J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

CABLE INSULATION

There basically are two means by which electric power is transmitted and distributed—by overhead lines and underground cables. In the United States, most electric power still is transmitted by overhead lines between the generating plants and load areas. Only about 1% of the US transmission lines are underground. Most of these are in urban areas where overhead rights of way are unavailable or where local ordinances mandate undergrounding. On the other hand, underground cables are used more frequently in distribution systems, due to safety, security, reliability, and ordinance requirements.

Cable Construction

In general, three conditions must be met in cable design. First, a material of high electrical conductivity must be provided for transmitting the energy. Second, it must be insulated electrically from its return circuit. Third, the insulating material must be protected from mechanical injury, and if it is hygroscopic, it must be protected from moisture. Figure 1 shows a conceptual cable design. The two main components of a cable are the conductor and the insulation. The conductor and insulation shields are used to reduce electrical stresses at the metal-to-insulation boundaries. The cable sheath is used to carry the fault current and in some cable types also provides corrosion and moisture protection. Mechanical protection normally is provided by the cable jacket.

Conductor

Cable conductors normally are made of either electrolytically refined, tough-pitch copper or 1350 grade aluminum. Conductor material selection is based on the following considerations: (1) cable rating (ampacity), (2) mechanical strength and flexibility, (3) cable size and weight limitation, (4) chemical stability, and (5) cost. Copper conductor is either soft, medium-hard drawn, or hard drawn. Aluminum conductor is either hard, three-quarters hard, or half-hard. The conductivity of the conductor is often increased by annealing it. However, this also lowers its tensile strength.

Copper has the advantage of having the lower resistivity; however, it also has the higher cost and weight. The dc resistivities of copper and aluminum at 20°C are 1.72 $\mu\Omega$/cm and 2.82 $\mu\Omega$/cm, respectively. The electrical conductivity of aluminum is critically dependent upon minute chemical and metallurgical impurities, which are difficult to eliminate in practical production (1). Impurities such as Ti and Mn will cause a large decrease in the electrical conductivity of aluminum. The variation in the dc resistivity with temperature is different for copper and aluminum and is given in the following equation (2):

$$R_T(\mathrm{dc}) = R_\mathrm{r}\frac{T_\mathrm{r}+T}{T_\mathrm{r}+t}\ \mu\Omega/\mathrm{m} \qquad (1)$$

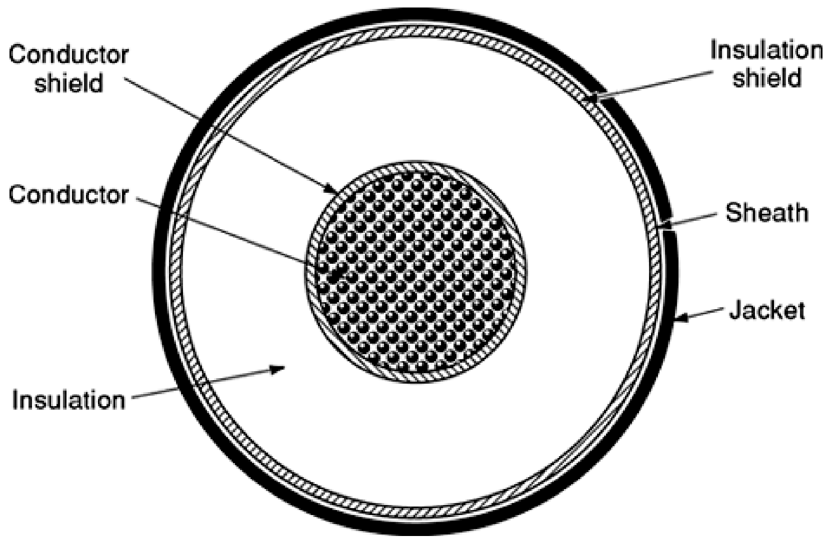

Fig. 1. Basic cross-section of a power cable.

where
R_T = resistance at temperature T, $\mu\Omega$/m
R_r = resistance at the reference temperature T_r, $\mu\Omega$/m
t = temperature of inferred zero resistance

In ac operation, the conductor dc resistance is increased by the skin and the proximity effect. The skin effect is the tendency of the ac current to crowd toward the surface of the conductor. The proximity effect is the distortion of current distribution due to the magnetic effects of other nearby currents. Other contributors to increases in the ac resistance are hysteresis and eddy-current losses in nearby ferromagnetic materials and induction losses in short-circuited nearby conducting materials. In general, the ac resistance of a conductor can be calculated using the following equations (2):

$$R(\text{ac}) = R(\text{dc}) \times K_1 \times K_2 \qquad (2)$$

where
$R(\text{dc})$ = dc resistance at 20°C, $\mu\Omega$/m
K_1 = ratio of dc resistance at the maximum permissible conductor temperature to that at 20°C
K_2 = ac/dc resistance ratio

Here

$$K_1 = 1 + \alpha\ (T_1 - 20) \qquad (3)$$

where
α = temperature coefficient of resistance
T_1 = maximum permissible conductor temperature

and

$$K_2 = 1 + (\lambda_s + \lambda_p) \qquad \text{for extruded oil-filled cable} \tag{4}$$

$$K_2 = 1 + \beta\ (\lambda_s + \lambda_p) \qquad \text{for pipe oil-filled cable} \tag{5}$$

where

λ_s = skin-effect coefficient
λ_p = proximity-effect coefficient
β = 1.7 and 2.0 for triangle and cradle arrangement, respectively

Both the skin-effect and proximity-effect coefficients depend on the conductor shape.

Conductors generally are stranded for flexibility. The shape of the cable conductor is either concentric-strand, compact-round, sector, hollow-core, or segmental. Round conductors are employed in nearly all extruded-dielectric cables and in smaller sizes of pipe-type cables. The conductor has concentric, compact, or compressed stranding. In the case of concentric-stranded conductor, as the conductor size increases, the skin effect and hence the ac/dc ratio increase. One way to reduce the skin effect is to apply a compact stranding, which decreases the conductor diameter for the same cable rating. Compact stranding may be advantageous where overall cable size is a limitation. Compression stranding provides a degree of size reduction between those of concentric and compact stranding.

Sector conductors are a variation of standard, stranded round conductor. 90° sector conductors often are used in four-conductor cables, while 120° sector conductors are primarily employed in three-phase solid-type and low- and medium-pressure gas-filed, paper-insulated, lead-covered (*PILC*) power cables. The latter have also found very limited application in extruded dielectric cables. Sector conductors permit a reduction in overall cable size for a given conductor size. All of the insulated conductors share a common outer covering.

Segmental conductors are made up of a number of individually stranded, shaped segments insulated from one another and cabled together to form a round, finished conductor. The segments usually are pre-spiraled during stranding, but sometimes are twisted together at the cable when the conductor is assembled. In North America, segmental conductor designs normally employ four segments and are widely used in pipe-type cables. The main advantage of segmenting is the reduction of the ac resistance.

Hollow-core conductor (annular conductor) is made of layers of concentric strands around a steel spiral core. It mainly is used in single-conductor, self-contained, oil-filled cables. Hollow-core conductor normally has a much lower ac/dc ratio than similar concentric conductor, due to the reduction of the skin effect resulting from the expanded diameter. The steel core is used to pressurize the cable internally.

