- L-P-383, *Plastic Material, Polyester Resin, Glass Fiber Base, Low Pressure Laminate*
- MIL-P-24364, *Plastic Sheet, Laminated, Thermosetting Electrical Insulating Sheet, Glass Mat*
- MIL-P-24364/1, *Plastic Sheet, Laminated, Thermosetting Electrical Insulating Sheet, Polyester Glass Mat Grade GPO-N1 (Classes 130, 155, and 180)*
- MIL-P-24364/2, *Plastic Sheet, Laminated, Thermosetting Electrical Insulating Sheet, Polyester Glass Mat Grade GPO-N2 (Class 130)*
- MIL-P-24364/3, *Plastic Sheet, Laminated, Thermosetting Electrical Insulating Sheet, Polyester Glass Mat, Grade GPO-N3*
- MIL-P-25395, *Plastic Material, Heat Resistant, Low Pressure Laminated Glass Fiber Base, Polyester Resin*

NEMA and ASTM Standards for Polyester Glass Mat Laminates

The following standards and specifications cover polyester glass laminates:

- NEMA Standard LI 1, *Industrial Laminated Thermosetting Products*
- ASTM D 1532, *Polyester Glass-Mat Sheet Laminate*

Grades

NEMA Standard LI 1 and ASTM Standard D 1532 list these grades:

- Grade GPO-1: general purpose
- Grade GPO-2: general purpose that requires resistance to flame
- Grade GPO-3: general purpose that requires resistance to flame and tracking.

Punching grades of the above are also available.

Standard sheet sizes: 24–48 inches in width, 36–90 inches in length.

Suppliers have their own proprietary grades, and will also make laminates to meet customer specifications.

Processing

A method, often called the hand lay-up process, does not require prepreg or high-pressure techniques. It is employed to make polyester sheets or shapes with glass mat or glass fabric reinforcement. The following steps are involved in making sheets (shapes are made in molds, but the process is essentially the same):

- Substrates are stacked by hand or by machine to the desired thickness on a platen in a low-pressure press.
- A predetermined amount of catalyzed polyester resin is poured on the plies of substrate.
- The material is "worked" by roller, squeegee, or other means to eliminate entrapped air and to ensure uniform distribution of resin.

TABLE 9-2 Typical Property Values for NEMA Grade Polyester Glass Mat Laminates

PROPERTY	TEST NUMBER ASTM	TEST NUMBER UL	GRADE GPO-1	GRADE GPO-2	GRADE GPO-3
Tensile strength, 10^3 psi	D 638		9.4	8.9	7.8
Compressive strength, 10^3 psi	D 695		38.9	39.0	33.1
Flexural strength, 1/16 in, 10^3 psi	D 790		22.3	24.6	22.1
Shear strength, 10^3 psi	D 732		13.4	13.4	11.6
Izod impact, ft·lb/inch of notch	D 256		8.0	10.7	8.9
Coeff. of thermal expansion in/in/°C × 10^{-5}	D 696		2.2	2.0	2.0
Water absorption, % 24 h, 1/16 in	D 570		0.3	0.6	0.4
Dielectric strength, volts/mil short time, 1/16 in	D 149		420	430	450
Dissipation factor, 10^6 cycles	D 150		0.01	0.01	0.01
Dielectric constant, 10^6 cycles	D 150		4.2	3.9	4.1
Temperature index		746B			
Electrical			—	130	130
Mechanical			—	160	160
Flame resistance		94	HB	V-0	V-0
Oxygen index	D 2863		21.8	36.0	35.0
Thickness as supplied, inches					
Minimum			0.031	0.031	0.031
Maximum			2	2	2
Specific gravity	D 792		1.78	1.97	1.81

Note: Tests are at room temperature except as indicated.

• The remaining steps are similar to those described in "Unclad Laminates Manufacture" (p. 272) in this chapter, except that pressures and temperatures are much lower and tailored to the resin and catalyst used.

Properties

These low-cost laminates possess a combination of desirable properties, including ease of fabrication, high flexural and impact strength, flame, arc, and tracking resistance, and good dielectric values.

Table 9-2 shows key property values for NEMA grade laminates.

Electrical/Electronic Uses

These materials are used in switchgear, transformer, rotating equipment, air conditioner, and television applications, as well as for substrates for printed circuits.

Sheet Molding Compound (SMC)

Sheet molding compounds (SMC) are especially well suited for making large parts by matched-die molding techniques for a wide variety of end uses. There are several merchant suppliers of sheet molding compound including Armco Composites, Hatco Poly-

ester Division of W. R. Grace, Haysite Reinforced Plastics, Plumb Chemical, PPG Industries, Premix, and Rockwell International. High-strength formulations are offered by Armco (USMC) and PPG (HMC and XMC).

Chemistry

Sheet molding compound is principally based on unsaturated polyesters to which are added vinyl-type monomers, such as styrene, vinyl toluene, diallyl phthalate, divinyl benzene, and triallylcyanurate. For more on this subject, see "Unsaturated Polyesters" (p. 248) in Chapter 8, *Insulating Coatings and Impregnants*.

The inherent tendency of polyester compounds to shrink as crosslinking occurs can be counteracted by addition of 10–15 percent by weight of a thermoplastic polymer which swells during the hot molding cycle. Acrylic copolymers, polyvinyl acetate, and polycaprolactones are commonly used "low-profile" additives which provide nearly zero shrinkage. A major product is acrylic-modified polyvinyl acetate in styrene solution, 40 percent solids. Low-profile additives are supplied as either two-part systems, to be mixed just prior to use, or as one-part premixed systems. Other compound ingredients include chopped glass fibers of $^1/_2$–2 inches in length, fillers, lubricants, thickeners, and catalysts.

Grades

Although sheet molding compound grades are commercially available from several major companies, most sheet molding compound molders produce their own sheet molding compound formulated to meet their specific requirements. Formulations cover a wide range of ratios of resin-to-glass-to-filler. Sheet molding compound is made by a continuous process, and is supplied in widths of 24, 48, and 60 inches.

Sheet molding compounds with exceptionally high physical properties are also available from a few suppliers. These products are known by designations such as HMC, XMC, and USMC (unidirectional sheet molding compound), and are characterized by glass content of 60–80 percent, compared with 30 percent for a typical sheet molding compound. Fire-retardant grades are made by incorporating alumina trihydrate into compound recipes.

Processing

A continuous process is used for making sheet molding compounds:

- A thoroughly mixed resin blend is continuously fed onto a polyethylene sheet on a moving conveyor belt.
- Glass fibers chopped to $^1/_2$–2 inches in length are deposited on the resin mix.
- A second application of resin mix is applied to coat the glass fibers.
- This composition is then covered with another polyethylene sheet and passed through kneading and compacting rollers to obtain a uniform dispersion.
- Finally, this "sandwich" is wound in rolls and stored for 24–72 hours or more until the sheet molding compound has reached through chemical thickening the right consistency (to dry sheet form) for molding.

To allow for poor distribution of resin and glass at the edges, the production sheet width is 4 inches wider than finished product width to permit trimming off 2 inches on each edge.

Prior to molding, the polyethylene films are removed, the sheet molding compound is cut to the desired size, and the charge is placed in the mold. To facilitate flow, the charge may be preheated at 100° to 120°F (38°–49°C). Mold temperature and cycle time are unique for each part design, and must be carefully determined by trial before production runs. Sheet molding compound, often processed with high pressure (1,000–1,200 psi) techniques, may also be molded at 300–700 psi using specially formulated resins. This permits use of larger platen areas and significantly lower cost presses.

Properties

Sheet molding compound molded parts are replacing metal in many applications where they have inherent advantages, including lighter weight, corrosion resistance, greater design latitude, and lower tooling cost. Dielectric properties are improved by increased resin content at the expense of reduced physical values. Products may be made flame retardant, but this may also lower other property values. Therefore, compounds should be formulated with consideration given to achieving the optimum balance of mechanical, dielectric, and flame-retardant properties to meet the requirements of the part to be molded.

