1960s and early 1970s, new technologies emerged in the polymeric material industry, resulting in the development of several polymer insulation materials for outdoor use. Today, polymer insulators made of either EPR or silicone are in use extensively around the world in all voltage classes. These insulators are lightweight and vandal-proof, have better contamination performance, are easy to install, and could be used to form large complex parts.

PORCELAIN INSULATORS

Porcelain—potassium aluminum silicate $(4K_2O \cdot Al_2O_3 \cdot 3SiO_2)$—is formed by sintering a mixture of clays, quartz, and feldspar (potassium aluminosilicate). Ultra porcelain, the highest mechanical and dielectric grade, is composed of aluminum oxide, barium oxide, and clay (2). Porcelain is a crystalline structure bonded together by a smaller amount of the vitreous matrix formed during the firing process. The ratio of crystalline and amorphous phases significantly affects the dielectric and physical properties of the porcelain. The formation and growth rate of the crystalline phase is determined by the temperature versus time profile of the firing operation. Porcelain clays usually are blended with enough water to wet the particles. The slurry is then vibro-energy-milled using ultrasound, or ball-milled. This process breaks up agglomerates and produces a narrow size range of discrete particles. A portion of the water in the slurry is removed by filter press to make a putty or paste. The putty or paste then is formed into the desired shape and subsequently dried to a sufficiently low moisture content so that it can be kiln-fired without cracking and to avoid air-void formation. During the kiln firing, insulator porcelain is normally fired at 1250°C. The surface of the insulator is glazed with a high-melting point colored glaze to make it smooth and impervious.

Insulators made of porcelain are characteristically hard, dense, and noncombustible. Values for compressive strength are 8 to 10 times tensile-strength values, indicating better performance under compression than under tension. A porcelain body has low impact strength and tends to fracture when struck sharply with a hard object.

There are three basic types of porcelain insulators, namely, pin-type, post-type, and suspension insulators. A pin-type insulator is for rigid mounting on a separable pin (Fig. 1). The relatively low margin of insulation, the risk of a mechanical shock or heavy power arc causing a deep fracture, possible puncturing the unit, limit the application of pin-type insulators to voltages below 69 kV. Pin-type insulators used in voltages higher than 20 kV usually are constructed by cementing
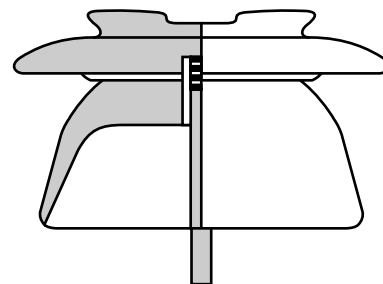
OUTDOOR INSULATION

An outdoor insulator is exposed to atmospheric conditions such as wind, sunlight, precipitation, and contamination. Today, outdoor insulating materials are either inorganic, such as porcelain and glass, or organic, such as ethylene-propylene rubber (EPR), polyethylene, cycloaliphatic epoxy (CE), and silicone rubber.

Since electricity first was generated in volume 100 years ago, ceramic materials have provided the electrical insulation for outdoor transmission and distribution lines. The performance of these materials is well known. Generally, they are reliable, cost-effective and have a long life expectancy. However, insulation devices made of ceramic materials are heavy, sometimes difficult to install and shatter when broken.

The first attempt to utilize nonceramic materials for outdoor applications occurred in the early 1960s (1), when CE found limited application both in England and the United States. However, for various reasons, including poor cold-temperature performance and insufficient weight reduction, CE did not gain acceptance for outdoor applications. In the late
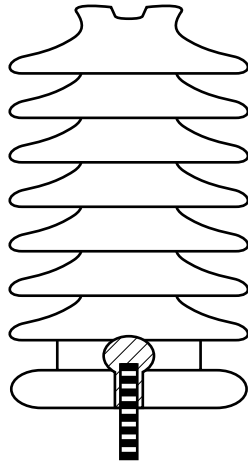

Figure 1. Pin-type insulator.

Figure 2. Post-type insulator.

two or more shells together. Thus, if a crack develops in one shell, the cement joint prevents it from passing through the entire insulator. Pin-type insulators are furnished with a thread formed in the porcelain or with a zinc or galvanized iron thimble cemented into the pinhole. For switch and bus support, insulators are furnished with metal caps and pins cemented to the porcelain and fitted with holes to which the bus connections can be made.

Post-type insulators have a columnar shape and are used for direct and rigid mounting (Fig. 2). They usually are installed on cross arms and as side-post insulators with special saddle-type bases in vertical configurations on the sides of the poles.