Insulation

The cable insulation must withstand not only the steady-state ac voltage but also transient lighting and switching surge voltages. In general, there are three kinds of cable insulation: tape (laminar) insulation, solid (extruded) insulation, and compressed-gas insulation. Tape insulation consists of oil-impregnated paper. The paper normally is lapped over the cable conductor and then impregnated with insulating oil. Tape insulation may or may not be pressurized. For low- and medium-voltage applications, pressure is not normally applied over the insulation. However, transmission-class tape cables are pressurized with either oil or gas. Solid insulation (extruded insulation) usually consists of polymeric material extruded onto the conductor. Both thermoplastic and thermosetting materials are used for cable insulation. *Thermoplastic* polymers soften to essentially a liquid state with increasing temperature, and then return to their solid state unchanged on cooling. On the other hand, *thermosetting* materials tend to retain their dimensional stability with increasing temperature up to their decomposition temperature. Thermoplastic materials used in cable insulation include polyethylene (*PE*) and polyvinyl chloride (*PVC*). Thermosetting materials include cross-linked polyethylene (*XLPE*), butyl rubber, ethylene–propylene copolymer (*EPR*), ethylene–propylene–diene terpolymer (*EPDM*), isobutylene (*butyl*), and styrene butadiene rubber (*SBR*). Other types of thermosetting materials, mainly used in instrumentation and control cables, are methyl chlorosilane (silicone), tetrafluoroethylene (*TFE* or Teflon), fluorinated ethylene–propylene copolymer (*FEP*), ethylene tetrafluoroethylene (ETFE or Tefzel), chlorosulfonated polyethylene (Hypalon), chloroprene (Neoprene), and polyvinylidene fluoride (*PVDE*). Gas insulation mainly consists of compressed SF_6 gas, or a mixture of SF_6 and air or pure nitrogen.

The performance of insulation principally is determined by the insulation's maximum electric stress. In a coaxial arrangement, this occurs in the insulation near the conductor. For a cable insulation with a uniform permittivity distribution, the maximum electric stress is given in the following equation (1):

$$E_{\max} = \frac{V}{r\,\ln(R/r)} \tag{6}$$

Normally either the impulse or the ac voltage requirement of the system in which the cable is installed is used to determine the cable's insulation thickness. The insulation thickness of a taped cable is determined by the following equation:

$$t = r\,[\exp(V/rE) - 1] \tag{7}$$

where

r = radius of the conductor including its shield
V = specified impulse voltage of the cable (fixed for each voltage class)
E = maximum electric stress [Eq. (6)]

Two formulas are available for solid-insulation, extruded cables. One is based on the impulse withstand voltage,

$$t = \frac{\text{BIL} \times \alpha \times \beta}{E_1 + t_0} \tag{8}$$

and the other on the ac withstand voltage of the cable,

$$t = \frac{E}{\sqrt{3}} \times \frac{\gamma}{E_2} + t_0 \tag{9}$$

where

BIL = basic impulse level
α = degradation factor
β = temperature factor
t_0 = thickness of the conductor shield
E_1 = mean electric stress for the impulse breakdown voltage
E = system voltage

Table 1: Typical Insulation Thickness of Paper-Taped and Extruded Cables as a Function of the Operating Voltage

System	Insulation Thickness (mm)	
Voltage (kV)	Paper Cables	Extruded Cables
15	2.54/2.92	4.45/5.60
25	3.42	6.60/7.62
35	4.32	8.76/10.67
69	7.24	11.05/16.50
138	12.83	20.32/21.13
230	19.30	19.81/21.60
345	26.29	
500	34.00	

$\gamma =$ degradation factor
$E_2 =$ mean electric stress for ac breakdown voltage

Typical insulation thicknesses of paper-taped and extruded cables are given in Table 1 as a function of the operating voltage.

Shield

Shielding is the practice of confining the electric field of a cable to the insulation of the conductor. Shielding normally is applied for cables operating at a circuit voltage above 2 kV for single-conductor cables and 5 kV for multiconductor cables. Cable shielding is accomplished with conductor (strand) and insulation shields.

A conductor shield is used to preclude excessive voltage stresses on voids between the conductor and insulation. To be effective, it must adhere to or remain in intimate contact with the insulation under all conditions. The insulation shield of a cable is employed to serve a number of functions: (a) to confine the dielectric field within the cable, (b) to obtain symmetrical radial distribution of voltage stress within the dielectric, (c) to reduce the hazard of electric shock, and (d) to limit radio interference.

For taped cables, the shield normally consists of carbon paper, metallic paper, or aluminum tape; for extruded cable, of carbon paper, semiconducting cloth tape, semiconducting rubber in the form of plastic layer, or copper tape. In extruded cables, the semiconducting rubber is extruded over the conductor and insulation of the cable.

Sheath

A sheath is applied over the insulation shield to provide adequate short-circuit current-carrying capacity and to provide drainage of the capacitive charging of the cable. For low-pressure, self-contained, liquid-filled, taped cables, the sheath is most commonly made of extruded lead, or of corrugated aluminum, bronze, zinc, or copper. In this type of cables, the sheath also protects the cable from moisture ingress and external mechanical damage. The sheath of pipe cable is made from copper, tinned copper, zinc, or stainless steel tape.

Two types of sheathing usually are applied in extruded cables. One is the screen sheath, which is applied in distribution-class cable—copper or aluminum applied helically over the cable. The second type of sheathing is the solid sheath, made from either a copper tape, bronze, or extruded lead.

Jacket

The jacket is applied over the cable as the last layer. Its main function is to protect the cable from mechanical damage and also from moisture ingress. Jackets normally are made from insulating material extruded over the sheath of the cable. Chloroprene, PVC, and polyethylene are appropriate for this purpose.

Dielectric Constant and Losses

A cable is a long capacitor, and energy must be supplied through the conductor to charge and discharge that capacitor 60 times each second. That current returns through the cable shield. The charging current limits the length of the transmission line. For example, in 345 kV cable, all the current-carrying capability of the conductor will be utilized in charging purposes when the cable is 42 km in length. It is possible to compensate for the cable capacitance by the use of shunt reactors; however, these devices are expensive and occupy costly real estate. The longest ac underground circuit used in the 230 kV to 345 kV voltage classes is about 30 km long. The cable capacitance and charging current are given respectively by (1,3),

$$c = \frac{0.0241\,\varepsilon}{\log_{10}(D_\mathrm{i}/D_\mathrm{c})} \times 10^{-3}\ \mu\mathrm{F/m} \tag{10}$$

and

$$I_\mathrm{c} = \frac{2\pi f c\, E_0}{304.8}\ \mu\mathrm{VA/m} \tag{11}$$

where

ϵ = dielectric constant
D_i = outer diameter of the insulation, mm
D_c = outer diameter of the conductor including shield material, mm
f = frequency, Hz
E_0 = ac line-to-ground voltage, V

The charging current calculated in Eq. (11) leads the system voltage by a 90° phase angle. However, all practical dielectric materials are *lossy*. The loss, which can be represented by a small resistance in series with the cable capacitor, means that the charging current is not exactly in quadrature with the voltage but lies at an angle θ with respect to the voltage, or an angle δ with respect to the total current, as shown in Fig. 2.

The power dissipation per phase, or dielectric loss, W_d, is given by the voltage times the in-phase component of the charging current I_c (4):

$$W_\mathrm{d} = E_0\, I_\mathrm{c} \tan\delta\ \mathrm{W/m} \tag{12}$$

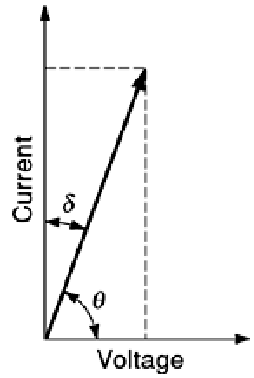

Fig. 2. Power and dissipation factors for a dielectric material.

