# CHAPTER 3

# Electrical Insulating Materials

## 3.1 Introduction

*Electrical insulating materials* ensure the integrity of desired paths of electromagetic power flow in electrical systems and equipment. They are materials at very high *resistivity* and can thus be used as isolators or separators between conductors having different potential (voltage) levels. In its use such as in isolators, an insulating material has the basic function of confining the current flow within the conductive circuit of a given device or part of equipment, thus protecting the latter from short circuits, current leakage, and similar undesirable malfunctions [1].

Insulating materials may be solid, liquid, or gaseous substances. They may be monolithic (discrete) materials or may be constituted by physically cohesive composites structured with multiple constituents. The electrical insulation property stems from the dielectric characteristics of the materials. Therefore, the term electrical insulating material, in general, encompasses the host of monolithic and composite dielectric materials having high electrical resistivity.

Based on the primary functions, electric insulation can be categorized as follows:

- Separation-type insulation
- Barrier insulation
- Creepage insulation

The *separation-type insulation* refers to the isolation of conductors at higher electrical potential from those at lower potential levels such as the ground. *Barrier insulation* is required to achieve a higher *breakdown strength* in specific applications. *Creepage insulation* is a special case of spacing insulation that avoids the creepage of electric flash-overs by virtue of having certain specified surface characteristics.

The secondary function of insulators can be grouped as follows :

- Mechanical supports for high-voltage parts.
- Protective enclosures for electrical systems or parts.
- Thermal dissipation adjuncts in heavy-current systems.
- Feed-through units serving as bushings for electrical leads at high potentials.

The general properties of interest for insulating materials are presented in Table 3.1.

## 3.2 Dielectric Characterization of Insulators

Microscopically, the forbidden gap energy in insulating materials is too wide for easy bridging of thermal excitation of bound electrons in the valence band to the conduction band. That is, in terms of band theory (Chapter 1), an insulating material is a medium of molecular units in which electrons are tightly bound to the atomic nuclei and are not free to move within the material. Termed also as a *dielectric*, such a material has molecules in which the atoms and their electrons and the nuclei are so arranged that one part of the molecule has a positive collection of electric charges while the other part is negatively charged. This separated set of opposite charges constitutes a *dielectric dipole*. Under the influence of external electric field force, these molecular dipoles turn or rotate to align (or polarize) themselves along the direction of the field force.

**Table 3.1 General Engineering Characteristics of Insulating Materials**

| Mechanical Properties | Electrical Properties | Thermal Properties | Chemical Properties | Miscellaneous Properties |
|---|---|---|---|---|
| Tensile, compressive, shearing, and bending strengths | Electric breakdown strength in the bulk medium | Thermal conductivity | Resistance to chemical reagents | Specific gravity |
| Elastic moduli | Surface breakdown strength | Thermal expansion | Effects upon adjacent materials | Refractive index |
| Hardness | Liability to track | Primary creep | Electro-chemical stability | Transparency |
| Impact and tearing strengths | Volume and surface resistivities | Plastic flow | Stability against aging and oxidation | Color |
| Viscosity | Dielectric permittivity | Thermal decom--position | Solubility | Porosity |
| Extensibility | Dielectric loss tangent | Spark, arc, and flame resistances | Solvent crazing | Permeability to gases and vapors |
| Flexibility | Insulation resistance (bulk and surface resistances) | Temperature coefficients of other properties | | Moisture adsorption |

*(continued)*

| Mechanical Properties | Electrical Properties | Thermal Properties | Chemical Properties | Miscellaneous Properties |
|---|---|---|---|---|
| Machinability | Frequency dependency of electrical properties | Melting point | | Surface adsorption of moisture |
| Fatigue | | Pour point | | Resistance to fungus |
| Resistance to abrasion | | Vapor pressure | | Resistance to aging by light |
| Stress crazing | | Low smoke generation | | Degassing |

Adapted from [2]: P. F. Bruins: Plastics for Electrical Insulation. (Interscience Publishers, New York: 1968). With permission of the author.

Should the field be alternating, the dipoles also reorient (or polarize) alternatively along the directional variation of the applied field at the same frequency. This *dielectric relaxation process* may be accompanied by a loss of energy, known as *dielectric loss.*

The orientation of dipoles along the applied electric field is referred to as *dielectric polarization*. The work done in establishing this polarization of dipoles is equal to $\varepsilon|E|^2$ depicting that the dielectric permittivity $(\varepsilon)$ of the material refers to the extent of *electrostatic energy* storage in the material; and the relaxation process if accompanied by any frictional forces, causes a loss in the dielectric energy storage.

Further, if the applied electric field force is very intense, it is possible that the molecular dipoles may rupture causing an *insulation breakdown*. This breakdown process is further augmented at elevated temperature ambients.