Suspension insulators consist of individual disk insulators nonrigidly coupled to each other [Fig. 3(a)]. Each unit consists of a shell and coupling hardware, cap-and-pin. Based on the coupling arrangement, two types of cap-and-pin units are available, the Clevis-type [Fig. 3(b)] and the ball-and-socket type [Fig. 3(c)].
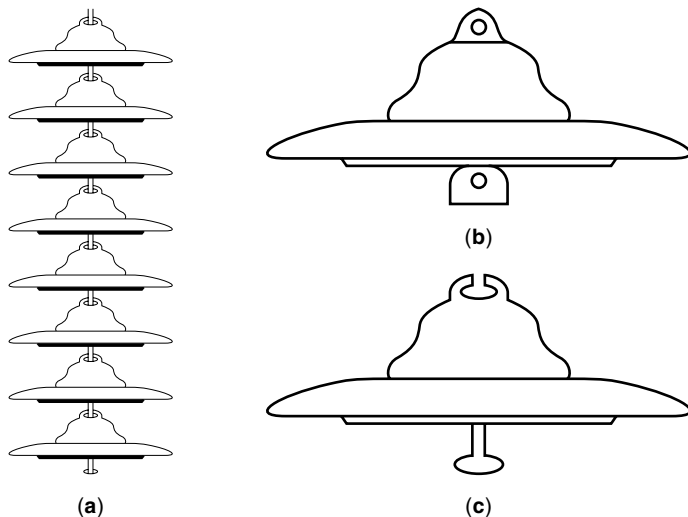

Figure 3. Suspension-type insulator. (a) Complete unit. (b) Clevis-type disk insulator. (c) Ball-and-socket type.
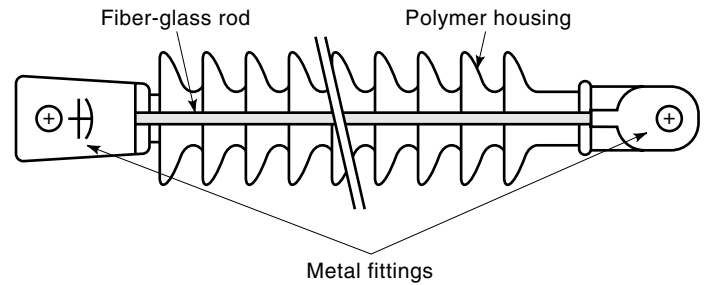

Figure 4. The basic components of the composite insulator.

GLASS INSULATORS

Glass is technically an amorphous liquid of extremely high viscosity, composed of silica (75%), soda ash (20%), and lime (5%), often combined with metallic oxides such as calcium, lead, lithium, and cerium (3). Electrical-grade glass consists of SiO_2, B_2O_3, and P_2O_5 structures that are relatively open to permit ionic diffusion and migration. Consequently, glass tends to be relatively lossy at high temperature, although at low temperature they can be used in overhead line insulators. Glass insulators are available in pin type and disk type.

COMPOSITE INSULATORS

A composite insulator consists of two materials combined to perform the total insulator function (Fig. 4). It has a structural member to provide mechanical strength and a weather-shedding component for surface stability and long-time electrical insulation. The structural member is a resin-reinforced pultruded fiberglass rod to which the attachment hardware is fitted. Weather-shedding parts made from materials that resist environmental stresses are fitted over the rod to protect the structural member and are shaped and spaced to provide maximum insulation between the attachment ends. The insulator housing, in the form of a sheath and sheds, can be directly molded or assembled in several pieces onto the fiberglass core. Electrical track and arc resistance-filled polymers are used to construct the housing of the composite insulators. Although all the weather-shed housing of composite insulators is made from polymer materials, some outdoor insulators such as pin-and-post insulators and cable termination used for lower voltages (up 35 kV class) are made entirely of polymer. Therefore, the generic name *polymer insulator* is perhaps a more correct term to describe outdoor organic insulators than composite insulators. Polymer insulators usually are manufactured as long-rod or post types. Figure 5 shows typical designs of long-rod polymer insulators.

POLYMER MATERIAL

Initially, polymeric insulators were considered as replacements for porcelain and glass for special applications, such as in areas with a high incidence of vandalism, urban locations with public hazards and right-of-way limitations, and areas with contamination problems (4). However, continued material development, improved manufacturing technology, and increased competition in the industry have resulted in some polymeric insulators which are economically comparable to
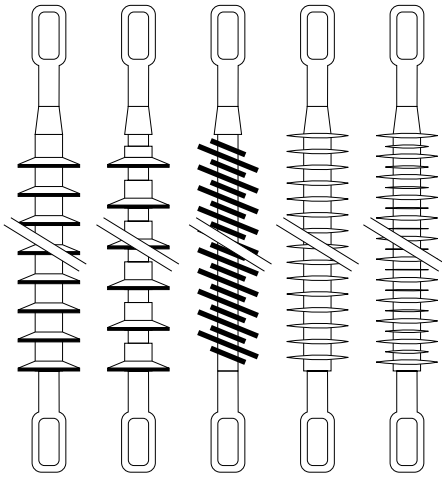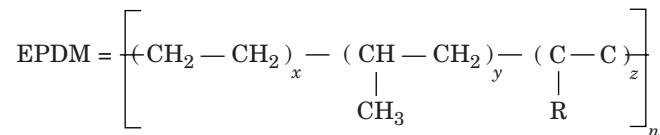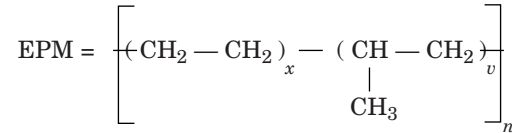
Figure 5. Typical long-rod-type polymer insulators.

dried, cooled again, and then compressed into bales. Below are the structural diagrams of EPM and EPDM.

$$EPM = \left[\left(CH_2 - CH_2 \right)_x - \left(\underset{\underset{CH_3}{|}}{CH} - CH_2 \right)_v \right]_n$$

$$EPDM = \left[\left(CH_2 - CH_2 \right)_x - \left(\underset{\underset{CH_3}{|}}{CH} - CH_2 \right)_y - \left(\underset{\underset{R}{|}}{C} - C \right)_z \right]_n$$

where R contains one unsaturated linkage. EPM and EPDM have fully saturated backbones, giving excellent resistance to ozone and oxygen. They are color stable and, when properly pigmented, have excellent weatherability. In general, EPR materials have outstanding resistance to heat, oxygen, ozone, and sunlight.