Electrical/Electronic Uses

Housings and components for business machines and appliances are major consumers of sheet molding compound. The principal dielectric use is in industrial controls and switchgear where high arc resistance and flame-retardant properties are required.

Bulk Molding Compound (BMC)

Similar chemically to sheet molding compounds, bulk molding compounds (BMC) use shorter length fibers of several types and are putty-like mixtures suitable for molding in match-metal dies. Principal merchant producers include American Cyanamid, Armco, Cincinnati Development, Glastic, Haysite Reinforced Plastics, Plumb Chemical, Premix, and Rodgers Engineering.

Chemistry

Polyester resins used in bulk molding compounds are similar to those in sheet molding compounds, including blending styrenated polyesters with low-profile (low-shrink) additives to produce a thickened compound. Alternatively, the resin is modified with vinyl toluene in nonthickened compounds where low-profile additives are optional.

Reinforcing fibers shorter than 1/2 inch include glass, sisal, asbestos, nylon and other synthetic fibers, with glass predominating.

Grades

As is the case with sheet molding compounds, most large bulk molding compound molders make their own compound. However, both thickened and nonthickened grades are commercially available. Typical grades commonly contain 15–35 percent fiber reinforcement. Bulk molding compound is available in bulk, extruded log, and close tolerance slug forms.

Processing

Bulk molding compounds may be made either in a batch process or in a continuous mixer. Batch equipment is essentially a sigma blade (shaped somewhat like the capital Greek letter sigma lying on its side) or spiral blade mixer with a wide clearance between the wall and the blades to avoid breaking of fibers during mixing. In this process, fibers are added last to minimize fiber damage.

For continuous mixing, special equipment such as a Baker-Perkins Ko-Kneader is required. This machine creates a kneading action by a combination of rotary and axial motion of its agitator.

Thickened systems are aged for 24 hours or more to reach the right consistency for molding. Bulk molding compounds may be molded by compression, transfer, and injection molding methods described in Chapter 4, *Thermosetting Molding Compounds.*

Properties

Bulk molding compound characteristics are similar to those of sheet molding compounds, although mechanical properties are somewhat lower because of shorter fiber lengths. The processing rate is one of the highest of any reinforced resin, and the process cost is one of the lowest for high-volume production. High mold cost makes the process uneconomical for short production runs.

Uses

The largest application for bulk molding compounds is in parts for motor vehicles using low-cost sisal- or glass-reinforced materials. Other major applications include power tool housings and parts for appliances and business machines. Parts made by injection molding include circuit breaker parts, standoff insulators, and electronic uses such as solenoids, transformer coils, switch bases, coil forms, and TV tuner parts.

Pultrusion

This rapidly growing technology is suitable for making profiled shapes in a continuous operation. Major pultruders serving the electrical/electronics industries include Creative Pultrusions, Glastic, Haysite Reinforced Plastics, and Stoughton Composites.

Chemistry

Unsaturated polyesters, similar to those described earlier in this chapter, are the principal resins used in pultrusion. Benzoyl peroxide is the preferred catalyst. Other resins used include epoxies, silicones, and vinyl esters. Formulations typically incorporate fillers, pigments, and flame retardants.

Grades

Resin systems are usually formulated to meet specific end use requirements.

Processing

The following steps are typical of the pultrusion process:

- Filaments, most often in the form of glass roving, are dispensed from center-pull packages or tangentially from rolls arranged to feed together at an impregnating tank.
- The filaments are saturated in the resin bath in the tank equipped with side guides, wet-out bars, orifices, and squeeze rolls.
- Profiles are preformed to approximate shape after leaving the resin bath and before entering the die.
- Final shaping and curing occur in a chrome-plated steel die designed to withstand the pressure of expansion during the curing process, which is exothermic. Die temperatures for polyesters range from 240° to 375°F (115°–190°C). Electrically heated dies permit heating zones within the die. Process speed is determined by the die length, resin characteristics, and type of preheating equipment (if used).
- The cured profile is pulled by devices of various designs positioned to permit the material to cool somewhat.
- Finally, a cutoff saw or shear operates automatically to cut the profile to the desired length.

Properties

Advantages (some of which are unique) of pultruded profiles include:

- Shapes are continuously produced
- Exceptional high strength in the longitudinal direction
- Adaptability to small cross-sectional areas
- Corrosion resistance (to replace metal)
- Adequate dielectric and low maintenance properties for high-strength structural parts.

Electrical/Electronic Uses

Typical applications include safety ladders, aerial booms for trucks, third rail covers for electric railroads, poleline hardware, and component parts for control and switchgear devices.

CLAD STRUCTURES

INTRODUCTION

Clad structures are used to make printed circuits, a technology that has evolved rapidly since the initial impetus provided by specialized military applications during World War II. For a time, it appeared that the manufacture of printed circuits was ideally suited to small businesses headed by technically competent, innovative engineers. However, certain inherent problems, which still exist to a lesser degree, blocked the road to profitability for these companies:

- Specifications and performance requirements for finished circuits were often difficult to meet with available basic materials and production processes. This resulted in a high percentage of rejects and low productivity.
- The manufacturing process involving photochemical, electrochemical, and chemical operations required continuous monitoring and adjustment throughout production runs.
- It is difficult and expensive to comply fully with increasingly stringent Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA), and state and local regulations and ordinances.

Most large users of printed circuits now etch their own circuits. Some companies also make resins, prepregs, and clad laminates, thereby controlling the entire manufacturing process. The circuits made by these large producers are often incorporated in devices of their own manufacture, such as computers, television sets, radios, telephones, calculators, and many motor vehicle applications.

SUPPLIERS

Rigid clad circuit materials are sold commercially by:

Cincinnati Milacron	NVF
General Electric	Polyclad Laminates
New England Laminates	Rogers
Norplex Oak	Spaulding Composites

Flexible clad circuit materials are sold commercially by:

Circuit Materials	Norplex Oak
Chase-Foster (Keane)	Rexham
Du Pont	Rogers
3M	Sheldahl
New England Laminates	TME

TECHNOLOGY

A printed circuit is a network of conducting metal (mostly copper) paths on, or imbedded in, a dielectric material. The circuit interconnects electronic components with significant savings in space, weight, and cost compared with circuits in which the components are interconnected by wires. Circuits may be single side, double side, or multilayer formed by laminating single side circuits. There are two methods in general use for producing printed circuits:

- The etched foil, or subtractive process, the most widely employed
- The additive process

Other, less commonly used methods include applying a die-stamped foil circuit to a dielectric, and forming a circuit with conductive ink.

The *etched foil* method employs a photochemical process to print the circuit pattern on a metal clad substrate. This pattern becomes chemically protected in the developing process, and all unprotected metal is etched away after the undeveloped chemicals are stripped with solvents. Etchants include ammonium persulfate, chromic and sulfuric acids, cupric chloride, and ferric chloride. Where circuits on both sides of a substrate or on layers in a multilayer laminate are to be connected, holes are drilled at appropriate locations. Circuits may then be connected mechanically using eyelets or tubelets, or by plated-through holes.

In the *additive* method, the circuit path is applied to the substrate by metal plating. This is accomplished by either the *fully electroless* process or the *semi-electroless* process. The term *electroless* means the metal is deposited while the part is in a bath by chemical reduction without application of an electric current. To facilitate the process, a noble metal plating catalyst is dispersed in the resin system. The cured substrate is coated with about 1 mil of adhesive consisting of an epoxy/phenolic resin blended with an elastomer, such as butadiene. To promote bonding, the adhesive surface is treated with a solution of chromic and sulfuric acids. Adhesives may be applied by curtain, roller, or dip coating. Curing is accomplished in a circulating air oven or by infrared radiation. Circuits are formed by screen printing, masking, and photoprinting techniques.