On the basis of the above outline on the dielectric characterization of insulators, the following parameters can be specified to quantify the dielectric properties of an insulator.

- Relative permittivity or dielectric constant, $(\varepsilon_r)$
- Complex (relative) permittivity, $(\varepsilon' - j\varepsilon'')$
- Dielectric loss tangent or dissipation factor $(tan\delta = \sigma/\omega\varepsilon = \varepsilon''/\varepsilon')$
- Dielectric $Q$ factor $(= 1/tan\delta)$
- Dielectric attenuation, $(\alpha = \omega\varepsilon_r^{1/2}\ tan(\delta/2c)$ nepers/meter$)$
- Dielectric breakdown strength

In the above parameters, $\sigma$ represents the a.c. conductivity of the material, $\omega = 2\pi \times$ *frequency*, and $c = 3 \times 10^8$ meters/sec represents the velocity of propagation of electromagnetic energy. Other quantities are pertinent to dielectric materials as elaborated in Chapter 2.

Apart from the microscopic aspects of the insulating materials being decided by their dielectric characterizations, there are macroscopic properties (both electrical and nonelectrical) of insulators of importance as normally conceived in engineering applications and indicated in Table 3.1.

## 3.3 Bulk Electrical Properties

**Insulation resistance**: This refers to the extent to which an insulator prevents the flow of electric charges through it. An ideal insulator has a bulk resistance of infinity with zero current flowing through it. In practice, insulation resistance can be divided into the following types :

- Volume resistance
- Surface resistance

*Volume resistance (R)* refers to the bulk resistance offered by the whole body of the insulating medium. In terms of bulk resistivity $\rho_v$ (ohm-meter), an insulator of length $\ell$ meter and area of cross-section a meter$^2$, the bulk resistance for the flow of electric current across this cross-sectional area is given by:

$$R_v = \rho_v \ell / a \qquad \text{ohm} \tag{3.1}$$

*Surface resistance ($R_s$)* depicts the resistance offered by the surface of an insulating material to the sheet of surface current on it. It has the unit ohm per square.

- Both bulk and surface resistances are affected by temperature. A typical variation of $R_v$ with temperature of an oil-impregnated paper is shown in Figure 3.1.
- Surface resistance ($R_s$) is influenced significantly by ambient humidity.
- Insulation resistance also depends on (to a small extent) the polarity of the applied voltage. This is due to the inhomogeneity of the material. Standard test methods to evaluate $R_v$ or $R_s$ duly take this into consideration.
- Insulation resistance decreases with the age of the material. The ambient conditions (such as thermal, moisture, chemicals, and mechanical stresses) plus the electrical overstressings (in terms of voltage and/or current) decide the life time and the aging rate.

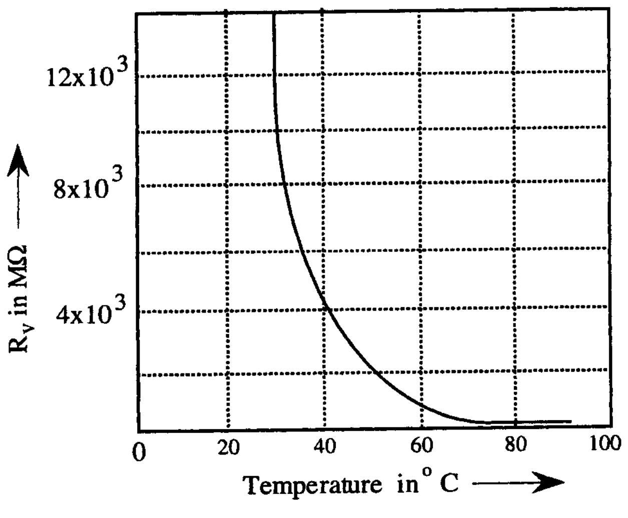


Figure 3.1 Bulk resistance *versus* temperature of an insulating material (oil-impregnated paper).

**Dielectric strength**: This is the *electrical breakdown strength* specified in terms of the maximum electric field strength that the material endures without experiencing molecular rupture. It is expressed in kilovolt/mm or volt/mil. Dielectric strengths of typical insulating materials are given in Table 3.2. These figures are only approximate and are significantly dependent on the physicochemical characteristics of the materials.

Factors which affect the dielectric strength of an insulator are:

- Temperature: The dielectric strength decreases with temperature, because the thermal energy accentuates the molecular rupture process.
- Humidity also reduces the dielectric strength.