Silicone polymers are produced by a complex series of chemical reactions starting from sand and alkyl or aryl halides (6). The sand first is reduced to elemental silicon by heating with carbon in an electric furnace:

$$SiO_2 + 2C \longrightarrow Si + 2\ CO$$
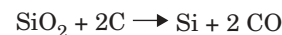
Silicon is transformed into silicone by heating silicon and copper in a tube with methyl chloride gas passing through it. A mixture of methylchlorosilanes is produced.

$$2\ CH_3Cl + Si \xrightarrow[\Delta]{Cu} \text{Mixture of}$$

$$\text{methylchlorosilanes} \begin{cases} (CH_3)_3\ Si\ Cl & \text{- Trimethylchlorosilane} \\ (CH_3)_2\ Si\ Cl_2 & \text{- Dimethyldichlorosilane} \\ CH_3Si\ Cl_3 & \text{- Methyltrichlorosilane} \end{cases}$$

Dimethyldichlorosilane is the basic intermediate for manufacturing dimethyl silicone rubber. It is separated from other components by fractional distillation. Subsequently, the silane is hydrolyzed to form silanol-stopped siloxanes, which are converted into dimethyl rubber by condensation polymerization under carefully controlled conditions. Alternatively, cyclic dimethylsiloxanes can be produced and converted to high-molecular-weight rubber by a ring-opening, base-catalyzed reaction.

$$\left[\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{Cl - Si - Cl}} \right]_n + 2\ H_2O \xrightarrow[\text{Reaction}]{\text{Hydrolysis}} \left[\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{HO - Si - OH}} \right]_n + 2\ HCl$$

$$\xrightarrow[\text{Reactions}]{\text{Condensation Polymerization}} \left[\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{Si - O}} \right]_n$$

Whether vulcanized with organic peroxides or platinum at an elevated temperature or at room temperature via RTV tech-

the ceramic ones, and this has led to their widespread use even for routine outdoor applications. Today, polymeric materials are used extensively for overhead line insulators, instrument transformer bushings, housing of arresters, and cable terminations. For instance, they have captured approximately 20% of the US transmission-line insulator market (5). Silicone rubber [both room-temperature vulcanized (RTV) and high-temperature vulcanized (HTV)] and ethylene-propylene rubbers (EPR) are the most widely used polymeric materials for outdoor applications. EPR is the generic name for two types of materials, namely a copolymer of ethylene and propylene monomers (EPM) and a terpolymer of ethylene-propylene and diene monomers (EPDM). Recently, high-density cross-linked polyethylene was also used for outdoor-electrical insulation in a variety of low-voltage applications. Cycloaliphatic epoxy has also found limited application in both Europe and the United States.

Polymers are composed of very large molecules. Each molecule (macromolecules) contains thousands of simple structures (monomers) arranged one after another in a long chain or stringlike manner (6). The chain arrangement repeats in regular cycles, so the structure can be written as certain segments, which repeat n times. Each polymer is commonly named after the raw material used to make it. When two or more different monomers are involved, the polymer is called a copolymer. The number of the segment (n) is a measure of the molecular weight of the polymer. Typically, when n is small (low molecular weight), the polymer exhibits low physical properties and in some cases it may be a gas or liquid. As n increases (molecular weight increases), the polymer's physical properties are improved. In the case of EPR, n can be as high as one million. However, n ranges from 3000 to 100,000 in silicone rubber used for outdoor insulation. In the case of low-molecular-weight (LMW) silicone fluid, n ranges from 3000 to 20,000.
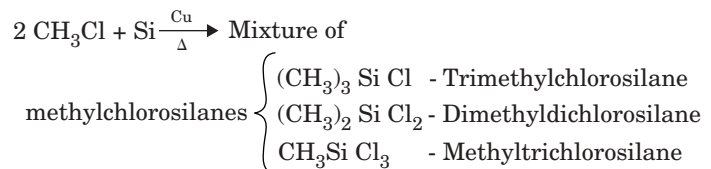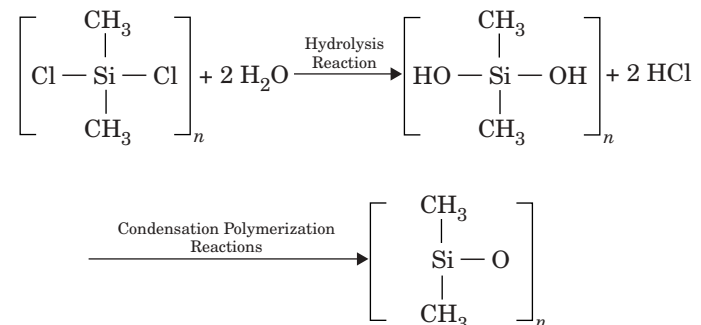
Ethylene-propylene rubber is normally manufactured in a continuous process in large reactors (7). The monomers, ethylene, propylene, and sometimes a diene (in the case of EPDM), along with the catalyst, are metered into the reactor and the polymerization takes place almost instantly at room temperature. After polymerization, the polymer is cooled, dewatered,