Table 2: Typical Values of ε, tan δ, and DLF for Various Insulation Types

Type of Insulation	ε	tan δ	DLF
Impregnated paper	3.5	0.0023	0.00805
Impreganted laminated paper–polypropylene	2.7	0.0007	0.00189
Crosslinked polyethylene (XLPE)	2.3	0.0001	0.00023
High-density polythylene (HDPE)	2.3	0.0001	0.00023
Ethylene–propylene rubber (EPR)	2.8	0.0035	0.00980
Electronegative gas or spacer	1	0	0

Thus, apart from the geometry, the insulation parameters that determine the dielectric loss are its dielectric constant (permitivity) ϵ and its dissipation factor tan δ. The product of tan δ and ϵ is known as the dielectric loss factor (*DLF*). The lower the DLF, the better the insulation is. Table 2 shows representative data for ϵ, tan δ, and DLF for various insulation types (1).

For small loss angles, which usually is the case for insulating materials, the dissipation factor tan δ is essentially the same as the dielectric power factor cos θ. Therefore, the dissipation factor often is called the "power factor".

The dielectric loss also is affected by the cable dimensions as follows:

$$W_{\rm d} = \frac{0.009055\, E_0{}^2 \varepsilon \tan \delta}{\log_{10}(D_{\rm i}/D_{\rm c})}\ {\rm W/m} \qquad (13)$$

where E_0, $D_{\rm i}$, and $D_{\rm c}$ are defined in Eqs. (10) and (11).

For impregnated-paper insulation, the dielectric losses are generally negligible below 69 kV. However, they account for about one-third the losses at 345 kV, and about half the losses at 500 kV. For laminar polypropylene insulation, dielectric losses are reduced to less than 10% of the total at 345 kV, and slightly more than 10% at 500 kV. On the other hand, dielectric losses for 138 kV XLPE insulation account for less than 1% of the total.

Cable Types

In general, cables can be divided into two groups: power cables, and control and instrumentation cables. Control and instrumentation cables are rated at either 300 V or 600 V. They are either two-conductor or multiconductor. On the other hand, power cables are used to transmit and distribute electric power. They are either single-conductor cables, so that three are needed to complete a circuit, or three-conductor cables (triplex cables).

Cables also are classified by their operating voltages as low-, medium-, and high-voltage cables. Low-voltage cables generally are rated at 600 V, regardless of the voltage actually used. The selection of these cables is oriented more toward physical than toward electrical-service requirements. Control and instrumentation cables, secondary cables, and building cables normally are classified as low-voltage cables.

Medium-voltage cables are rated from 2001 V to 35 kV. They generally are used in the distribution and subtransmission systems, primarily for interconnection between substations. High-voltage cables are used at transmission-class voltages (115 kV to 765 kV). Transmission cables either can be dc or ac. Power cables are classified according to their type of insulation as paper-taped (laminar), extruded (solid), or compressed-gas cables

Oil-Impregnated Paper Taped Cables. Oil-impregnated paper tape (laminar insulation) is the most common cable insulation used for bulk power transmission and distribution. It is a composite of paper and oil. Impregnated paper insulation consists of multiple layers of paper tapes, each tape from 50 μm to 200 μm in thickness, wrapped helically around the conductor. The majority of paper used for power cables is kraft paper, made from coniferous wood such as pine, spruce, and cedar (5,6). Such wood is composed of about 40% cellulose, 30% hemicellulose, and 30% lignin.

Cellulose, which is the main component of paper, is a carbohydrate, specifically a polysaccharide whose base sugar unit is $C_6H_{10}O_5$. The number of units in the chain-type molecule is called its degree of polymerization (*DP*). The individual molecular chains tend to align themselves into bundles (microfibrils), which consist of crystalline regions separated by amorphous regions. Thousands of microfibrils combine into a long tubular structure called a fiber. Many properties of paper are improved by making the paper with cellulose of long chain lengths (high DP). This type of structure, called *α-cellulose*, may have a DP as high as 10,000. On the other hand, β- and γ-cellulose have shorter chain structures.

Hemicellulose is a nonfibrous polysaccharide material, with a shorter chains than cellulose. Its DP is in the range of 150. Hemicellulose can contribute to interfiber strength, but is also quite lossy.

Lignin is an amorphous polymer that binds the cellulose fibers and hemicellulose into a strong wood structure.

For ultrahigh-voltage (*UHV*) laminar cables, paper made of synthetic fiber such as polypropylene also is used. The main advantage of the polypropylene laminar paper (*PPLP*) insulation over kraft paper insulation is its lower dielectric loss.

The laminar papers are impregnated with high-viscosity insulating oil after they are applied over the cable conductors. Insulating oil for power cable should retain excellent electrical properties for a long time and also should possess the correct viscosity. The viscosity of insulating oil depends on the type of cable (7). Figure 3 shows a standard criterion for insulating oils used in solid-type laminar, oil-filled paper, and pipe-type paper insulation. The cable insulating oil is either mineral oil or alkylbenzene synthetic oil.

In general, there are three types of laminar cables: solid paper cables, oil-filled cables, and pipe cables. Solid cables are used for voltages ranging from 5 kV to 69 kV, while oil-filled and pipe cables are used for 46 kV to 500 kV. These cables are described in the following sections.

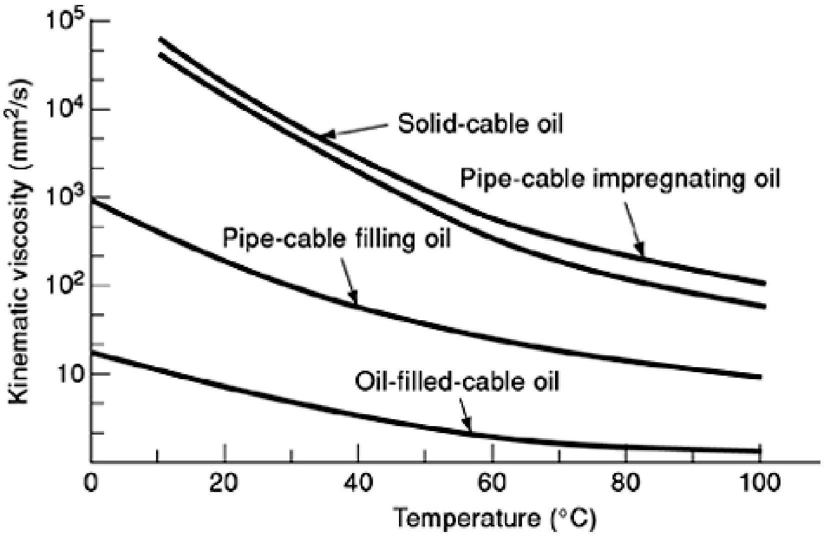

Fig. 3. Viscosity criteria for cable oil.

Solid-Type Paper Cable. Solid-type paper cables basically consist of paper insulation that is applied over the conductor, dried, and then impregnated with a viscous oil and hermetically sealed in a lead or lead-alloy sheath. These cables are used in distribution and subtransmission underground systems up to 69 kV. They either are single-conductor or three-conductor cables. Single-conductor cable usually is employed where heavy loads are to be handled, since it can be made in standard size up to 1267 mm^2 [2500 million circular mils (MCM)]. It also is desired where phase isolation is required.

