasing and even avoiding the use of stabilizers based on heavy metals, eg, lead.

5.1.3. Colorants

Pigments are the main colorants used in PVC, but some dyes are also employed (see Colorants for plastics).

5.1.4. Lubricants

Process aids or lubricants promote smooth and rapid extrusion and calendering, prevent sticking to extruders or calender rolls, and impart good release properties to molding compounds. In some cases use of lubricants allow slightly lower processing temperatures.

Table 2. Wire and Cable Insulation PVC Formulations, Parts by Weight

Component	Low cost for low temperature	For high temperature applications	Nonmigratory plasticizer
PVC	100	100	65
dioctyl phthalate	70		
diundecyl phthalate		25	
trimellitate		25	
nitrile rubber			35
lead-based stabilizer	7	6	5
clay	20	20	
calcium carbonate	10	10	
antioxidant system	0.25	0.5	2
antimony trioxide			3
stearic acid			0.25
acrylic-based modifier			5

5.1.5. Fillers

These are used to reduce cost in flexible PVC compounds. It is also possible to improve specific properties such as insulation resistance, yellowing in sunlight, scuff resistance, and heat deformation with the use of fillers (qv). Typical filler types used in PVC are calcium carbonate, clays, silica, titanium dioxide, and carbon black.

The PVC formulations shown in Table 2 represent typical compounds used by the wire and cable industry. PVC compounders have developed new PVC-based formulations with very good fire and smoke properties (can pass the UL 910 Steiner Tunnel test) that compete with the more expensive fluoropolymers. These can be used in fabricating telecommunication cables usable for plenum area applications.

5.2. Magnet Wires

Magnet wires can be classified as coated wires, coated wires with fibrous wrappings, and wires with impregnated fibrous wrappings; the last two categories are older technologies. Wires coated with only an organic coating are frequently referred to as enamel wires or simply coated wires. The organic coating (one or multilayers) is applied directly to the conductor and is a dielectric material.

Examples of thermoplastic coatings are fluoropolymers, eg, Teflon or polyamides, eg, nylon. Thermosetting coatings are more resistant to cut-through and have superior resistance to heat and solvents. The silicones, polyimides, and fluorocarbons are best suited for very high temperatures applications, the polyurethanes for ease of removal, and epoxies for solvent and chemical resistance. Several other polymers are also used to coat the magnet wires. A summary of their advantages and limitations are given in Table 3 (18).

5.3. Power Cables

The materials mostly used to produce power cables are ethylene copolymers loaded with conductive carbon black for semiconductive shielding layers, polyethylene or ethylene–propylene rubber-based compounds as insulations, and either thermoplastic materials (eg, polyethylene, PVC) or thermosetting (based on chlorinated polyethylene (CPE), chlorosulfonated polyethylene (CSPE), chloroprene, etc) for jackets.

5.3.1. Insulation

Cross-linked polyethylene (XPLE) and ethylene–propylene rubber (EPR), both thermosets, are the primary extruded dielectrics used in medium and high voltage power cables (Table 4).

Table 3. Properties of Coated Wires[a]

Coating	Thermal rating, °C	Advantages	Limitations
poly(vinyl formal)	105	toughness, dielectric strength; compatible with other coatings; heat-shock resistant	crazes in polar solvents
polyurethane	105	dielectric strength, chemical resistance, moisture, and corona resistance; compatible with solvents and chemicals; solderable without stripping	low thermal resistance
polyamide (nylon)	105	toughness, dielectric strength, solvent resistance; solderable; good windability	high moisture absorption; high electrical loss at all frequencies
poly(vinyl formal)–poly(vinyl butyral)	105	bondability, dielectric strength; heat–shock resistant	vibration; high mechanical stress
polyester	155	toughness, dielectric strength, chemical resistance, cut-through resistance	hydrolyzes in moist sealed atmosphere
polytetrafluoroethylene (Teflon)	200	thermal stability, chemical stability, dielectric strength; low dielectric constant	high abrasion; high gas permeability; cold flow; poor adhesion
polyimide	220	high overload resistance, thermal resistance, chemical stability, radiation resistance; high cut-through resistance	stripping difficulty; crazes in some solvents

[a]Ref. 18.

Table 4. Components Used in Power Cable Insulations Based on EPR, Parts by Weight

Component	Low (to 5 kV)	Medium (to 35 kV)	High (to 138 kV)
EPR	100	100	100
low density PE	0–20	0–20	0–20
paraffinic wax	0–5	0–5	0–5
stearic acid	1–3		
calcium carbonate	50–100		
calcined clay	100–200		
silane treated clay		100–150	50–100
paraffinic oil	50–150	0–30	0–20
zinc oxide	0–5	0–5	0–5
lead oxide		0–5	0–5
antioxidants	1–2	1–2	1–2
coupling agent	1–2		
peroxide	3–6	3–6	3–6

High dielectric strength and very low electric conductivity make polyethylene an outstanding insulator for electric power cable at low voltages as well as high voltages used by transmission cables. Polyethylene is also the most suitable dielectric for all types of high frequency cables because of its low dielectric loss at high frequencies and its remarkable mechanical properties.