nology, silicone rubber exhibits thermosetting characteristics. It will not soften, melt, or drip under conductor-overload conditions. Because of the silicon-oxygen backbone, silicone is resistant to sunlight and heat and is flexible over a wide range of temperatures. Silicone rubber is a hydrophobic material due to the organic groups attached to the silicon atom.

Formulation

Once silicone, or EPR, materials have been manufactured, they must be compounded into suitable material to use in high-voltage outdoor applications. Polymer compounding is the science of mixing the raw polymers with other chemicals to produce a polymer compound that has specific properties for an application. Ingredients used to compound polymers suitable for outdoor applications (7) are as follows:

Vulcanizing Agents. Vulcanizing agents are ingredients used to cause a chemical reaction, resulting in the cross-linking of elastomer molecules. The material is converted from a soft, tacky material to a stiff, temperature-stable material. Organic peroxides are most widely used for high-voltage applications.

Coagents. Coagents protect the already cross-linked bonds between the polymer and vulcanizing agent from being torn apart.

Antidegradants. Antidegradants are used to retard the deterioration of the rubber compound initiated by oxygen, ozone, heat, and light.

Processing Aids. Processing aids are added to rubber compound to help mold flow and release and aid the mixing of the compound.

Fillers. Fillers are used to reinforce the base elastomer, which can increase the physical properties or impart certain processing characteristics. There are two types of fillers: reinforcing and extending. The reinforcing fillers can improve tensile strength, modulus, tear strength, and abrasion resistance. The attending fillers are a loading or nonreinforcing material used to impart some desirable property. Alumina trihydrate (ATH) is used in nearly all insulators to impart a high resistance to electrical tracking and inflammability.

Coupling Agents. Coupling agents provide a chemical bond between the filler and the elastomer. Using coupling agents can improve greatly the electrical properties, modulus, and tensile strength.

Plasticizers and Softeners. They are used to aid mixing, modify viscosity, or provide flexibility at low temperatures.

Molding and Curing

Molding is the process of forming the final shape of the insulator. Curing is the process of cross linking and vulcanizing the rubber. Manufacturers use two molding processes to mold outdoor-polymeric insulators. The first one is the direct-injection molding process, where compound materials are injected under pressure to a heated molding cavity where cross linking occurs. The compound materials are injected at different locations to establish a uniform mold flow into the molding cavity. The second type is compression molding. In this process, compound materials are first extruded over the fiber-

glass rod in a low-temperature, low-pressure process. The extruded product then is sandwiched between the two halves of a heated molding cavity and pressure is applied to it. Cross linking occurs inside the molding cavity. Both techniques leave longitudinal mold lines.

Two other assembly techniques are used to form the insulator into its final shape. In the first technique, the polymer sheath is applied over the core in a low-pressure, low-temperature extrusion. The sheet then is placed inside an oven at approximately 300°F (148 °C) to cross link the polymer. Sheds are made separately through injection molding and are attached over the sheath through an adhesive. Insulators fabricated using this process leave only circumferential mold joints at the outer edge of the sheds. In the second technique, the insulator housing is molded separately without the core in modules using injection molding. Each module then is attached to the fiberglass rod using silicone grease. Modules are attached to each other through interlock rubber joints, leaving both longitudinal mold lines and radial joints.

Factors Influencing Long-Term Performance of Polymer Insulators

The main challenge to polymeric materials is the progressive degradation of their dielectric and mechanical properties due to the combined effects of sunlight, moisture, surface discharges, ozone, temperature extremes, and a diversity of contaminants. Unlike ceramic materials, which have been proven to be stable over the practical lifetime of insulators in aggressive environments, polymeric materials have certain known weaknesses.

Environmental stresses contribute to dielectric deterioration of an insulating material due to moisture absorption, physical changes of its surface, and chemical changes in composition. Under the synergistic action of electrical and environmental stresses, materials further deteriorate by dry-band activity on the surface and treeing in the bulk of the material. Dry-band activity may lead to material erosion or tracking, which may lead to a flashover.

Weather. Outdoor weathering is a natural phenomenon that affects all materials to some extent. The weather components most likely to cause significant changes in the properties of polymeric materials are the ultraviolet (UV) components of sunlight, atmospheric oxygen, and moisture.

Ultraviolet Light. Light can cause a chemical change only if the energy of the individual photons is at least equal to the lowest bond energy found in the polymer molecule. It has been stated that UV light of wavelengths from 2800 Å to 4000 Å has sufficient energy to break several different types of chemical bonds such as C—H, C—C, C—Cl, C—Si, some of which are present in all common polymers. The breaking of chemical bonds, known as scission, reduces molecular weight and degrades the polymer, which may be result in loss of both mechanical and electrical properties such as strength, elongation, electrical strength, track resistance, and water resistance. Approximately 5% of the total sunlight reaching the earth's surface falls within this wavelength range and may cause degradation unless particular care is taken in the choice of polymer and additive.