Single-conductor solid-type paper cable consists of either a concentric round or a compact concentric round conductor, a carbon black strand shield, a oil-impregnated paper insulation, carbon black insulation shield, a lead sheath, and a protective jacket; see Fig. 4.

There are two designs of three-conductor solid-type paper cables—belted and shielded cables. *Belted* cables have part of the insulation applied on each conductor, and then the three conductors are assembled and the rest of the insulation applied overall as a belt; see Fig. 5(a). Belted cables are used up to 15 kV. In *shielded* cables, also called H-type, all the insulation is applied on each conductor and a ground shield is applied over each conductor before assembling; see Fig. 5(b). They are used for voltages up to 69 kV. Both designs are made with either round or sector conductors.

In addition to the lead sheath, solid cables can be obtained with a variety of protective jackets, including the following:

(1) Coverings such as neoprene, polyethylene, PVC and chloroprene are used for corrosion resistance.
(2) Armor wire is used where heavy mechanical protection and longitudinal strength are desired. Galvanized steel, aluminum, copper, and bronze wires are applied over heavy cushioning of saturated jute.
(3) Jute, flat steel tapes, and more jute are applied for direct burial in the ground.

Self-Contained Fluid-Filled Cable. Self-contained fluid-filled (*SCFF*) cables are used for power transmission at voltages of 69 kV up to 500 kV. SCFF cable is pressurized internally with a dielectric liquid through a hollow core at the center of the conductor. Earlier, low-pressure oil-filled (*LPOF*) cables were pressurized to 17.25 kPa to 34.5 kPa; newer designs with reinforced sheath operate at 517 kPa. The SCFF cable operates on

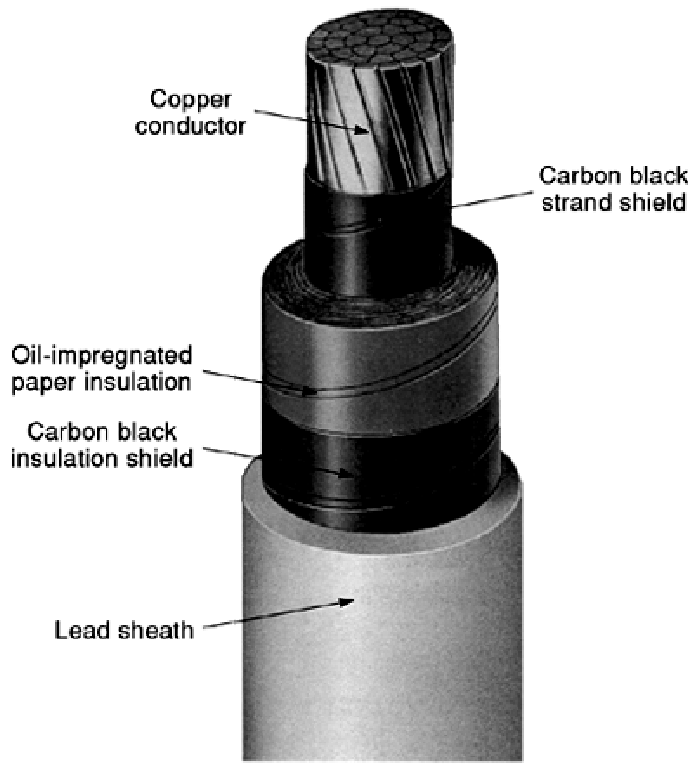

Fig. 4. Single-conductor solid cables (courtesy of Okonite Cable Company).

the principle of complete exclusion of gas. Sealed reservoirs allow low-viscosity oil to flow in and out as the volume changes with operating temperature. This suppresses ionization of trapped gas. Pressurizing the fluid also impedes moisture ingress, if there is a leak in the sheath.

The most common design is single-conductor cable with a 1.25 cm to 1.905 cm hollow core for oil feed; see Fig. 6. The cable is insulated with a high-quality tape insulation and is hermetically sealed with metallic sheath such as extruded lead or aluminum for pressure retention and for mechanical and moisture protection. In the United States, the sheath consists of either single or double lead. For higher-pressure operation, the lead sheath often is reinforced with nonmagnetic tapes such as stainless steel tapes. Corrugated aluminum and sometimes copper sheath are most commonly used outside the United States. Both lead and aluminum sheaths corrode with time. Therefore, most cables today are installed with a plastic jacket such as polyethylene or PVC.

High-quality dielectric fluid is used to impregnate the insulation and to fill the cable core. Mineral oil was used through the 1960s; such cables are called self-contained oil-filled (*SCOF*). Synthetic alkylbenzenes have been used since then in SCFF cables.

Three-conductor oil-filled cables are in service at 69 kV with conductor sizes up to 329.42 mm^2 (650 MCM). In this construction, oil channels are provided in each intersite, consisting of helical tubes from steel strip. Three-conductor cables with larger conductors are too heavy and rigid for convenient installation and operation.

Low-Pressure Gas Cable. The low-pressure gas cable is made by mass impregnation as in solid cable, but prior to removal from the impregnating tank, the oil is pumped out and the cable is filled with nitrogen gas

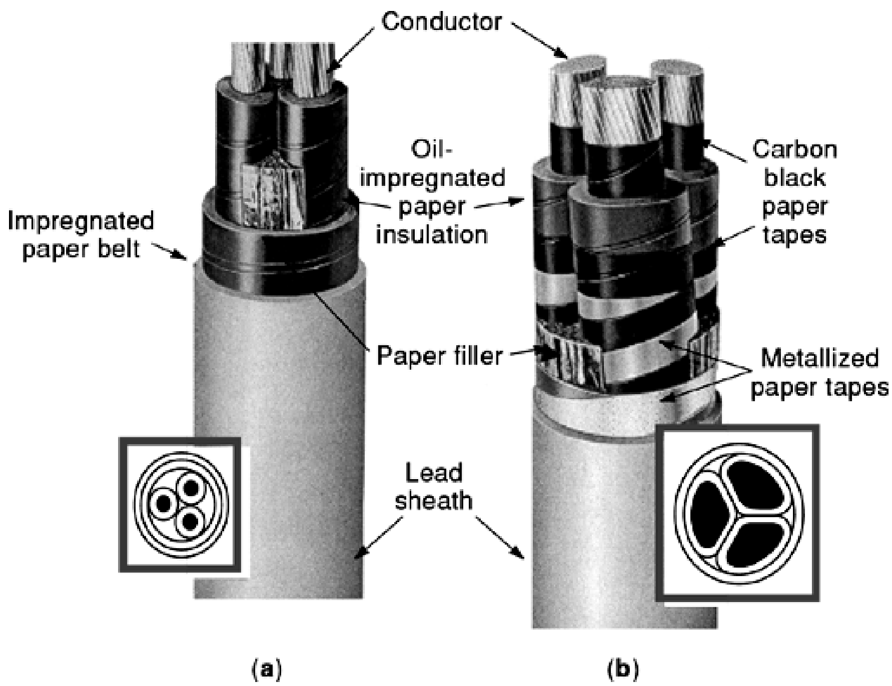

Fig. 5. Three-conductor solid cables: (a) belted type, (b) H-type.

while still hot. Tubes are provided in the interstices of the cable to permit feeding gas from the termination and joints. One tube is made from solid copper, while the other two are steel spiral tubes. The copper tube provides positive gas flow throughout the entire length of the circuit. It is broken at each joint to feed gas into the joint, and from there it feeds back into the open spiral tubes.