The power factor of polyethylene which provides the measure of the power loss in the insulated conductor increases slightly with an increase in the temperature of the atmosphere or the electrical equipment, both of which may fluctuate widely. It also increases slightly with an increase in the humidity of the surroundings.

Improved heat resistance is the most important advantage of cross-linked polyethylene (XLPE) over thermoplastic polyethylene. A power cable with XLPE insulation can operate at conductor temperatures of 90°C. Since conductor temperature is proportional to the amount of current sent through the cable, more power can be sent through an XLPE cable than through a noncross-linked cable of the same size. Thus in heavily populated areas, fewer or smaller XLPE cables can be installed. In appliance wire applications, cross-linking allows compounds to be formulated for 125°C service temperatures, well above the melting point of the noncross-linked base resin.

Compared to a typical cross-linked polyethylene-based compound, the typical EPR-based compounds used for medium voltage cables contain much larger amounts of ingredients. Besides being higher in cost, when compared to XLPE the EPR-based insulations display certain inferior electrical properties, such as higher dielectric loss, lower dielectric and impulse strength, especially when measurements are done on newly produced cable, before field operation. However, the longtime field service records have shown numerous positive features for the power cables insulated with compounds based on EPR that are making them attractive to customers interested in cables with a long life history in the field (19).

Compared to XLPE, the EPR-based insulation compounds used in power cables have the following characteristics: greater flexibility and ease of installation; easier splicing and terminating in all weather; lower coefficient of thermal expansion at high temperatures, generated during emergency overloads and short circuits, thus lower tendency to separation between insulation and insulation shield layers as well as between the components of the cable and of the premolded splicing kits that typically are based on EPR; superior resistance to degradation caused by partial discharges in voids within the insulation or at the interface between the insulation and the shielding layers of the power cables; and less tendency to water treeing degradation and failure, possibly due to the lower crystallinity of EPR and to higher filler content vs polyethylene-based formulations of EPR compounds (19).

Besides using polyethylene and EPR as materials of choice for the insulations of power cable, there are a few other technologies that are less popular but still in use. In pressurized filled cables, the cable is kept full of oil under pressure by oil reservoirs connected to cables. Solid paper insulated cables, where the oil is impregnated into the paper tape during manufacturing, are used for low voltages due to corona effects that may occur at high voltages in the voids that may exist in layers. However, for high voltages (up to 230 kV) the oil is kept under pressure to fill the eventual voids.

Extruded materials are used for power cables from 5 kV up to 138 kV for underground distribution and transmission lines; the 230 kV cable is still in infancy. Compared to the low voltage cables (up to 5 kV) that use simpler materials, the medium voltage cables (5 to 35 kV), the high voltage power cables (up to 138 kV), and the very high voltage cables (230 kV and higher) contain specially developed materials due to the more difficult and special applications concerns.

5.3.2. Shields

Power cable (conductor) shields provide a smooth, continuous, conductive, and isopotential interface between the conductor and insulation (Fig. 5). The geometry of the conductor strands permits air gaps between the outer wires of the stranded conductor and the inner surface of the extruded insulation. Without a stress control layer, excessive electric gradients can cause partial discharges within these gaps that harm the insulation. There are two design approaches: most shields are either semiconductive shields that use large amounts of carbon black mixed in polymeric-based formulations, or stress-relieving shields that are based on materials with high dielectric constant. Brand names for the latter are Permashield or Emission Shield.

The interface between conductor shield and insulation is the region of the highest stress in the cable insulation structure. Any imperfections at this interface, especially sharp protrusions of the conductor shield into the insulation, will cause high local electrical stress that may reduce the dielectric strength of finished cable. Calculation of the stress enhancement, for a 15 kV cable with a 4.4 mm (175 mil) insulation thickness, indicates that the common round 50 μm (2 mil) radius protrusions increase the electrical stress by a factor of 30 and a sharp 5 μm protrusion will increase the electric stress by as much as 210 times (11, 20).

Trees originating at a shield–insulation interface are mostly due to the existence of protrusion from the shields. They are referred to as vented trees; if moisture is present, they are called vented water trees. Particulate contaminants present in the insulation, and waterborne ionizable materials that find their way into the insulation, are also causes of tree formation.