Most polymers in the pure state are transparent to UV light within the wavelength range from 2800 Å to 4000 Å. However, due to oxidation during processing or in service, the photoactive group may be present, which can absorb UV light and cause degradation. Silicone rubber contains low molecular weight (LMW) fluid in the bulk of the material that with time migrates to the surface, which acts as a UV radiation absorber.

Atmospheric Oxygen. Mechanical and electrical properties of polymeric materials can be destroyed by oxidation, accelerated by the UV light of the sun. Generally, oxidation will induce further chain growth and linkage, resulting in a hard, rigid material, or chain scission, which results in a plastic or viscous mass. Chain growth or cross linkage will usually decrease elongation and increase hardness and tensile strength, whereas chain rupture will have the opposite effect. Some materials continue to harden and some soften, whereas others show an initial hardening followed by softening. The degree of oxidation is affected by such factors as the type of polymer, kind and density of cross linkage, and content of carbon black. In practice, polymeric materials usually incorporate some form of UV absorber together with antioxidant for protection during processing and service.

Moisture. Various materials absorb varying amounts of water that may affect them in different ways. Moisture, such as rain, dew, condensation, or high humidity, can attack and degrade different polymers in a number of ways:
- Production of hydroxyl radicals in the presence of sunlight, which can further precipitate radical reactions in the polymer, leading to degradation.
- Freezing of water in surface imperfections can cause loss cracks, causing more water to lodge and further cracking from freezing.
- Pollutants dissolved in a surface moisture film can cause loss of electrical integrity via erosion and tracking.
- In certain polymers moisture may dissolve out plasticizers and stabilizers, causing embrittlement or reduced ability to resist oxidation.
- Adsorbed or absorbed water increases the electrical losses that may result in a redistribution of electrical stress and hence failure.

Pollution. Pollution affecting polymeric materials can be classified in two types—gaseous pollution and solid contaminant. Common gaseous atmospheric contaminants are ozone, sulfur oxides, and nitrogen oxides. They may be due to direct emission from manufactured sources or to photochemical reactions in the atmosphere. In the presence of UV sunlight or the UV rays and heat generated from dry-band arcing, these gaseous contaminants react chemically with the polymer surface and may cause significant changes in its properties and performance. For instance, sulfur dioxide reacts with hydrocarbon in the presence of UV light, resulting in sulfuric acid formation. This acid would damage highly filled polymer systems by reacting with the inorganic filler and cause high leakage currents in humid conditions. The chemical reactions of the gaseous contaminants may cause a ductile material to crack, a nontracking material to track, and a hydrophobic material to become hydrophilic. Typical solid contaminants include coal dust, fly ash, general airborne dust, salt, sand, cement dust, and soot and may be neutral, acid, or alkaline in nature. Solid contaminants affect both ceramic and polymer insulators the same way and are discussed in detail in another section.

HYDROPHOBICITY

Free surface energy, due to unbalanced molecular configuration at a surface, is a characteristic of any material. If a liquid drop is placed on the surface of a solid, it tends to spread out on the surface or remain in drop form, depending on the relative free-surface energies of the two. If the liquid is water and it tends to remain in drop form, the solid material is called hydrophobic; if it spreads out, the material is called hydrophilic (see Fig. 6).

Porcelain and glass materials have high surface energies, and subsequently they are classified as hydrophilic. On the other hand, both silicone and EPDM have low surface energies. Initially, both exhibit hydrophobicity. However, both materials lose their initial hydrophobicity and become hydrophilic when they are exposed to prolonged wetting due to the reorientation of the hydrophobic methyl (CH_3) group at the insulator surface. Loss of hydrophobicity due to prolonged wetting is temporary in both silicone and EPDM. Prolonged exposure to dry-band arcing destroys the chemical bond between the methyl (CH_3) group and the backbone of both silicone and EPDM resulting in a permanent hydrophilic surface. However, silicone will recover this type of lost hydrophobicity through diffusion of low molecular weight polymer chains from the bulk of the material.

It has been hypothesized that under prolonged wetting, the water droplets on the surface of the polymer insulator grow until they are large enough to leave the positions on which they have grown and run down the surface (8). Such movement is further accelerated as the droplets sweep up other droplets in their path. Gravity dictates the direction of the drift (downward migration). When the droplets are moving downward, two types of interfacial forces are present. The high surface tension of water provides a high interfacial energy force for surface molecules to orient to minimize the interfacial tension. The interfacial force to reorient the molecules at the interface of the insulator and water seems weaker than the interfacial driving force at the point where air, wa-
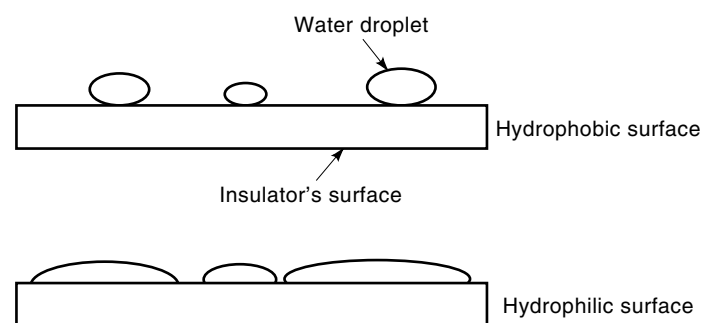
Figure 6. Hydrophobic surface versus hydrophilic surface.

ter, and the insulator surface meet (triple point). Therefore, the interfacial driving force at the triple point may be responsible for reorienting the methyl groups away from the surface and thus reducing the hydrophobicity. The hydrophobicity lost due to reorientation of molecules is small, and both silicone and EPDM materials recover rapidly after the wet period ceases.