Additive circuit conductors are marginally less ductile than circuits formed by etching. Conductor paths are formed only where required, eliminating all etching and cleaning steps needed for the subtractive method. However, electroless copper is higher in cost than copper used in the subtractive method, which offsets savings in labor, waste copper, and process materials. The additive method should, in general, be considered when less than 35 percent of the surface area of the substrate is to be covered with copper, or when it is desired to eliminate the problem of undercutting of the sidewall inherent in the etched process—an advantage in extremely fine line circuits.

The semi-electroless process requires only a thin electroless deposition on the substrate surface, since desired conductor thickness is achieved by subsequent electroplating. Adhesion promotion and catalyzation or precatalyzation of the substrate is required for adequate bonding and metalization. Further processing parallels that of the subtractive method, although copper loss is about one-tenth as much, since the

metal film is only one-tenth of a mil thick. Both additive processes require that the surface of the substrate be free of defects which would adversely affect adhesive coating and bonding operations.

A relatively new additive circuit technology involves the use of *polymer thick film inks* on organic resin substrates. This ink consists of a polymer, usually epoxy base, capable of crosslinking on heating, a conductive material, such as silver, dispersed in the polymer, solvents, and other ingredients necessary to adjust the physical characteristics to the consistency for proper application. The resulting circuit paths are of higher resistance than in the subtractive method, and their reliability and precision are inferior. However, inks for use on ceramic substrates requiring firing at relatively high temperatures do produce highly reliable conductor lines. These inks consist of mixtures of metal, oxide, and glass powders less than 10 microns in diameter, suspended in an organic vehicle. Application is by screen printing (the preferred technique), spraying, or brushing. After application, the ink is dried at 100°C to remove the solvent, and then fired at 300°–1,000°C to decompose the organic binder and bond the glass to the substrate in a film 0.0005–0.002 inch thick. Resistor thick film compositions may be applied in a similar way.

When production runs are long enough to absorb the cost of dies, *die stamping and embossing* techniques are often the most advantageous methods. A die is made to cut out from the conductive metal material a pattern which is then bonded to the substrate by a heat-activated adhesive. This method eliminates the chemical processes and number of production steps required by other methods, and ensures uniformity and good registration and line definition without undercutting. It also permits use of thicker conductors with greater current-carrying capability than possible with other printed circuit methods. However, this method is not as suitable for fine line or closely spaced circuit paths.

SUBSTRATES FOR PRINTED CIRCUITS

Widely used substrates for printed circuits include the following:

- High-pressure thermoset laminates described earlier in this chapter, with FR-4 grade accounting for about 80 percent of total.
- Alumina ceramics containing 75–99 percent Al_2O_3 which feature:
  - Permanent dimensional stability
  - Extreme hardness
  - Chemical inertness
  - Good impact strength
  - High operating temperature
  - Moderately high thermal conductivity.
- Sapphire (Al_2O_3), a crystalline variety of alumina. Synthetic sapphire is made by a crystal-growing process, including ribbon shapes suitable for substrates after polishing. This material has exceptionally high thermal stability and dielectric constant of 11.5 parallel to the C-axis. It is widely used for silicon-on-sapphire (SOS) hybrid IC and other microwave systems.

- Beryllia (BeO) porcelains, possessing exceptionally high thermal conductivity (30–100 Btu versus 16 Btu for alumina) and a dielectric constant of about 6.4. They are used where these properties are desired.
- Quartz and vitreous silica (SiO_2) substrates having dielectric constant of 3.2, lowest of any inorganic material.
- Polytetrafluoroethylene resin glass microfiber or alumina microfiber reinforced structures, noted for a uniform dielectric constant of 2.20–2.33 over a wide frequency range. These substrates are especially well suited for microwave circuit applications.
- Flexible substrates:
  - Polyester film
  - Polyester film on woven glass fabric
  - Polyimide film
  - Polyimide film on woven glass fabric
  - Polyamide-imide film
  - Epoxy coated polyester mat
  - Epoxy coated polyamide mat
  - Epoxy coated woven glass fabric
  - Fluorinated ethylene-propylene (FEP) film
  - Polytetrafluorethylene (PTFE) coated woven glass fabric
  - Polyamide film
  - Polyurethane film
  - Polyvinyl fluoride film
  - Polyethylene film
  - Polyvinyl chloride film
  - Polycarbonate film
- The advent of multichip modules (McM-D) has required novel dielectric insulations consisting of spin-deposited polymers, either polyimide (PI) or benzocyclobutene (BCB). These polymers form dielectric bases with low moisture absorption, low dielectric constant, high thermal stability, and excellent planarization.

For more information on ceramic substrates, see Chapter 15, *Ceramic and Glass Insulations*, p. 417.

SEMICONDUCTOR SILICON

The tremendous strides in dramatically reducing the size, while significantly improving the capabilities, capacities, and speed of electronic equipment such as computers, calculators, and communications equipment is attributable to the development of semiconductor technology based on the silicon chip, or integrated circuit (IC). Other semiconductor materials include gallium arsenide, germanium, silicon carbide, and selenium.

Ultrapure (99.97 percent pure) silicon is inherently a poor conductor of electricity. It is made semiconducting by diffusing controlled amounts of selective impurities, or dopants, such as phosphorous (*n*-type) or boron (*p*-type) into its surface. In the *n*-

type semiconductor, the semiconductor material has fewer external ring electrons than the dopant. The extra electrons do not fit the crystal structure and are available to carry current. The *p*-type semiconductors contain an impurity that has fewer electrons in the outer ring than the semiconductor has, thereby providing locations for electrons to visit in producing current.

The semiconductor grade is made by reduction of purified silicon tetrachloride or trichlorosilane with hydrogen. Silicon is deposited on hot (1,470°F, 800°C) filaments of tantalum or tungsten. In a newer, exothermic process, sodium fluorosilicate is reacted with sodium to produce silicon tetrafluoride. Further reaction with sodium yields high-purity silicon.

To make single-crystal silicon suitable for slicing into wafers, single-crystal rods are grown from the purified silicon by either the Czochralski or the floating-zone method. In the former process, a seed crystal is touched to the surface of a molten crucible charge of silicon. As the molten silicon solidifies on the seed crystal, the growing crystal is slowly pulled from the melt. This method is used to produce most commercial single-crystal silicon rods up to 100 millimeters in diameter.

The floating-zone method starts with a rod of polycrystalline silicon. A small zone at one end is melted using induction heating. Then, by moving the induction coil, the molten zone is made to move along the length of the rod. Under proper conditions, the material behind the molten zone will solidify as a single crystal. A major advantage of this process is that the molten material does not contact any other material from which it can pick up impurities. Both methods of growing single crystals also further refine the silicon because most impurities remain in the molten silicon rather than solidify in the crystal.

Circuit paths as narrow as $^{1}/_{25,000}$ inch are created by complex photochemical, etching, diffusion, and vacuum deposition processes. Using these techniques, digital watches are made with about 5,000 transistors on a single chip no larger than a child's fingernail; about 20,000 transistors on a chip are required for a pocket calculator; and 100,000 transistors are located on a chip for a small computer. Chips using $^{1}/_{2}$ micron geometries which will hold up to 4,000,000 transistors are under development.

COPPER FOILS

Copper foils used in printed circuits may be produced either in rolling mills or by electrodeposition. The rolling process foil has twice the tensile strength of the electrodeposited copper and tends to have fewer pinholes and better flex resistance, making it more suitable for flexible cables subject to frequent or severe bending. However, electrodeposited copper predominates for etched circuits. In this process, copper from a solution of copper sulfate or copper cyanide is plated on a revolving steel drum, from which it is continuously stripped, cleaned, and dried. The side next to the drum is smooth and shiny, while the other side has a grainy matte finish for bonding to the substrate. Adhesion is further improved by oxide treatment, known as Treatment "A," applied to the rough side of the copper, resulting in a tenfold increase in bond strength. More recently introduced processes include "XP," a light oxide treatment developed to reduce oxide staining in multilayer laminates, and "GT," a nickel flash treatment

designed for use primarily with polyimides to increase bond strength at elevated temperatures. About 60 percent of the copper foil used for printed circuits is 0.0014 inch thick, or 1 ounce per square foot; 30 percent is 2 ounce copper; the remaining 10 percent is $^1/_2$ ounce or 3 ounce copper. Other metal foils are used for special purposes. These foils include nickel alloys such as Kovar, aluminum, and beryllium copper.