**Table 3.2 Dielectric Strength of Typical Insulating Materials**

| Materials | Dielectric Breakdown Strength (kilovolt/mm) |
|---|---|
| Porcelain (For low voltage applications) | 2–4 |
| Porcelain (For high voltage applications) | 10–15 |
| Natural rubber | 20–25 |
| Synthetic rubber | 5–40 |
| Laminated asbestos | ~4 |
| Mica | ~80 |

**Dielectric permittivity and dielectric loss (dissipation factor):** Most of the insulating materials used in practice have *relative permittivity* (*dielectric constant*) in the range of 2 to 10 in their monolithic applications. Typical insulating materials and their dielectric constant and dielectric loss parameters are presented in Table 3.A.

Both the dielectric constant and the loss tangent of dielectric materials are affected by temperature and humidity. The dielectric constant is, however, influenced to a lesser extent only.

**Electrical resistance:** The indicators of *electrical resistance* properties of an insulation material are: (i) Insulation resistance which refers to the ratio of direct current applied to electrodes embedded in the test material to the total current between them; (ii) Volume resistivity which measures the electrical resistance between the opposite faces of a unit cube of material; and, (iii) surface resistivity which depicts the resistance between two opposite edges of a unit square of a material. Electrical resistance, in general, is decided by the inherent chemical composition and the homogeneity of the test material.

**Arc resistance**: *Arc resistance* is an indicator of the surface breakdown characteristics of an insulating material. Its values are determined by the time in seconds for breakdown along the surface of the test material. Surface contaminants and moisture are the determining factors in deciding the arc resistance value of a material.

**Table 3.3 Classification of Insulating Materials on the Basis of Limiting Temperature Performance**

| Materials | Limiting Temperature °C |
|---|---|
| Cotton, silk, paper and similar materials without impregnation with oil, rubber, or polyvinyl chloride | ~90 |
| Same as above, but impregnated with polyimide resins | ~105 |
| Enameled wire insulations on bases of polyurethane and epoxy resins, and molding powder plastics | ~120 |
| Inorganic materials (mica, fiberglass, asbestos) impregnated with varnishes, or other compounds | ~130 |
| Polyester epoxies, varnishes, and other heat-resistant varnishes | ~155 |
| Composite materials with mica and fiberglass as base materials and asbestos impregnated with silicones or silicone rubber | ~180 |
| Mica, ceramics, glass, Teflon™ | ~255 |

## 3.4 Solid Insulating Materials

The existing gamut of solid insulating materials is extremely diverse in origin and poses significant vagaries in their properties. Essentially, these materials can be grouped as: (i) Natural organic substances such as paper, cotton, rubber, etc.; (ii) Inorganic natural materials like mica; and (iii) synthetic products like plastics.

For engineering applications, the choice of an electrical insulator depends upon the severity of electrical, thermal, and mechanical stresses it would face in its applications. Among these, thermal stresses are given primary considerations inasmuch as even small temperature changes would induce considerable damage to insulators *via* chemical degradation, cracking, melting, etc. causing eventual reduction in its life time. Solid insulators are classified on the basis of thermal considerations and grouped under each limiting temperature. A classification of insulating materials on the basis of limiting temperature is presented in Table 3.3.

The characteristics and applications of commonly used insulating materials are presented in Table 3.A.

## 3.5 Liquid Insulating Materials

These are mainly used with a common purpose as heat transfer media as well as electric insulators. They form adjunct insulating systems along with solid insulators. The general characteristics required for a good liquid insulator are:

- High breakdown strength
- High impulse strength
- High volume resistivity
- Compatible dielectric constant
- High specific heat and thermal conductivity
- High flash point
- High chemical stability
- Good gas absorbing properties
- Low viscosity
- Low density
- Low solubility
- Low solvent power
- Good arc quenching characteristics
- Nonflammable
- Nontoxicity

Typical liquid insulators and their properties are listed in Table 3.4.

**Table 3.4 Typical Liquid Insulators and Their Applications**

| Liquid Insulator | Temperature Range (°C) | Applications |
|---|---|---|
| Mineral oil | –50 to 110 | General, all-purpose |
| Askarels | –50 to 110 | High voltage transformers, capacitors, switch gears |
| Silicone liquid | –95 to 210 | High voltage transformers |
| Halogenated hydrocarbons (excluding askarels) | –50 to 200 | General purpose electrical appliances, gas insulated cables |
| Synthetic hydrocarbons | –50 to 110 | Cables, capacitors, and switch gears |
| Organic esters | –50 to 110 | Electronic appliances |
| Vegetable oils | –50 to 110 | (Obsolete) |

The electrical insulation parameters of typical liquid insulating materials are furnished in Table 3.5.