If contaminants are present on the insulator surface and the insulator is subjected to a lengthy wetting, such as fog or light rain, the leakage current increases significantly once the surface of the insulator loses its hydrophobicity due to reorientation of the hydrophobic methyl groups. The increase in the leakage current leads to dry-band arcing. The dry-band arcing on the wetted surfaces deforms the polymer chains, cross links chains, and removes some hydrophobic methyl (CH_3) groups from the surface, causing a permanent loss of surface hydrophobicity in locations where prolonged dry-band arcing occurred. However, only silicone insulators will recover hydrophobicity lost due to dry-band arcing as LMW chains diffuse to the surface and replace the deformed surface layers. Such recovery depends on the length of exposure and the dry-band arcing intensity. It ranges from 2 to 40 h. The slow recovery is caused by the slow migration of the LMW fluid.

CONTAMINATION PROCESS

Typical solid contaminants include coal dust, fly ash, general airborne dust, salt, sand, cement dust, and soot and may be neutral, acid, or alkaline in nature. These airborne particles may be of natural origin or they may be generated by pollution that is mostly a result of industrial, agricultural, or construction activities. A common natural deposit is sea salt, which causes severe contamination of outdoor insulators in coastal areas. Salt also is a major contaminant source in inland areas, because it is used on highways to remove snow and ice during winter. In the presence of moisture and electrical stress, solid contaminants are either ionic or inert.

In inland contamination, both hydrophobic and hydrophilic insulators in most cases are covered with a uniform layer of pollution. However, in the case of sea pollution, the contaminant distribution on the surface of hydrophobic and hydrophilic insulators is different because the contaminant consists mainly of salt, which is dissolved in the water droplets. The water-repellent surface of a hydrophobic insulator is covered by droplets. When these droplets dry, the insulator surface is covered by spot contamination. On hydrophilic insulators, on the other hand, saltwater droplets cover the surface with a uniform film of salty water. Drying produces uniform salt contamination layers.

POLLUTION FLASHOVER

Outdoor insulation design of high-voltage systems is most often determined by switching-overvoltage requirements. The design also is determined by the lighting-overvoltage requirements in some other cases. In clean, wet conditions, the strength is usually twice the stress in the extra-high voltage (EHV) and ultra-high voltage (UHV) class and about three times in the lower voltage range. There are many records of power-frequency flashovers without any evidence of switching or lighting overvoltages. These flashovers usually occur in

light wet weather conditions, such as dew, fog, or drizzle, and are caused by insulator surface contamination.

The flashover process of a polluted insulator has various stages. First, the pollution layer is wetted, leading to large leakage current flow. The ohmic current dries the low-resistance layer and evaporates the water. Drying is more intense near the end fitting and under the petticoats, where current density is high. As a result of the high evaporation, small dry bands are formed in these regions leading to the formation of partial-arc bridging the dry-band regions (dry-band arcing). The increase in the intensity of the dry-band arcing reduces the overall strength of the insulator, leading to a complete flashover.

Flashover requires the surface insulator to be contaminated and also requires wet conditions. An insulator with a dry contaminant is as good as a clean one. Heavy rain usually washes contaminants away from the surface. Only light wetting such as fog, dew, condensation, and drizzle can cause flashover. The flashover mechanism in hydrophobic and hydrophilic insulators is different because of the differences in the surface-water repellent of the two materials.

Flashover of Hydrophilic Insulators (Porcelain)

Under dry conditions, the equivalent circuit of a porcelain insulator may be represented only by a network of capacitance (9). The distribution is usually nonuniform, primarily because of the capacitances between insulator units and ground. Under wet and contaminant conditions, the surface impedance is a combined capacitance and resistance. The resistance values are influenced by the drying effect created by leakage current, a function of the voltage across the unit. Therefore, resistance of different units is not equal. The surface resistance of the units under high-voltage stress is higher than that of units under low-voltage stress. Usually, high-voltage stress is concentrated at the high-voltage section of the insulator, drying the contamination layer in this region until it forms a dry zone. As wetting increases, this is accelerated, leading to arcing bridging units at the high-voltage end of the insulator. The bridging action causes overvoltage for the insulator in the other sections and produces heavier activity (scintillation arcing) along the insulator. This activity appears as surge currents. These surge currents dry up the insulator surface in the wet zone, linearize the voltage distribution along the region not bridged by the scintillation arcs, and extinguish automatically owing to their own linearization. This heavy activity does not make the insulator surfaces in the wet zone as dry as those of the dry zone of the insulator. Hence, the whole voltage distribution remains nonuniform. After the activity has ceased, the insulator surface under low-voltage stress begins to absorb moisture, lowering the surface impedance values. On the other hand, the insulator sections near the high-voltage end are difficult to wet because of the higher surface temperature of this section. Therefore, the voltage distribution along the insulator once more becomes nonuniform enough to produce another surge. This process is repeated until a complete flashover bridging the entire insulator develops.