ADHESIVES

Foils are usually bonded directly to epoxy/glass prepregs, with the epoxy resin acting as the bonding agent. A polyvinyl butyral/phenolic adhesive is used to bond foils to phenolic substrates.

Adhesives for flexible clad circuits are predominantly polyesters of a saturated type containing hydroxyl groups and isocyanates for crosslinking upon application of heat and pressure. These adhesives may be applied in solution form or as cast film.

Copper foil may be bonded to fluorocarbon and polyimide type flexible substrates with a silicone pressure-sensitive adhesive. A high-molecular-weight polyacrylic adhesive is also used for polyimide flexible circuits.

COVERCOATS

The function of a covercoat for a printed circuit is to provide complete electrical insulation over the conductor paths, to seal out moisture, and to add mechanical strength to the laminate. The covercoat may be melt-bonded, adhesive-bonded, or applied by solution coating.

- In *melt-bonding* or *fusion bonding*, the overcoat film is adhered to the base in a platen press or roll laminator. Sufficient heat and pressure are applied to melt the film momentarily, after which the construction is cooled under pressure. To ensure good adhesion, the conductor foil surface requires special treatment.
- *Adhesive-bonding* permits use of polyester and polyimide covercoat films, which are not suitable for melt-bonding. Since the high heat required for melt-bonding is not needed, adhesive-bonding provides better dimensional control for the construction. It is standard practice to use the same covercoat film as used in the base laminate.
- *Solution-coating*, the lowest cost method, eliminates the need for lamination of a preformed, prepunched film by heat and pressure. Repairability of circuits is also facilitated where solution coating is used: the covercoat may be selectively stripped by solvents, or a low-melting-temperature covercoat may be used which will melt or vaporize under heat of a soldering iron. The disadvantages of this method are that coatings are more likely to contain pinholes, and solvents must comply with worker safety and environmental guidelines. A wide variety of coatings is available:
  - Silicones (thermal properties)
  - Epoxies (moisture and abrasion resistance)
  - Polyurethanes (low temperature flexibility, solderable)

- Butyl rubbers (low temperature flexibility, moisture resistance)
- Polyesters (solderable)
- Acrylics (strippable)

MULTILAYER CIRCUITS

Printed circuit materials, usually of epoxy or polyimide types, may be layered to form multilayer circuits. These high-density constructions, requiring precisely controlled production techniques, offer significant savings in size and weight.

The manufacturing process consists of these basic steps:

1. Circuits are etched on thin laminates (less than 0.032 inch thick).
2. The laminates are then laid up to the desired construction with two or three bonding layers of prepreg between circuit layers.
3. These multilayer books are cut to size and positioned in a molding frame by means of locating pins.
4. The frame with lay-up is placed in a press, making sure platens are parallel to within 0.001 inch (0.0025 centimeters).
5. The press is closed and heated to the desired temperature, usually in the range of 300° to 450°F (149°–232°C) at a pressure of about 500 pounds per square inch (35.2 kilograms per square centimeter).
6. After approximately 1 hour, the press contents are cooled under pressure to about 120°F (49°C).
7. The frame is unloaded from the press and the circuits removed.

Each step must be carefully monitored to ensure circuits of acceptable quality. Causes of rejects include voids, blisters, displaced layers, delamination, and board distortions.

Circuits may have up to 40 layers with a thickness of only 0.40 inch (1 centimeter) and contain plated-through holes 0.020 inch (0.05 centimeter) in diameter on 0.050 inch (0.13 centimeter) centers. Holes must be located and drilled with great accuracy. Interconnections from layer to layer are made by electroplating copper through holes. For multilayer circuits to be acceptable, it is essential that circuit paths be exactly aligned.

FLEXIBLE CIRCUITS

Flexible circuits provide the capability to work with complex configurations in three dimensions, and are ideal materials for applications where they are subject to continual flexing. A wide variety of substrates is suitable for making flexible circuits, including those listed in "Substrates" in this chapter and discussed in Chapter 10, *Dielectric Films*.

Adhesives required to bond the layers together are discussed in "Adhesives" in this chapter. The most commonly used method for applying adhesives is from solution. This process consists of the following steps:

1. The adhesive coating is applied to the substrate or foil by reverse or direct roll, gravure, or knife-over-roll technique.
2. Solvent is evaporated in a heated tunnel.
3. The web is passed around a hot roll to activate the adhesive.
4. The next layer is laminated to the composite by a rubber-covered nip roll.
5. The process is repeated until all the desired layers are laminated.

Epoxy prepregs contain no solvent, and may be bonded directly to the foil without the evaporation step. Pressure-sensitive silicone and acrylic adhesives require only pressure to bond at room temperature. In another process, adhesive melt is applied by extrusion, after which layers are laminated by a nip roll.

When a thin film is laminated to a plain weave fabric by a high-bond-strength, elastic adhesive, the resulting material exhibits a significant increase in bias stiffness compared with the combined bias stiffness of component layers. This is caused by the bonding of the fibers to each other and also to the film.

FEDERAL SPECIFICATIONS FOR PRINTED CIRCUITS

There are several Federal specifications for printed circuits, among which the following are significant:

• MIL-P-13949, *Plastic Sheet, Laminated, Metal Clad.* This specification is approved for use by all departments and agencies of the Department of Defense, and covers the requirements for fully cured, metal-clad laminated, plastic sheets (glass and paper base), and semi-cured (B-stage), resin impregnated, glass cloth (prepreg) to be used primarily for the fabrication of printed-wiring boards for electrical and electronic circuits. Substrates are identified as follows:

PX—Paper base, epoxy resin, flame resistant

GE—Glass (woven-fabric) base, epoxy resin, general purpose

GF—Glass (woven-fabric) base, epoxy resin, flame resistant

GB—Glass (woven-fabric) base, epoxy resin, hot strength retention

GH—Glass (woven-fabric) base, epoxy resin, hot strength retention and flame resistant

GP—Glass (nonwoven-fiber) base, polytetrafluoroethylene resin, flame resistant

GR—Glass (nonwoven-fiber) base, polytetrafluoroethylene resin, flame resistant, for microwave application

GT—Glass (woven-fabric) base, polytetrafluoroethylene resin, flame resistant

GX—Glass (woven-fabric) base, polytetrafluoroethylene resin, flame resistant, for microwave application

GI—Glass-fabric base, polyimide resin, high temperature

GY—Glass (woven-fabric) base, polytetrafluoroethylene resin, flame resistant for microwave application.

Among test requirements are tests for peel strength, peel strength after thermal stress, after temperature cycling, at elevated temperatures, and after exposure to process conditions.

• MIL-P-55110, *Printed-Wiring Boards*. This specification is approved for use by all departments and agencies of the Department of Defense, and covers the certification and performance requirements for rigid single-sided, rigid double-sided, and rigid multilayer printed-wiring boards with plated-through holes. Possible major defects are classified as follows:

- Bonding of conductor and peeling of conductor: Any looseness of bond on any conductor length, any peeling of conductor (defect most prevalent at terminals and at ends of conductor contacts).
- Broken eyelet: Part of eyelet missing. Circumferential splits.
- Seating of eyelet: Eyelet not properly seated perpendicular to the board.
- Plated-through hole: (1) In excess of 10 percent void of surface in hole rejectable; (2) voids at interface of hole rejectable; (3) circumferential separation rejectable.
- Superfluous conductor: Potential cause of short. Clearance less than that specified in master drawing for electrical spacing.
- Eyelets: Total voids in solder around eyelet exceeding 30 percent of the periphery in funnel flanged eyelets. Cracks in solder around eyelet.
- Reduction in width of conductor at any point exceeding 20 percent of the minimum specified conductor width on the master drawing.
- Conductor and lead spacing violating the requirements on the master drawing.
- Plating on top surface of conductors and in plated-through holes: Lack of plating or less than minimum specified. Plating adhesion defect.
- Cracks, chips, or bulges on board surfaces.
- Unspecified removal of board material: Any visible unspecified removal of board material (such as removal about conductors to increase insulation resistance or indication of contamination). A minor change in surface appearance due to removal of unspecified material.
- Warp or twist of board: Warp or twist in any board shall not exceed 1.5 percent.
- Spacing of holes: Other than that specified on the master drawing.
- Annular ring (at narrow point):
  a. The projecting flange or eyelet or standoff terminal extending beyond the annular ring.
  b. Measuring less than 0.015 inch (0.38 mm) beyond the edge of unsupported hole.
  c. Measuring less than 0.002 inch (0.05 mm) for internal terminal areas.
  d. Measuring less than 0.05 inch (0.13 mm) beyond the edge of plated-through hole.