Low-pressure gas cables are used for steep grades, because little oil drainage will occur, since the cable already has been drained during manufacture at a temperature equal to the maximum operating temperature of the cable.

Pipe Cable. Pipe cable consists of three insulated conductors installed in a steel pipe (Fig. 7. The free volume in the pipe is filled with either insulating fluid or gas at 1.378 MPa pressure. High-pressure gas-filled (*HPGF*) cables are used up to 138 kV, and high-pressure fluid-filled cables (*HPFF*) are in use up to 500 kV.

The cable insulation material for pipe cable is either high-quality kraft paper or (recently) a polypropylene laminated paper. The insulating paper is impregnated with mineral or synthetic fluid, alkylbenzenes, or polybutenes. The above three fluids also are used to pressurize the HPFF cables. For HPGF cables, nitrogen normally is used to pressurize the cable. In pipe-type cable, skidwires are applied helically around the individual cables to reduce friction and provide cable protection during installation. Figure 8 shows a 115 kV, 1.521 mm^2 (3000 kCM) HPGF cable.

Extruded Cables. Extruded dielectric cables use polymer material, extruded over the cable conductor, as the insulation. Polymer materials used in extruded cables include butyl rubber, ethylene-propylene rubber, low- and high-density polyethylene, and cross-linked polyethylene.

High-density polyethylene is produced by polymerizing ethylene gas into the material at relatively low pressure (0.1 MPa to 10 MPa), while low-density polyethylene is polymerized thermally under high pressure (100 MPa to 200 MPa) (8,9). Polyethylene exhibits an extremely low dissipation factor, high volume resistivity, and high breakdown strength in contrast to other insulating materials. However, polyethylene is vulnerable

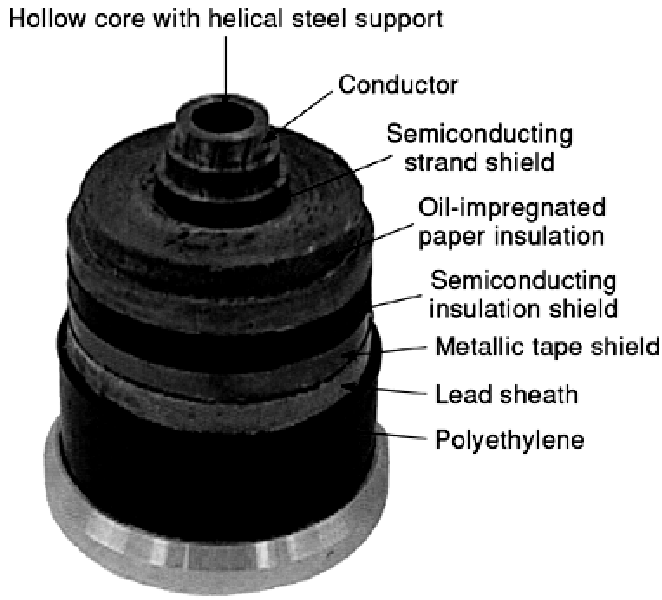

Fig. 6. Self-contained oil-filled cable (courtesy of Pirelli Cable Company).

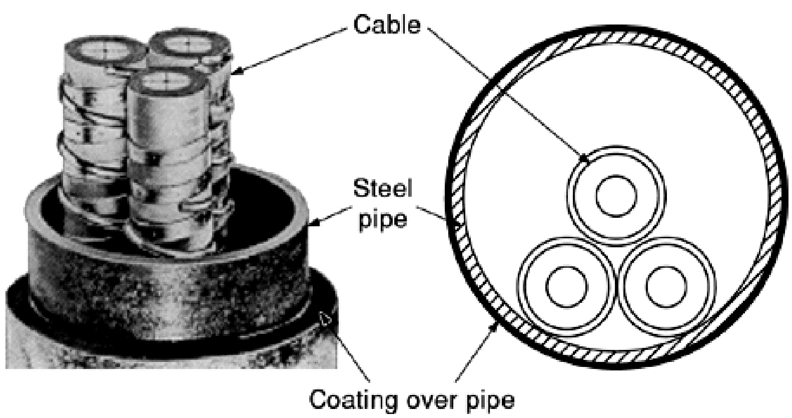

Fig. 7. Pipe-type cable (courtesy of Okonite Cable Company).

to environmental temperatures above 75°C and has a critical softening point between 105°C and 115°C. The thermal stability and performance of polyethylene is enhanced greatly by cross-linking. Polyethylene can be cross-linked either by radiation or by chemical reaction. In today's cable industry, polyethylene is cross-linked with the aid of peroxide (such as di-α-cumyl peroxide) under high temperatures and pressure.

Butyl rubber is a copolymer of isobutylene and isoprene. Ethylene propylene rubber (EPR) is a copolymer of ethylene and propylene. EPR cable insulating material contains seven to nine chemical ingredients, of which EPR constitutes approximately 45% to 50% by weight (9). The EPR backbone of the insulation determines its basic physical and electrical properties. The mineral filler normally constitutes from 25% to 35% of the insulating material and enhances its physical properties. Other agents include antioxidant, cross-linking, and processing agents.

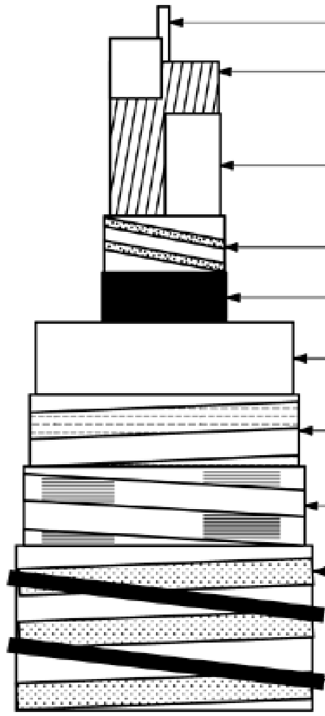

Fig. 8. 115 kV high-pressure gas-filled cable (courtesy of Pirelli Cable Company).

Extruded cables have superseded laminar cables for low and medium voltages and are replacing high-voltage and extra high-voltage paper-tape cables. Today, extruded cables are in use up to 500 kV.

Distribution-Class Extruded Cables. The basic construction of distribution-class extruded cables is as follows:

(1) The *conductor* is either copper or aluminum concentric round. In low-voltage cable, solid aluminum wire also is used.
(2) The *strand shield* consists of either a semiconducting tape or an extruded semiconducting layer.
(3) The *insulation* consists of EPR, PE, or XLPE.
(4) The *insulation shield* consists of either a semiconducting tape or an extruded semiconducting layer.
(5) The *metallic shield* in extruded cables is either a concentric copper or aluminum wire or screen, or copper tapes applied helically.
(6) *Water-impervious sheaths* are provided with some cables operating at 25 kV and above. They consist of corrugated metal such as bronze. At lower voltages, a plastic moisture barrier is sometimes added underneath the covering jacket.
(7) The *covering jacket* is made of PVC or PE.

In some types of distribution-class cables, the concentric shield wire is applied over the covering jacket, and in a few other types it is incorporated in the jacket. Figure 9 shows several distribution-class extruded cables.