Flashover of Hydrophobic Insulators

The performance of EPDM material under contamination is somewhat similar to porcelain as the contaminant layer of the surface will dictate its wetability. However, silicone is differ-
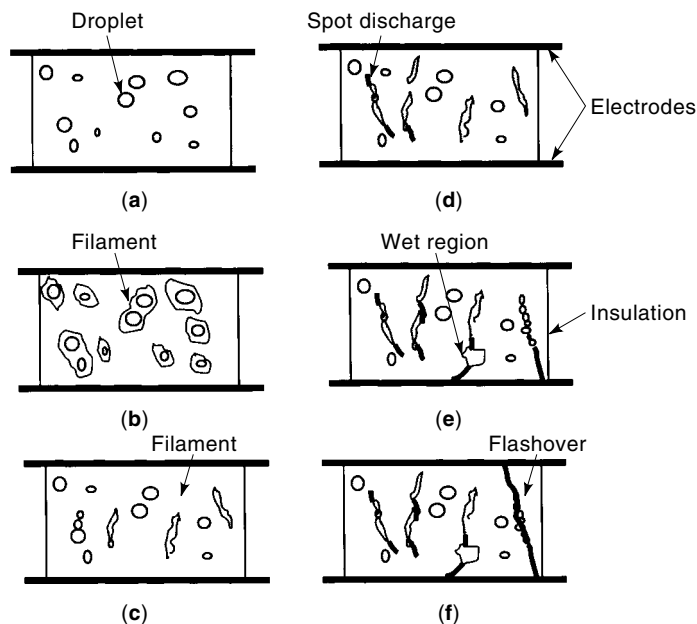
Figure 7. Development of flashover of hydrophobic insulators.

ent due to the presence of LMW fluid in the bulk of the housing. If contaminant collects on its surface, diffusion drives LMW polymer chains out of the bulk of the material. The LMW polymer fluid forms a lattice-type thin layer on the top of the pollution layer. This ensures that the surface regains hydrophobicity [Fig. 7(a)]. Light wetting conditions produce water droplets on the surface. Diffusion drives the pollutants through the thin LMW chains of the polymer layer (10). Solid contaminant dissolves in the water droplets, which become conductive. Diffusion also drives water from droplets through the thin polymer and into the dry pollution. This generates a highly resistive layer around each drop. Continuous wetting increases the density of the droplets on the surface that joins the wet regions and results in a high-resistance layer, which is covered by conductive water droplets. The voltage drives a small leakage current through the highly resistive layer. Since the electrolyte has a negative thermal coefficient, the resistance will decrease slowly due to heating. Simultaneously, drying increases surface resistance. The two opposing phenomena reach equilibrium at a lower leakage current level. At this point, the insulator is covered by a highly resistive layer, scattered with conductive droplets [Fig. 7(b)]. Wetting increases the droplet density and reduces the distances among droplets. The interaction between the ac electric field and droplets produces an oscillating force, which flattens and elongates the droplets. If the distance is small, the neighboring droplets coalesce and filaments are formed [Fig. 7(c)]. The filaments are conductive regions, surrounded by high-resistance areas. The filaments are formed randomly all over the surface. Filaments reduce the distance between the electrodes, which leads to an increase in the electric field between adjacent filaments. This field intensification produces spot discharges between the filaments [Fig. 7(d)]. Spot discharges consume the thin polymer layer around the droplets and destroy hydrophobicity. Reducing hydrophobicity eventually joins the filaments together. The filament elongation results in further field intensification and further appear-

ance of spot discharges at the end of the filaments. High electric fields around the electrodes produce coronas and surface discharges. These localized discharges destroy hydrophobicity, which leads to irregularly shaped formations in the wet regions [Fig. 7(e)]. Filament coagulation also forms the wet regions. Increasing the filament's length and forming wet areas finally shorts the insulator by a conductive, electrolytic path, resulting in a flashover [Fig. 7(f)].

As explained above, the two key elements to a pollution flashover are contaminants and moisture. Scintillation arcing occurs only if the leakage current develops enough heat in some areas to evaporate more moisture than is falling on the surface. This condition normally is met with fog, mist, or drizzle. For the same contaminant level, the length of the wetting period to cause flashover varies significantly between porcelain and silicone insulators. In porcelain, if enough contaminants are present on the surface, a wetting period of a few minutes is all that is normally needed to cause flashover. In silicone, the light wetting must be sustained for days. However, as the silicone insulator ages, the amount of LMW fluid is reduced and so is the wetting period needed to cause flashover.