- Terminal holes: Ragged holes with chipping or cracking in the wall of the holes, and bulging around the holes or reduction of the hole diameters with base laminate material such as fibers. Ragged metal foil edge. Metal foil deformed into a hole, torn or lifted. Size of holes not as specified in the master drawing.
- Delamination: Internal or external separation of base material (paper or glass).
- Spurs or whiskers: Presence of spurs or whiskers.
- Nodules: Cause reduction in hole diameter to less than specified on the master drawing.

Minor defects include:

- Cuts, cracks, or scratches in conductor: Board visible through copper (copper may be visible through overplating when overplating is specified).
- Cuts, cracks, or scratches completely across conductor or more than $^1/_2$ inch along conductor.
- Size of holes: Size of holes (other than terminal holes) not as specified in the master drawing.
- Loose standoff terminal: Any standoff terminal that can be turned or removed by hand before soldering.

IPC SPECIFICATIONS FOR PRINTED CIRCUITS

The Institute for Interconnecting and Packaging Electronic Circuits (IPC) has the following applicable specifications:

- IPC-L-108A, *Thin Laminates, Metal Clad Primarily for High-Temperature Multilayer Printed Boards*
- IPC-L-109A, *Glass Cloth, Resin Preimpregnated (B-Stage) for High-Temperature Multilayer Printed Boards*
- IPC-L-110A, *Preimpregnated, B-Stage Epoxy-Glass Cloth for Multilayer Printed Circuit Boards*
- IPC-L-112, *Foil Clad, Polymeric, Composite Laminate*
- IPC-L-115A, *Plastic Sheet, Laminated, Metal Clad for High-Temperature Performance Printed Boards*
- IPC-L-130, *Thin Laminates, Metal Clad, Primarily for General Purpose Multilayer Printed Boards*
- IPC-FC-220B, *Flat Cable, Flat Conductor, Flexible, Unshielded*
- IPC-FC-222, *Flat Cable, Round Conductor, Unshielded*
- IPC-FC-231, *Flexible Bare Dielectrics for Use in Flexible Printed Wiring*
- IPC-FC-232, *Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Wiring*
- IPC-FC-240C, *Flexible Printed Wiring*

- IPC-FC-241, *Metal-Clad Flexible Dielectrics for Use in Fabrication of Flexible Printed Wiring*
- IPC-FC-250, *Double Sided Flexible Wiring with Interconnections*
- IPC-D-300F, *Dimensions and Tolerances for Single and Two Sided Printed Wiring Boards*
- IPC-AM-361, *Rigid Substrates for Additive Process Printed Boards*
- IPC-ML-905B, *Performance Specifications for Multilayer Printed Wiring Boards*
- IPC-ML-990, *Performance Specification for Flexible Multilayer Wiring*

ASTM STANDARDS FOR COPPER-CLAD THERMOSET LAMINATES

The American Society for Testing and Materials (ASTM) has established these standards for copper-clad thermoset laminates:

- D 1867, *Copper-Clad Thermosetting Laminates for Printed Wiring*. This specification covers ten grades of copper-clad thermosetting laminates, with copper foil bonded to one or both surfaces. These grades (similar to NEMA grades described earlier in this chapter) and their key requirements are listed in Table 9-3. Table 9-4 lists thickness tolerances for copper-clad sheets.
- D 5109, *Test Methods for Copper-Clad Thermosetting Laminates for Printed Wiring Boards*

UL STANDARD FOR PRINTED WIRING BOARDS

Underwriters Laboratories has developed the following standard:

- UL 796, *Printed Wiring Boards*

DEVELOPMENT PROGRAMS

Solventless adhesives for bonding flexible circuits are being evaluated. These would greatly reduce or eliminate measures otherwise necessary to comply with Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) standards and regulations governing solvent emissions.

High-performance adhesives and improved processing systems and substrates for the additive process are under continuous development.

Multilayer circuit technology is being refined to improve production precision and efficiency.

TABLE 9-3 Requirements for Copper-Clad Thermoset Laminates for Printed Circuits (Conditioning by ASTM Method D 618) (ASTM D 1867)

PROPERTY	GRADE									
	XXXP	XXXPC	FR-2	FR-3	FR-4	FR-5	FR-6	CEM-1	G-10	G-11
Peel strength, min lb/in width 1-oz copper	6	6	6	8	8	8	7	7	8	8
Volume resistivity, min, Ω·cms $^{1}/_{16}$–$^{1}/_{8}$ in	10^7	10^7	10^7	10^8	10^9	10^9	10^9	10^9	10^9	10^9
Surface resistance min, ohms	10^6	10^6	10^6	10^7	10^7	10^7	10^7	10^7	10^7	10^7
Dielectric breakdown parallel to laminations, min kV, step-by-step	15	15	15	30	40	40	30	40	40	40
Dielectric constant max @ 1,000 Hz	5.3	5.3	5.3	4.8	5.4	5.4	4.3	—	5.4	5.4
Dissipation factor max @ 1,000 Hz	0.05	0.05	0.05	0.040	0.035	0.035	0.03	0.040	0.035	0.035
Flexural strength min, psi										
Lengthwise	12,000	12,000	12,000	20,000	60,000	60,000	15,000	50,000	60,000	60,000
Crosswise	10,500	10,500	10,500	16,000	50,000	50,000	15,000	40,000	50,000	50,000
Water absorption max, %, $^{1}/_{16}$ in	1.00	0.75	0.75	0.65	0.25	0.25	0.40	0.30	0.25	0.25

TABLE 9-4 Thickness Tolerances for Copper-Clad Sheets (Plus or Minus, Inches) (From ASTM D 1867)

	CLASS I			CLASS II	
	GRADES XXXP, XXXPC, FR-2, FR-3		GRADES FR-4 FR-5, CEM-1[c], FR-6, G-10, G-11	GRADES XXXP, XXXPC, FR-2, AND FR-3	GRADES FR-4, FR-5 G-10, G-11
OVERALL THICKNESS INCLUDING COPPER, in[b]	1 oz, 1 SIDE	1 oz, 2 SIDES 2, 3, 4, AND 5 oz COPPER	ALL WEIGHTS OF COPPER— 1 AND 2 SIDES	ALL WEIGHTS OF COPPER— 1 AND 2 SIDES	ALL WEIGHTS OF COPPER— 1 AND 2 SIDES
1/32 (0.031)	0.004	0.0045	0.0065	0.003	0.004
3/64 (0.046)	0.005	0.0055	0.0075	0.0035	0.005
1/16 (0.062)	0.0055	0.006	0.0075	0.004	0.005
3/32 (0.093)	0.007	0.0075	0.009	0.005	0.007
1/8 (0.0125)	0.0085	0.009	0.012	0.006	0.009
5/32 (0.156)	0.0095	0.010	0.015	0.007	0.010
3/16 (0.187)	0.010	0.011	0.019	0.008	0.011
7/32 (0.218)	0.011[a]	0.012[a]	0.021	0.009	0.012
1/4 (0.250)	0.012[a]	0.012[a]	0.022	0.009	0.012

[a]These values do not apply to grades XXXPC and FR-2.