**Table 3.5 Electrical Insulation Parameters of Some Liquid Insulators**

| Electrical Insulation Parameters | Liquid Insulation Materials | | |
|---|---|---|---|
| | Mineral oil | Synthetic Hydrocarbons | Askarels |
| Insulation breakdown strength in kilovolt per 2.5 mm | 35-50 | 45-55 | 20-50 |
| Impulse breakdown strength in kilovolt per 25 mm | | | |
| Positive impulse | 75–100 | – | – |
| Negative impulse | 100–200 | | |
| Dielectric dissipation factor (loss tangent) at 100°C | 0.003 | < 0.0005 | 0.03 |
| Bulk resistivity ($\times 10^9$ ohm-meter) | ~1000 | ~300 | ~10 |
| Dielectric constant | 2.3 | 2.2 | 5.0 |

## 3.6 Gaseous Insulating Materials

Typically the following classes of gases are usable as insulating media:

- Pure elements: N, H, He, Ar
- Air
- Oxide gases: $CO_2$, $SO_2$
- Electronegative gases: $CH_2Cl_2$, $SF_6$
- Hydrocarbons: methane, ethane, propane and freon

The insulating characteristics and applications of gaseous insulators are listed in Table 3.6.

Electronegative gases have a higher dielectric constant than air. For example, the relative permittivities of $CCl_4$ and $SF_6$ are 6.4 and 2.4, respectively. These gases are nonflammable and nonexplosive. They are widely used in high voltage systems. $SF_6$ is colorless, nontoxic, and almost chemically inert. Also it has good thermal stability and arc-quenching properties.

Electronegative gases have a great affinity for free electrons and as a result, they show very high breakdown strength.

Hydrocarbon gases are hardly used for electrical insulations purposes inasmuch as they are highly inflammable.

**Table 3.6 Gaseous Insulators and Their Relative Properties**

| Gaseous Insulators | Density | Parameters Relative to Those of Air | | | |
|---|---|---|---|---|---|
| | | Thermal Conductivity | Thermal Capacitor | Breakdown Strength | Applications |
| Air | 1 | 1 | 1 | 1 | Used in low breakdown situations only (<3 kv/mm) |
| N | 0.98 | 1.1 | 1.05 | 1 | Non-oxidizing, noncorrosive applications (under pressure) |
| $CO_2$ | 1.5 | 0.6 | 0.9 | 0.9 | Used in fixed capacitors; better dielectric constant than air |
| H | 0.07 | 6.7 | 14.4 | 0.6 | Used as a coolant |

## 3.7 Composite Insulators

Composite insulators can be synthesized to offer outstanding electrical insulation properties. Typically, the following multiconstituent insulating materials are used in practice:

- Asbestos/polyethylene fiber
- Asbestos/paper/polystyrene resin
- Asbestos/varnish/cotton fiber
- Paper/polyester film
- Mica/polyester or epoxy bases/alkyd binder

The aforesaid materials, in general, can be broadly classified as:

- Resin-rich system
- Resin-poor system

## 3.8 Inorganic Insulation Materials

At high temperatures, normally organic insulators fail to perform as required. In such situations inorganic compounds offer better physical, thermal, and dielectric stability. Typical inorganic insulators are:

- Silica glass (silica + alkali + base)
- Nonalkaline glass
- Ceramics (silica + alumina + magnesia + boron oxide + titania or zirconia)
- $TiO_2$ based high permittivity ceramics
- Mica (silicates of alumina and potash)
- Micanites (composites made with mica plus binders)
- Asbestos (fiberous magnesium silicates)

## 3.9 Concluding Remarks

Electrical insulating materials, though generally dielectrics, have multiple roles to play in practical applications. They should offer desirable mechanical, thermal, and chemical characteristics under operating environments. Therefore, both monolithic and composite insulating materials constitute a select class of dielectrics either chosen from available generic dielectrics or synthesized appropriately to meet the operational requirements.

## References

[1] W. T. Shugg: *Handbook of Electrical and Electronic Insulating Materials.* (Van Nostrand Reinhold Co., New York: 1986).

[2] P. F. Bruins (Ed.): *Plastics for Electrical Insulation.* (Interscience Publishers, New York: 1968).

[3] M. Clark: *Insulating Materials for Design and Engineering Practice.* (John Wiley and Sons, New York: 1962).

[4] T. Tanaka: Electrical insulation and its future. Proc. 21st Symp. Elec. Insulating Materials, 1968 (Scientific Publishing Division of MYU K. K, Japan), pp. 7-17.

## Defining Terms

*Arc Resistance:* Characteristic parameter of an insulator in offering an inhibitory trend to the breakdown-induced arc discharges.

*Bulk resistance:* The volume resistance offered by a material of finite length and area of cross-section by virtue of its electrical resistivity characteristics.

*Dielectrics:* Covalently bonded materials with very large forbidden gap which disallow free electrons in the conduction band for electrical conduction.

*Dielectric strength:* Maximum electric field sustained in a dielectric without an electrical breakdown characterized by high current conduction.