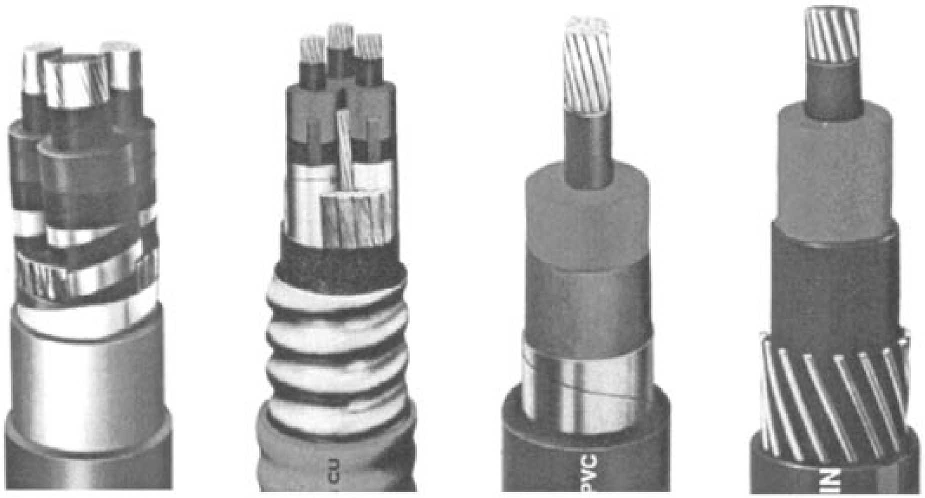

Fig. 9. Several distribution-class extruded cables (courtesy of Okonite Cable company).

Transmission-Class Extruded Cables. Conductors used in transmission-class extruded cables are stranded round copper or aluminum. However, the conductor is segmental for conductor size larger than 633.5 mm^2 (1250 kCM). The conductor shield consists of two components. A semiconducting bedding is wrapped over the conductor to prevent the semiconducting shield from entering the strand interstices during extrusion. The insulation shield also is an extruded semiconducting layer. The conductor shield, the insulation, and the insulation shield are extruded simultaneously in a triple extrusion process. In addition to the extruded semiconducting insulation shield, copper wires, copper tapes, or a combination of the two are applied over the insulation shield. This metallic shield carries the charging current and any fault current that may occur.

To prevent the ingress of water, sheaths made of lead, corrugated aluminum, or metal foils often are applied over the metallic shield. The sheath normally is covered by PVC or PE jackets to prevent corrosion and also to provide mechanical protection. Figure 10 shows several transmission-class extruded cables.

Submarine Cables. The basic design of submarine cables is similar to that of conventional cables, except for their exterior mechanical design, sheath requirements, and bonding methods. Submarine cables are equipped with wire armoring to protect them from external mechanical damage and to provide mechanical strength to allow for installation and retrieval. A hermetic seal against water is provided by means of a lead sheath and metallic tape reinforcement. Submarine cables also are designed to prevent corrosion of the exterior, especially the armor wire. Figure 11 shows the typical construction of a submarine cable.

Submarine cables either can be tape-insulated or extruded dielectric cables. However, the bulk of the present submarine cable system consists of paper-taped cables such as pipe cables, self-contained fluid-filled cables (Fig. 12), solid-type paper cables, and gas-filled pressurized cables.

Dc Cables. Unlike ac cables, dc transmission cables bear no charging current and no dielectric losses. This permits dc power transmission to be considered over long distances without compensation and with reduced losses. The insulation of ac cables is designed to withstand the peak voltage. In contrast, dc cables are designed to withstand the average dc voltage. Therefore, the design electric field of dc insulation, in principle, can be selected as high as times that of ac insulation.

Most dc cable applications have been for underwater installation. All type of cables developed for ac application can be utilized for dc transmission. However, most of the present dc cables are paper-insulated cables,

Fig. 10. Several transmission-class extruded cables (courtesy of Mitsubishi Cable Industries, Ltd.).

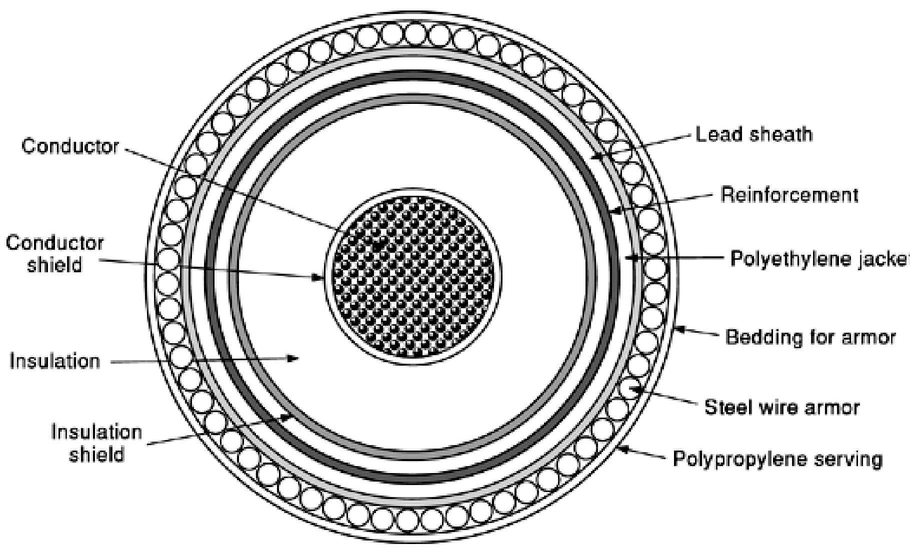

Fig. 11. Typical construction of a submarine cable.

specifically solid-type, gas-filled, and SCFF cables. Space-charge buildup in extruded cables has prevented them from being considered for dc application so far.

Compressed-Gas Insulated Cables. Compressed-gas insulated (*CGI*) cables evolved from the metal-enclosed bus duct. They use the gas as the main insulating medium. Basically, they consist of coaxial metal tubes isolated with moderate-pressure gas, typically SF_6 or SF_6–air or –nitrogen mixtures. There are two main designs of CGI cables: one comprises three identical isolated cables: the other has three conductors enclosed in

Fig. 12. SCFF submarine cable (courtesy of Pirelli Cable Company).

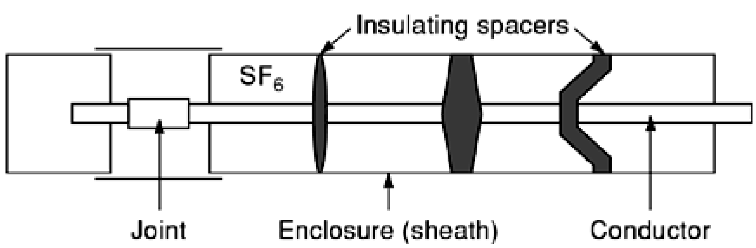

Fig. 13. Typical section of isolated phase of CGI cable.

one pipe. The isolated phase consists of an inner tube, which serves as the line potential, and an outer tube to provide electrical sheath. This also serves as an enclosure containing the insulating gas at a moderate pressure (344.7 kPa). The inner tube is supported by epoxy-resin solid insulating spacers. CGI cables are manufactured in modular components, which can be assembled readily into permanent systems. Figure 13 shows a typical section of isolated phase of CGI cable.

Special Cables. Special cables are products designed for applications in which exposure to high temperatures, radiation, moisture, corrosive atmospheres, or other harsh environmental hazards are anticipated. Such installations include nuclear power plants, petrochemical industries, steel and glass fabrications, pulp and paper manufacturing, mass-transit systems (railroads), waste-to-energy facilities, marine vessels, aircraft, and mining.