The carbon black in semiconductive shields is composed of complex aggregates (clusters) that are grape-like structures of very small primary particles in the 10 to 70 nanometer size range (see Carbon, carbon black). The optimum concentration of carbon black is a compromise between conductivity and processibility and can vary from about 30 to 60 parts per hundred of polymer (phr) depending on the black. If the black concentration is higher than 60 phr for most blacks, the compound is no longer easily extruded into a thin continuous layer on the cable and its physical properties are sacrificed. Ionic contaminants in carbon black may produce tree channels in the insulation close to the conductor shield.

The conductive carbon black particles suspended in the compound's polymeric base may assume configurations that will create high stress points at the interface between the conductor shield and the insulation. These points, similar to protrusions, can be very sharp and cause localized voltage stresses which significantly exceed the electric stresses calculated for a uniform surface. These extremely high local voltage stresses, caused by protrusions and/or carbon black particles suspended in the semiconducting compound, can initiate cold electron emission from carbon black particles and/or initiate partial discharges, which in turn may cause insulation breakdown (20).

5.3.3. Insulation Shields

The insulation shield is a layer applied over the insulation (see Fig. 5). It plays much the same role as the conductor shield in protecting the insulation from the damaging effects of ionization at the outside of the insulation surface, therefore it too must always remain in intimate contact with the insulation and be free of voids and defects at the interface. As an integral component of cable grounding, the insulation shield must be a resistive shield, providing a uniform ground around the insulation during field service; it also contributes to the grounding of the cable during switching surges, short circuits, or lightning strikes.

The electric stress at the interface between the insulation and the insulation shield is less than at the conductor shield–insulation interface.

Most medium voltage cables are made with insulation shield layers that are bonded but easily stripped from the insulation in order to avoid pockets of air at the interface and at the same time to allow easy field handling for termination and splicing (during installation).

The cables designed for use at voltages over 49 kV require that the conductor and insulation shields be firmly bonded to the insulation in order to avoid any possibility of generating corona at interfaces; strippable insulation shields are not accepted. The AEIC specifications for cables rated for 59–138 kV require a volume resistivity of one order of magnitude lower than for the medium voltage cables.

The most important parameter that affects the resistivity is the amount of carbon black particles, and of secondary importance is the type and especially the shape of the carbon black particles. The susceptibility of the carbon black to oxidation may possibly lead to high resistivity of insulation shields. The type of polymer used in a semiconducting material is also an important parameter that can affect resistivity.

Processing conditions also significantly affect the lengths and numbers of continuous carbon black chains, therefore the semiconducting shields must be applied with a minimum of residual mechanical stress.

5.3.4. Jacketing Materials

Besides the metallic protective coverings (based on aluminum, copper and copper alloys, lead, steel, and zinc), the most popular jacketing materials are based on polymeric materials that can be either thermoplastic (with limited high temperature use) or thermosetting.

Polyethylene has been the most popular material for power cable jacketing due to its moisture resistance, abrasion resistance, toughness, and especially its relatively low cost. The original low density polyethylene (LDPE) has been replaced by high density polyethylene (HDPE), and by the newer linear low density polyethylene (LLDPE). The main reasons for this change are its superior flexibility and environmental stress–crack resistance as well as lower shrinkage tendency when compared to HDPE. Poly(vinyl chloride) (PVC) is still widely used where the flame retardancy and chemical resistance is important. Polyamides are limited to smaller size wires when the mechanical toughness is required. Polyurethanes are used for areas where the abrasion resistance is important. Thermoplastic elastomers (TPE) that are typically blends of thermoplastic polymers such as polypropylene with elastomers such as EPR, confer a combination of physical strength and flexibility (see Thermoplastic elastomers).

Ethylene vinyl acetate (EVA) polymers are used in thermoplastic and thermosetting jacketing compounds for applications that require flame retardancy combined with low smoke emission during the fire as well as the absence of halogen in the composition.

Thermosetting jackets are still used in applications that require high temperature rating. Polychloroprene, eg, Neoprene, was the first synthetic rubber used in wire and cable jackets due to its good resistance to sunlight, fire, and chemicals. Chlorosulfonated polyethylene (CSPE), eg, Hypalon, has replaced most Neoprene due to its superior heat, light, and moisture resistance combined with easier processibility. Chlorinated polyethylene, eg, Tyrin, is very similar to CSPE polymer except it does not contain inherent sulfur; therefore, the vulcanized CPE-based compounds have good colorability and also can be used in contact with bare copper cables such as in manufacturing heater cords. Jacket materials that contain nitrile rubber are used in compounded form with various ingredients in jacketing applications that require oil resistance or resistance to color fading of colored jackets. Sometimes the nitrile rubber-based elastomeric compounds contain PVC as a component in order to improve their ozone resistance (see Nitrile rubber,).

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