[b]Conversion factor: 0.001 in = 0.0254 mm

1 oz = 28 g.

[c]No standard has been developed for thicknesses greater than 3/32 in.

Note 1—At least 90% of the area of the sheet shall be within the tolerances given, and at no point shall the thickness vary from the nominal by a value greater than 125% of the specified tolerance.

Note 2—For a sheet having a nominal thickness not listed in the table, the tolerance shall be the same as for the next larger nominal thickness.

Note 3—Cut panels, less than 18 by 18 in, meet the applicable thickness tolerances in 100% of the area of the panel.

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The goal of integrated circuit engineers, said to be well within the realm of possibility, is to squeeze 10,000,000 transistors on a single chip.

MARKET TRENDS

The trend to miniaturize electronic circuits has made dramatic progress through the 70s, 80s, and 90s. This trend and progress is certain to continue with increasing use of integrated microcircuits on chips of silicon or gallium arsenide (much higher price, but six times faster).

Thin laminates for multilayer circuits are growing at almost double the rate for standard clad laminates.

There is increasing demand for flatter boards to avoid "popping" components once they are inserted.

10

Dielectric Films

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INTRODUCTION

The term *films*, as used in this handbook, also includes thin sheets. Generally speaking, films have thicknesses of 0.003 inch or less and sheets are over 0.003 inch thick. However, Federal Specification MIL-I-631 sets 0.002 inch as the demarcation thickness and ASTM Standard D 2305 covers "polymer films not over 15 mils (0.0015 inch) thick." Thicker sheets and substrates used for flexible printed circuits and flexible cable are covered in Chapter 9, *Unclad and Clad Structures*. Tapes slit from films are covered in Chapter 12, *Tapes and Coated Fabrics*.

Although by far the largest volume use for films is in packaging, they have important applications as phase and layer insulation in transformers and rotating equipment and as electronic capacitor dielectrics.

TECHNOLOGY

Film manufacture is accomplished by several processes, but consistently high-quality products are as much the result of process design and control as of equipment type or capacity. Production techniques may be quite simple, as in the case of extruded film, or highly complex, as in the case of blown film. The major film forming processes are these:

- *Extrusion* is one of the most versatile and widely used methods. A single-screw extruder for films consists essentially of a hopper (for resin storage), a barrel provided with means to both add and extract heat, a metering screw (which picks up resin under the hopper, heats and carries it through the barrel, and develops sufficient pressure to force it through a die), and a die (which spreads the melt into film). There are many styles of screw design. Screw selection depends primarily on the resin to be processed. The ratio of the barrel length to the bore diameter, commonly referred to as the L/D ratio, is usually in the range of 20:1–90:1. Shear energy imparted by the action of the screw on some resins often requires heat to be extracted from the melt by cooling the barrel. With other resins, it is necessary to add heat to obtain the desired consistency in the melt. Generally, film in widths up to 120 inches is extruded onto three nonnipping cooling rolls of 12–36 inches in diameter. Alternatively, a water bath is sometimes used for cooling the film. Multiscrew extruders are available for specialized applications, such as the processing of heat-sensitive materials or materials that must leave the die at relatively low temperatures. Extruded film may be oriented by stretching as it passes between heated nip rolls, where a second set of rolls rotate slightly faster than the first. Transverse orientation is accomplished by tenter frames, similar to those used in stretching textiles, with the film first heated to increase its ductility. The tendency of the stretched film to relax is reduced by passing it through a heated oven. After cooling, the film is wound into master rolls.
- *Blown film* is made by vertical extrusion of a plastic tube through an annular die provided with a means of feeding compressed air into the center of the tube. At the start of the process, the open end of the tube is drawn together and sealed. The air line is opened and a bubble is formed, usually $1^1/_2$–3 times the tube diameter. The

bubble is cooled by cold air, and then collapsed by wood slats or rollers, changing shape to a two-layer, flat film, which now becomes single-ply. Machine tension orients the film in the direction of bubble travel. The blowing action imparts transverse orientation. Thus, the film is biaxially oriented. The many variables in this process make precise control necessary to avoid variations in film thickness, low tensile strength, low impact strength, hazy film, blocking, and wrinkling. In comparing blown film with unoriented extruded flat film, the former has no losses in edge trimming (flat film edges are thickened because of neck-in), mechanical properties are better because of biaxial orientation, and equipment and die costs are lower. The extruded flat film process, however, yields superior optical clarity, has generally higher output, maintains closer thickness tolerances, and handles a wider range of melt viscosities.

- *Coextrusion* involves the simultaneous extrusion through a common die head of the same or different materials. Many variations of this technique are possible, including using a center layer as an adhesive, and foamed/film constructions (alternatively made in a separate laminating operation). Die design is crucial in this process where two or more extruders are coupled to a single die head. Most coextrusions bring the separate melts together prior to being extruded, although this can also be done outside the die. Precise control is necessary over screw speed, and melt pressures and temperatures. This process, although complex, makes possible the manufacture of a single film with superior properties to those of its component films taken separately.

- *Solvent casting* consists of forming a solution of the film resin particles and additives in a suitable solvent and thoroughly filtering this solution to remove all contaminants. The purified solution is then cast from a slot die onto a moving, endless, highly polished stainless steel belt. The solvent is removed by controlled heating as the belt passes through an oven. Finally, the finished film is stripped from the belt at the take-off station. Gauge control is achieved by adjusting the die opening across its width. The film produced by this method is free of strain and orientation with equal properties in all directions. If desired, the film may subsequently be oriented. This process is always used for cellulose triacetate, and is also used where wanted for fluoropolymers, polysulfones, polycarbonates, and polyimides (before imidization). Solvent casting is slower and much more expensive than extrusion or blown film methods, and measures must be taken to ensure solvent handling complies with worker safety and health and environmental guidelines and legislation.

ASTM STANDARD FOR TESTING FILMS

The American Society for Testing and Materials has developed the following standard:

- D 2305, *Standard Methods of Testing Polymeric Films Used for Electrical Insulation*.

This standard covers the testing of homogeneous organic polymer films not over 15 mils (0.4 mm) thick that are to be used for electrical insulation. Procedures include:

- Conditioning
- Dielectric breakdown voltage and dielectric strength
- Insulation resistance
- Permittivity (dielectric constant) and dissipation factor
- Resistance method for measuring the tendency to corrode metals
- Sampling
- Strain relief
- Tensile properties
- Thickness
- Volume resistivity

Applicable ASTM documents are cited for conducting these tests.

FEDERAL SPECIFICATION FOR FILMS

The governing Federal Specification for films is:

• MIL-I-631, *Insulation, Electrical, Synthetic-Resin Composition, Nonrigid.* This specification has been approved by the Department of Defense for use of the Departments of the Army, Navy, and the Air Force. It covers only the basic characteristics required by the synthetic insulating material, as such, and the methods suited to their satisfactory determination. *Film* is defined as material in thicknesses of 0.002 inch or less, in widths greater than 3 inches. Material 3 inches or less in width, slit from film, is defined as *film tape*. *Sheet* is defined as material in thicknesses greater than 0.002 inch and in widths greater than 3 inches. Material 3 inches or less in width slit from sheet is defined as *sheet tape*.

The following film types are identified:

Type A—Polyethylene
Type B—Cellulose acetate butyrate
Type C—Cellulose acetate or cellulose triacetate
Type D—Ethyl cellulose
Type E—Vinylidene chloride copolymer
Type F—Polyvinyl chloride and its copolymers
Type G—Polyethylene terephthalate

Requirements are listed for these properties for each type:

- Dielectric strength
- Dielectric constant
- Dissipation factor
- Volume resistivity
- Tensile strength
- Elongation
- Softening temperature
- Lengthwise shrinkage

DEVELOPMENT PROGRAMS

There is available technology for producing a virtually unlimited number of films and film composites to meet requirements for state-of-the-art electrical insulation applications. Development efforts focus on production techniques to make films free of contaminants and surface imperfections.