Cables used in nuclear power plants are required to have a 40 year life expectancy under normal operating conditions. They also must operate during a loss-of-coolant accident and should be flame-retardant. Nuclear facilities' cables are exposed to radiation, heat, and water vapor. These effects greatly degrade the insulation of conventional cables.

Both insulation and jacket either are made of antiradiation material or, often, of material containing antiradiation agents. Saturated polymers such as EPR, chlorosulfonated polyethylene (Hypalon) and chlorinated polyethylene (Chloroprene) seem best suited for antiradiation purposes. Silicon and ethylene tetrafluoroethylene (Tefzel) also are used for the insulation and jacket, especially in high-temperature applications. Nuclear cables often are equipped with a moisture barrier made of polytetrafluoroethylene (*PTFE*). For high-temperature applications, reinforced mica tapes and PTFE coated with glass braid are used as an overall jacket.

Cables for the oil, gas, and petrochemical industries often are installed in ground heavily contaminated with hydrocarbons. Unless special precautions are taken, these hydrocarbons will attack the cable and may lead to eventual electrical failure. Cables for such installations have extruded lead alloy sheaths to protect the insulated cores from hydrocarbon attack.

Electric cables seldom cause fires. However, once on fire, they can contribute significantly to the dangers. Cables containing traditional PVC materials can emit dense black smoke and harmful halogen gases (e.g., hydrochloric acid), which are dangerous to people and damaging to equipment, especially in confined areas. Standard power cables often are sheathed with materials to enhance their fire performance.

Splices (Joints) and Terminations

Splices are required to joins cable sections together where the circuit's length exceeds the allowable continuous cable lengths, which are limited by manufacturing, shipping, or installation considerations. Splices either can be normal splice, T splice, insulation splice, or stop and semistop joints. Normal joints are used to splice cables of the same kind in a straight line, while T joints are used to branch cables. Insulation joints are used to isolate the sheaths of two cable sections from each other. This kind of joint normally is used in a cross-bonding system. Stop splices are used in the long circuit of fluid-filled cables for oil feeding and maintenance purposes. They connect cables electrically and block oil flow. On the other hand, semistop joints are utilized in pipe-type cables. They allow oil or gas to flow through a bybass valve in normal operation, but the flow can be stopped when necessary.

Basically, a cable splice is made of four components. The first one is the connection of the cable conductors to each other, either through a compression sleeve or by welding. The second component is the tapering down of the insulation on each cable to some predetermined dimensions. This is called *stepping* in laminar cables, and *penciling* in extruded cables. The third component is the stress-relief cone of the joint, and the fourth is the casing of the joint.

Types of cable joints are the hand-taped joint, the field mold joint, the premolded (prefabricated joint), the semi-premolded joint, and the back-to-back *GIS* joint. Laminar cables normally use hand-taped or premolded joints, while all splice types are applicable to extruded cables.

Terminations, which are required where cables are connected to overhead lines or electric apparatus, are designed to possess the same integrity as their associated cables. The three components of any termination are the conductor leadout rod, the insulation-reinforcing layer with a stress cone, and the casing (porcelain, except in distribution cables, where polymer is aggressively replacing porcelain). Cable terminations are designed to eliminate stress concentration resulting from the ending of cable insulation and shield. Using a stress cone effectively separates the shield from the insulation surface and distributes the stress. All cable terminations, independently of operation voltage, use a stress-control cone. However, for subtransmission and transmission terminations at 60 kV and up, in addition to a stress cone, a secondary stress-relief control unit is necessary to distribute dielectric stress over the length of the porcelain insulator. A porcelain stress-control unit is utilized in conventional, nongraded terminations for 69 kV to 161 kV. Such a unit cannot be used at higher voltage, due to excessive internal-diameter requirements. In these cases capacitance-graded terminations are used. These can be coaxial type or doughnut type. Coaxial terminations consist of a series of cylindrical electrodes, coaxial with the cable, formed by intercalating aluminum foils between the paper layers, while doughnut terminations consist of a stack of toroidal capacitors connected in parallel.

Cable Aging Processes

Paper insulation thermally decomposes on exposure to high temperatures. The degradation rate is a function of temperature, and the extent of the degradation depends on the exposure time. Low-temperature degradation in solids in the absence of oxygen is generally known as *thermolysis*, while high-temperature degradation under the same conditions is known as *pyrolysis*. Through chemical degradation, paper releases carbon oxides and water. The latter will be absorbed by the paper, increasing its dissipation factor and hence increasing the dielectric losses. This situation also can lead to a reduction in the dielectric breakdown voltage of the paper. The localized heat generated from the increase in the dielectric losses will further accelerate the paper's chemical degradation. As paper releases hydrogen and oxygen in oxygenated compounds, its composition is enriched in carbon (browning and carbonization). The browning of paper will further increase its dissipation factor and reduce its dielectric strength.

To prevent thermal aging in paper cables, two requirements have to be met. First, limit the conductor load, which generates heat due to ohmic losses. Secondly, prevent moisture contamination. Paper cables have an operation temperature limit of 85°C, with allowance to 100°C or 105°C for short emergency periods. Paper-insulated cables are well protected against moisture ingress.

Chemical degradation in paper also can be caused by partial discharges (*PD*s) (10,11). Partial discharges can be initiated in insulation voids. Voids usually are present in paper cables at the butt spaces and in tape overlap. Voids also can be introduced during the cable taping process as the result of wrinkling or tearing of tapes, or collapsing of tapes into adjacent butt spaces. These voids are filled with the insulating fluid during impregnation and are not expected to cause PDs at normal conditions. However, as oil migrates during load cycling, these voids can become depleted of impregnation fluid. Voids also can be generated in cable at the butt space (tape overlap) as the result of excessive cable bending during installation and mechanical movement of the cable. Excessive bending also can cause PDs through shifting of shield tapes. Although the paper insulation resists the ion bombardment and related events associated with PDs, the impregnating oil does not. PDs induce oil waxing, which creates further voids, increasing the PD intensity. Consequently, heat generated from PD activity can chemically degrade the paper, leading to local thermal instability and hot spots. Such degradation by PDs is more severe if the voids occur near the cable conductor. This can cause cable failure much faster than PD activity elsewhere in the insulation.

Solid cables have the highest failure rate among the three types of paper cables, because a solid cable operates at ambient pressure. As the cable is heated during daily load cycles, the expansion of the impregnating fluid forces it outwards through the paper laminations. When the cable subsequently cools, there is no pressure available to force the impregnating fluid back through the laminated wall to maintain impregnation. Voids are formed in the dielectric insulation at the butt spaces and tape overlaps. The load cycling also causes a permanent distension of the lead sheath, and on subsequent cooling the pressure in the cable falls below atmospheric pressure. Moreover, in addition to the radial movement of impregnating fluid, there will be, over a period of time, a tendency for longitudinal displacement of the fluid in inclined sections of the cable. PDs (local ionization) in these voids can lead to cable failure. In solid cables this failure mechanism is slow and contributes to about 20% of all cable failures. The other 80% are caused mainly by corrosion and moisture ingress through the lead sheath. The presence of moisture in the cable insulation increases dielectric losses, causing local thermal degradation. Cable failure by this mechanism takes place rather rapidly.