In ceramic insulators, it is common to use the leakage length alone without the surface area to compare the insulation performance of different insulators. However, for composite insulators, the surface area varies greatly with insulator design. The ratio of leakage distance-to-surface area for a specific voltage class is a far more significant parameter in selecting composite insulators for use in contaminated areas than simply the leakage distance alone. Designs with a long leakage distance and a small surface area perform better because these characteristics limit the magnitude of leakage current. However, this characteristic becomes less significant when compared with the aging characteristic of the materials. Therefore, this type of ranking should be applied only to insulators made from the same weather-shed compound.

INSULATORS FOR HIGHLY CONTAMINATED INSTALLATIONS

Contaminated areas include coastal and heavy industrial installation. With tougher emission control laws, the latter is not considered a major source of contamination in the United States and other many industrial nations. However, emissions in a large number of nations are still unregulated. Line installations near railroad tracks also are considered high-contamination areas because of the by-product emissions from the diesel engines.

In contaminated areas, the majority of insulation failures are triggered by contamination deposited on the insulator surface. Several options are available for insulators used in contaminated areas:

Silicone Rubber Insulator. Silicone rubber has shown superior performance in highly contaminated areas due to its ability to prevent water sheeting on the surface (hydrophobicity) and to recover its surface hydrophobicity. Silicone rubber insulators now are frequently used around the world for these environments.

Overinsulation. This is the best countermeasure for all contamination levels. It is achieved by using a longer insulator or by employing fog-type insulators, which

have up to 150% leakage current distance of that of standard-type insulators.

Application of Coating. Coating the porcelain surface with low-surface energy materials such as silicone grease, RTV silicone, and sometimes Teflon, has been used extensively in the United States and in many other countries.

Semiconducting Glazed Insulators. Porcelain insulators with a resistive coating are available. The heat produced by the resistive coating keeps the surface dry and to a certain extent provides a linear potential distribution.

Mixture of Free Silicone with EPDM Insulator. Adding a mixture of free silicone oil to the base of EPDM will give the insulator some of the silicone rubber properties.

Washing. Washing and cleaning deenergized insulators is also effective. Live line-washing, for which special set-ups have been developed, is employed primarily in substations, and sometimes for lines.

DIRECT CURRENT INSULATORS

Under alternating current (ac) voltage, the field distribution along the surface of the insulator is determined by the surface resistance and by the self-capacitance of individual insulator units and the stray capacitance both to grounded and to energized parts. However, under direct current (dc) voltage, it is determined by surface resistance, which can differ by many orders of magnitude from one material to another. Static state dc fields are less stable than ac fields because of environmental changes such as temperature, pollution, and wetting. Environmental changes lead to rapid developments of dry-band arcing.

Under ac stress, if dry-band arcing occurs, it extinguishes itself as the current crosses zero. However, dry-band arcing under dc stress continues. Therefore, the key element for dc insulator design is to minimize the leakage current and hence dry-band activities. This is mainly accomplished by overinsulation. Insulators with silicone rubber housing have performed well in dc applications because of low leakage current and superior performance under environmental stresses. Surface-coated porcelain also is used. Corrosion at the ball bolts requires that porcelain insulators be equipped either with zinc sleeves or corrosion interception sleeves.

COATING

Porcelain and glass insulators have high-energy surfaces and wet readily by allowing water to spread over them in a continuous film in the presence of fog, mist, or rain. If contaminants are present on the surface, leakage-current develops. Uncontrolled leakage current leads to intense dry-band arcing followed by insulation flashover. To suppress the leakage current, the surface of porcelain and glass insulators is coated with hydrophobic, low-surface energy materials. This provides water repellency, which prevents continuous water filming forming on the surface, and thus suppresses the leakage current.

Silicone grease is widely used and may be the ultimate in low-surface energy and insulator stability in wet-condition environments due to the effects of mobile fluid. The primary limitation is that soft grease will collect and absorb all of the solid dirt particles that come in contact with the surface. When the grease coating becomes overly saturated with solid pollution, the low-surface energy quantities are lost.

Certain silicone elastomers and Teflon do not retain every solid dirt particle that hits their surfaces. Low-energy solid surfaces exhibit selectivity in the exact type of solid dirt particles that become permanently attached to the surface by naturally occurring processes. They attract only low-energy dirt particles. High-energy particles are not naturally deposited or are removed when exposed to rain.

MECHANICAL STRENGTH

Post-type insulators are subjected to bending load, whereas suspension and dead-end insulators are stressed with tensile loads. Post-type insulators employed in distribution and transmission lines are required to sustain 1270 kg bending load. However, tensile load requirements for suspension and deadend applications depend on the voltage class. In distribution class voltages, a tensile load of 6800 kg is required while transmission-line insulators require withstanding a maximum load of 11,350 kg. In longer span and larger conductor applications, the withstand-tensile load is approximately 15,900 kg.

Compressive strength of porcelain is 8 to 10 times its tensile strength, indicating better performance under compression than under tension. Therefore, insulators made of porcelain always are loaded through compression rather than tension. For suspension applications, this is accomplished by assembling several individual units in tandem (string insulator). The units are attached through ball and socket fittings.

The fiberglass core mainly controls the mechanical strength of composite insulators. Fiberglass has high tensile and compression strength and also is fully elastic and highly flexible.

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NEZAR AHMED
NAGU SRINIVAS
Detroit Edison