MARKET TRENDS

Use of dielectric films and composites will parallel trends in the electrical industry.

DIELECTRIC FILMS

These films are covered in the sections which follow, with typical property values shown in Table 10-1.

- Cellulose acetate (CA) and cellulose triacetate (CTA)
- Fluoropolymers (PTFE, PFA, FEP, ETFE, PVDF, ECTFE, PCTFE)
- Ionomer
- Polycarbonate (PC)
- Polyester (PET)
- Polyethylene (PE)
- Polyimide (PI)
- Polyparabanic acid (PPA)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyvinyl chloride (PVC)
- Polysulfone
- Polyethersulfone

Cellulose Acetate (CA) (Film)

Cellulose films were among the first films to be used as dielectrics. Cellulose acetate (CA) film is produced by ICI, 3M, and XCEL. Cellulose triacetate (CTA) film is made by Eastman Chemical and XCEL.

Chemistry

Cellulose acetate, also called *secondary acetate* or *diacetate*, is made by acetylating wood pulp or cotton linters with acetic acid or acetic anhydride, using a sulfuric acid catalyst. This ester is then partially hydrolyzed to form a thermoplastic product solu-

ble in acetone and capable of being plasticized by lower alkyl phthalates and alkoxyalkyl phthalates.

Cellulose triacetate is fully acetylated, purified cellulose, made in a similar reaction but omitting the hydrolysis step. Solvents include methylene chloride, chloroform, and tetrachloroethane. The film is formed by the solvent casting method.

Federal Specification for Cellulose Acetate Film

The following Federal specification has been developed for cellulose acetate film:

- L-P-504, *Plastic Sheet and Film, Cellulose Acetate*

Grades

Cellulose acetate and cellulose triacetate are available as glossy, clear films, or with a matte finish on one side to prevent slippage and increase visibility in coil winding applications.

Properties

Cellulose acetate and cellulose triacetate are designated as Class 105 insulations. Dielectric properties are good except for low moisture resistance. Key property values are shown in Table 10–1.

Electrical/Electronic Uses

Cellulose acetate is used to wrap coils, as layer and interphase insulation, as wire covering, and as capacitor insulation. A major use for cellulose triacetate is as a base for magnetic tape.

Fluoropolymers (Film)

This family of high-price films is useful for applications requiring performance beyond the capabilities of other films. In general, fluoropolymer films are characterized by exceptionally wide useful temperature range, excellent dielectric properties, and outstanding resistance to attack by chemicals.

Chemistry

The basic chemistry and structures of the fluoropolymer resins used for films are covered in "Fluoropolymers" (p. 146) Chapter 5, *Extrusion Compounds*.

ASTM Standards for Fluoropolymer Films

The American Society for Testing and Materials has developed the following specifications for fluoropolymer films:

- D 3368, *FEP-Fluorocarbon Resin Sheet and Film*
- D 3369, *Polytetrafluoroethylene (PTFE) Resin Cast Film*
- D 3595, *Polytrifluoroethylene (PCTFE) Extruded Sheet and Film*

TABLE 10-1 Typical Property Values for Dielectric Films

	ASTM TEST	CELLULOSE ACETATE (CA)	CELLULOSE TRIACETATE (CTA)	FLUOROPOLYMERS PTFE	PFA	FEP	ETFE	PVDF	ECTFE	PCTFE	IONOMER
1. Tensile strength, psi × 10^3	D 882	7–16	9–16	3.3	4–7	2.5–3.0	7–8	6.0–6.5	8.0–10	5–10	5
2. Elongation %	D 882	15–55	10–50	300	200–600	300	300	300–500	150–250	200–600	250–450
3. Bursting strength, 1 mil thick, Mullen points	D 774	30–60	50–70	—	—	11	—	—	—	28–31	—
4. Tearing strength (propagating), g/mil	D 1922	4–10	4–30	10–100	40–70	125	600–900	50	900–1,300	2.4–40	30–125
5. Water absorption, % 24 h, 1 mil thick	D 570	3–8.5	2–4.5	nil	0.03	0.01	0.02	0.04	0.02	nil	0.4
6. Water vapor transmission rate, g/100 sq in 24 h	E 96E										
@ 73°F (23°C), 90% R.H.		10–40	30–40	—	—	—	—	2.6	—	—	—
@ 100°F (38°C), 90% R.H.		—	—	—	—	0.4	1.65	—	0.6	0.02–0.05	1.5–2.0
7. Permeability to gases cm^3/100 sq in/24 h @ atmospheric pressure, 73°F (23°C), 0% R.H.	D 1434										
O_2		117–150	150	—	—	750	100	14	25	7–15	2.6
CO_2		860–1,000	880	—	—	1,670	250	5.5	110	16–40	10–12
8. Dielectric strength, volts/mil, short time	D 149										
50% R.H., 73°F (23°C), 1 mil film		4,000	4,000	2,200–4,400	4,000–5,000	5,000	5,000	—	5,000–6,000	3,000–3,900	—
9. Dielectric constant @ 73°F (23°C)	D 150										
10^3 cycles		3.6	3.2–4.5	2.0	2.0	2.0	2.6	8.4	2.6	2.6	2.4
10^6 cycles		3.2	3.3–3.8	2.0	2.0	2.0	2.6	6.6	2.6	2.3	2.4
10. Dissipation factor @ 73°F (23°C)	D 150										
10^3 cycles		0.013	0.016	0.0001	0.0002	0.0002	0.008	0.018	0.002	0.023	0.002
10^6 cycles		0.038	0.033	0.0001	0.0002	0.0003	0.0005	0.170	0.013	0.012	0.007
11. Volume resistivity, Ω cm, 73°F (23°C)	D 257	10^{15}	10^{15}	10^{18}	10^{18}	10^{18}	10^{16}	2×10^{14}	10^{16}	10^{18}	10^{16}
12. Chemical resistance (G = Good, F = Fair, P = Poor)											
Strong acids	D 543	P	F	G	G	G	G	G	G	G	G
Strong alkalies	D 543	P	P	G	G	G	G	G	G	G	G
Greases and oils	D 722	G	G	G	G	G	G	G	G	G	G
Organic solvents	D 543	P	F-P	G	G	G	G	G	G	G	G
13. Maximum use temperature °F (°C)		250 (120)	250 (120)	500 (260)	500 (260)	400 (205)	300 (150)	300 (150)	330 (165)	300 (150)	190 (90)
14. Thickness range, mils											
Minimum		0.88	2.0	0.25	0.5	0.5	—	0.5	0.5	0.75	1.5
Maximum		30	20	30	90	30	—	40	90	10	3.8
15. Maximum available width, inches		60	47	48	48	48	48	50	54	48	72
16. Specific gravity	D 1505	1.3	1.3	2.1	2.2	2.2	1.7	1.8	1.7	2.1	0.9

*MD = Machine direction.
TD = Transverse direction.