The above two failure mechanisms are unlikely to occur in SCFF or pipe-type cables, as these cables are maintained under positive pressure. If voids are generated during load cycling, the high pressure of the fluid or gas will force itself into these voids (12,13). Therefore, under normal operating pressure, these voids always are filled with insulating fluid or high-pressure gas. Dielectric strengths of high-pressure fluids and gases are sufficiently high. The positive pressure of impregnation fluid in the cable prevents moisture from entering the cable in case of a puncture to the metal sheath of SCFF cables, or the pipe of pipe cables.

Failure in SCFF cables is attributed to excessive loading of the cable over a long time or to sheath corrosion. Leaks can lead to a pressure drop and cable failure. As the cable pressure drops, the expansion and contraction of the cable during daily load cycling produces voids in the butt spaces and tape overlaps. PDs in these voids will be more severe than those in solid cables, as the stress is higher in SCFF cables and can lead to cable failure in a short time.

Pipe cables rarely fail within the cable length. Cable failures are more often observed at joints or terminations, due to cable movement caused by physical stresses. The very few failures reported away from cable splices can be attributed to damage to the cable during pulling, accidental oil leaks, or hot spots induced by proximity to steam lines.

The aging mechanism of extruded cables is different from that of impregnated-paper-insulated cables. Extruded cables are insulated with polymer materials. Polymer degradation occurs either by *scission* reaction or by *crosslink* (or *growth*) reaction. Scission reaction is the breakup of the long, chainlike molecules, while crosslink reaction occurs when many chains join at many points, resulting in an extensive insoluble network. The latter often makes the material become brittle and crack. Several fundamental types of degradation have been recognized. The most important processes that affect polymers in service are thermal, oxidative, and electric stress degradation.

Thermal degradation in the absence of oxygen usually degrades the polymer to lower-molecular-weight materials. Occasionally crosslinking also occurs (14,15). The breakup of the polymer chain is caused by two mechanism: random chain scission and chain depolymerization. The initial break in chain may take place anywhere along the molecule with equal probability, producing two polymer radicals. The location of the next scission event will depend upon which mechanism is operative. When chain scission occurs randomly, the next scission may take place at any link producing products with a mixture of large and small molecules. However, in chain depolymerization, once initiation has occurred, chain links no longer have an equal probability of breaking. Rather, scission will always occur at the position of the last link, near a free radical, resulting in large amounts of monomer.

Oxidative degradation in polymer normally does not occur until a certain period of time has elapsed (16,17). During this time, oxygen is absorbed by the polymer, and the rate at which this occurs depends upon the temperature, the polymer structure, the degree of crystallinity, and the extent of crosslinking. In order for the polymer to oxidize, polymer free radicals have to form. Radiation, heat, mechanical forces, or very reactive species such as atomic oxygen and ozone, which often are generated by PDs, promote such a reaction. Once the radical has formed, molecular oxygen then may combine with it to form peroxides and hydroperoxides.

Oxidation of long-chain polymer molecules usually occurs with an attack upon a tertiary carbon and abstraction of its H atom (16). This results in a chain scission, and it represents the first step in degradation. After the first event, the reaction has many varieties, liberates a range of low-molecular-weight materials, and is autocatalytic, so that it accelerates with time. Oxidation in underground cable insulation is not a rapid process, because the concentration of oxygen is limited. Moreover, antioxidant agents are added to the cable insulation while it is being formed.

Electric stresses in polymer cause a phenomenon called *treeing* (18,19). Generally, trees are classified into two types: water trees and electrical trees. In general, there are two distinct time periods in treeing; the first is an initiation period, and the second is a propagation period, during which treelike figures grow in the insulation. Both electrical and water trees usually initiate at imperfections at the interface or in the bulk of the insulation under the stress of an electric field. In the case of the water tree, water must be present, too. Imperfections that initiate trees can be summarized as follows (20):

(1) Microvoids inherently induced during the curing of polymer, especially by steam-curing method
(2) Defects in the core screen
(3) Cavities due to gas formation and shrinkage in insulation
(4) Inclusion of foreign particles that separate gases, mainly due to moisture in the particles
(5) Bubbles caused by gas evolution in the conductive screen
(6) Cavities caused by field emission from microscopic protrusions at the semiconducting layers
(7) Small cavities at tips of foreign particles, asperities, or needles, due to differential thermal expansion of the polymer and the metal
(8) Cracks produce by mechanical fatigues (high Maxwell compressive forces in the dielectric, caused by the high electric fields at local excrescencies when ac voltage is applied, produce mechanical fatigue cracking in the polymer)
(9) Cracks and brittleness produced by thermal stresses
(10) Cavities induced by charge injection and by extraction

Electrical trees propagate through the occurrence of PD, which erodes the cavity's inner layers that produce it (21,22). The bombardment of the high- and low-energy ions produced by PD damages the polymer insulation, as it causes scission reactions. Photoemission (ultraviolet light) from the PD my change the chemical structure of the insulation. The other effect of PD is the decomposition of polymer through chemical reaction with activated oxygen (excited oxygen molecules) or atoms generated by PD. This reaction occurs at the inner surface material of the cavity, which oxidizes and produces mainly water and carbon dioxide, and in turn erodes.

The shape of an electrical tree is determined by the intensity of the field enhancement at the site where it is generated. Higher local fields produces bush-type trees, and lower fields produce branched trees. Cable failure occurs when the branches of the tree bridge the insulation.

Water trees propagate by noninterconnected microvoids partly filled with water. The propagation mechanisms involve electromechanical forces, diffusion of water, and chemical action, including oxidation (23,24). Water trees can be either broccoli or bowtie types. Broccoli-type trees grow from the conductor or the shield of the cable, while bowtie-type trees originate in the bulk of the insulation. Water trees by themselves do not cause breakdown. However, if the tree is partly filled with water, an electrical tree will originate at its tip and possibly cause insulation failure. Water trees are more pronounced in medium-voltage cables, as these cables often lack water barriers.

Cable Testing

To ensure high reliability, cables are subjected to a variety of tests before being installed and during operation. In general, cable testing can be conveniently classified into five categories:

(1) Development Tests These tests often are made by the cable manufacturer. They include basic laboratory tests such as ac breakdown, dissipation factor, impulse voltage, PD, and mechanical bending. The objective of these tests is to compare the results with those for similar equipment or with industry standards.
(2) Qualification Tests These tests are made to ensure that a particular cable and its associated manufacturing processes meet industry standards. These tests often are performed in accordance with standards set by

AEIC or *IEC*. Qualification tests include mechanical bending, dissipation factor, ionization, high-voltage time, impulse withstand, and PD tests. They also may include other tests, which are parts of a purchase agreement, such as load-cycling tests.

(3) Installation (Proof) Tests These tests are made after the installation of cable and prior to service. The objective is to confirm that the cable is installed properly and also to confirm if the cable has met the requirements agreed upon between the manufacturer and the purchaser. They include high-voltage withstand tests such as dc, ac, or ultralow-frequency (*ULF*) tests.

(4) Maintenance Tests These tests are made to prevent cable-system failure during operation. They include ac, dc, and ULF withstand tests, PD tests, dissolved gas analysis (*DGA*), dissipation-factor tests, and insulation resistance tests (for instrumentation cables).

(5) Special Tests These tests are intended to address certain cable-system problems. They include long-term accelerated tests, load-cycling tests, mechanical-bending tests, thermomechanical-bending tests, load-cycle and polarity-reversal tests, and accelerated-water-treeing tests.

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NEZAR AHMED
NAGU SRINIVAS
Detroit Edison