TABLE 10-1 (*Continued*)

POLYCARBONATE (PC)	POLYESTER (PET)	LOW DENSITY POLYETHLYENE (LDPE)	POLYIMIDE (PI)	POLYPARABANIC ACID (PPA)	POLYPROPYLENE		POLY-STYRENE (PS)	POLYVINYL CHLORIDE (PVC)	SULFONE POLYMERS	
					(PP) UNORIENTED	BIAXIALLY ORIENTED	BIAXIALLY ORIENTED	PLASTICIZED, EXTRUDED	POLYSULFONE EXTRUDED	POLYETHERSULFONE EXTRUDED
7.5–9.5	1.5–4	1.5–4	25	16	4–7	23–25	9–12	1.4–10	8.4–10	10–12
85–110	150	200–800	70	75	800–850	90	10–20	100–500	64–110	20–150
no brk	55–80	10–12	75	—	—	—	16–35	20	—	—
20–25	12–27	50–300	8	6	MD-20* TB-450*	MD-3* TD-10*	5	60–1000	9–12	7–16
0.35	0.5	0.01	2.9	2.8	0.005	0.005	0.04–0.10	neg.	0.3	2.1
—	—	—	—	—	—	—	—	—	—	340
11	1.6–1.8	1.0–1.5	5.4	—	0.7	0.25–0.4	7–10	5–30	18	—
300	3–6	500	25	—	150–240	160	300	300–1,100	230	90
1,075	15–25	2,700	45	—	500–800	540	900	30–6,000	950	405
6,300	7,000–7,500	5,000	7,000	6,400	—	5,000	5,000	1,800 (5 mil)	7,500	5,800
3.0	3.2	2.2	3.5	3.4	2.2	2.2	2.4–2.7	4–8	3.1	3.5
2.9	3.0	2.2	3.4	—	2.2	2.2	2.4–2.7	3.3–4.5	3.0	3.5
0.0015	0.005	0.0003	0.0025	0.003	0.0003	0.0003	0.0005	0.07–0.16	0.0008	0.00035
0.010	0.016	0.0003	0.010	—	0.0003	0.0003	0.0005	0.04–0.14	0.0034	0.006
10^{16}	10^{18}	10^{16}	10^{18}	—	3×10^{15}	5×10^{14}	10^{16}	10^{14}	10^{16}	10^{17}
G	G	G	G	G	G	G	G	G	G	G
P	P	G	P	P	G	G	G	G	G	G
G	G	P	G	G	G	G	G-P	G	G	G
G-P	G	F	G	G	G	G	G-P	P-F	P	G-P
270	300	200	465	340	270	270	160	220	300	356
(132)	(150)	(90)	(240)	(170)	(130)	(130)	(70)	(105)	(150)	(180)
0.25	0.08	0.3	0.3	1.0	0.75	0.45	0.25	0.5	0.1	0.1
30	14	10	5	5	10	3.5	20	40	30	30
45 cast 54 extr	120	240	60	—	69	120	76	80	52	52
1.2	1.4	0.9	1.4	—	0.9	0.9	1.05	1.2–1.4	1.2	1.4

Federal Specification for Fluoropolymer Film

The following Federal specification has been developed for fluoropolymer film:

- L-P-523, *Plastic Sheet and Film, FEP-Fluoropolymer, Extruded*

Grades and Characteristics

Suppliers, grades, advantages, and limitations of fluoropolymer films are shown in Table 10-2.

Processing

All fluoropolymer films except polytetrafluoroethylene are made by conventional extrusion techniques. Polytetrafluoroethylene film is skived (shaved continuously from the surface of a cylindrical block of molded resin), paste extruded and sintered, or cast from aqueous dispersion, after which the water is removed by heat and the resin fused at over 700°F (370°C). Polyvinylidene fluoride film is solvent-cast as well as extruded.

Properties

Key film property values are shown in Table 10-1.

Table 10-2 Summary of Characteristics of Fluoropolymer Films

FLUOROPOLYMER	SUPPLIERS	GRADES	ADVANTAGES	LIMITATIONS
Polytetrafluoro-ethylene (PTFE)	Carborundum Chemplast Dixon Garlock W. L. Gore Norplex Oak Polymer Corp. Carborundum	Cast Paste extruded followed by sintering Dispersion cast (free of pinholes)	Widest useful thermal range of all plastics (−267° to 260°C). Unaffected by virtually all chemicals. Dielectric constant is relatively unchanged (about 2.1) with time, frequency, or temperature. Arc resistance over 300 with no carbonization. Oxygen index over 95%.	Cannot be melt processed. Poor resistance to corona and radiation.
Perfluoroalkoxy (PFA)	Du Pont	Standard grade Modified grade treated to adhesions on one side.	Dielectric, mechanical, thermal, and chemical properties equal to PTFE. Better mechanical properties than FEP above 150°C. Can be processed by conventional extrusion techniques.	Lower abrasion resistance and higher in price than PTFE.
Fluorinated ethylene-propylene copolymer (FEP)	Du Pont	Standard grade Modified grade treated to promote adhesion on one or both sides	Dielectric, mechanical, chemical properties equal to PTFE and PFA. Thermal range −73° to 205°C. Can be processed by conventional extrusion techniques. Oxygen index of 95%.	Narrower useful thermal range than PTFE or PFA. Not as tough as PTFE. Price between PFA and PTFE.

(*continued*)

Table 10-2 (*Continued*)

FLUOROPOLYMER	SUPPLIERS	GRADES	ADVANTAGES	LIMITATIONS
Ethylene-tetra-fluoroethylene (ETFE)	Du Pont Hoechst Celanese	Standard grade Modified grade treated to promote adhesion on one side	Mechanical properties better than other fluoroplastics except PCTFE. Can be processed by conventional extrusion techniques.	Dielectric properties not quite as good as PTFE, PFA, and FEP. Lower max operating temperature than PTFE, PFA, FEP, and ECTFE. OI of 28–32%. Price about the same as PFA.
Polyvinylidene fluoride (PVDF)	Ferro Rexham Westlake	Cast Cast Extruded	Can be solvated by organic esters and ketones as well as processed by conventional extrusion techniques. High abrasion resistance and resistance to UV and nuclear radiation. Oxygen index of 44%. Lowest price of fluropolymers.	Highest dielectric constant and dissipation factor of all fluoropolymers. Chemical resistance lowest. Useful thermal range (–62° to 150°C) narrowest.
Ethylene-chloro-trifluro ethylene copolymer (ECTFE)	AlliedSignal	Standard extrusion grade	Highest tensile strength abrasion resistance of all fluoropolymers. Good dielectric properties. Can be processed by conventional extrusion techniques. Oxygen index of 60. Lowest specific gravity (1.68) of all fluoropolymers. Outstanding permeability resistance to water vapor, gases, liquids.	Attacked by hot amines (otherwise good chemical resistance). Price about equal to FEP.
Polychlorotrifluoro-ethylene (PCTFE)	AlliedSignal	Good barrier property grade Good dimensional property grade	Excellent resistance to oxygen, ozone, fuming oxidizing acids, sunlight. Outstanding barrier to gases and liquids. Good abrasion resistance. Can be processed by conventional extrusion techniques. Good dielectric properties.	Precise control of temperature required in processing to prevent degradation. Attacked by some halogenated solvents. Price is highest of all fluoropolymers.

Electrical/Electronic Uses

Principal uses are for severe conditions of temperature or environment. Applications include:

- Wrapped insulation on high-temperature wire and cable
- Motor coil, phase, and ground insulation
- Capacitor dielectric
- Substrate for flexible printed circuits and flexible cables
- Pressure-sensitive tapes

Imide Polymers: Polyetherimide (PEI) (Film)

A recent (1993) entry into the dielectric film market, polyetherimide film, produced by General Electric with the trademark Ultem 5000, competes with polyimide film for some Class 180 and above transformer and motor applications. The film is reported to have dielectric strength comparable to polyimide film with higher thermal conductivity and lower moisture absorption at significantly less cost. Minimum film thickness is 1 mil.

Compared with aramid paper, PEI film has much higher dielectric strength and lower moisture absorption, thus permitting smaller and more efficient equipment designs.

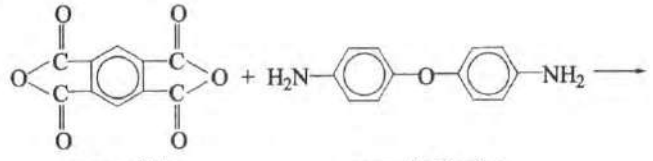
For information on the chemistry and key properties of PEI resin, see "Imide Polymers: Polyetherimide (PEI)," p. 83, Chapter 3, *Thermoplastic Molding Compounds*.

Imide Polymers: Polyimide (PI) (Film)

Polyimide film, first commercially available in 1966, has the best thermal properties of all organic films. It is inherently flame resistant and remains useful in environments of intense radiation. The film is made by Du Pont under the trademark Kapton in the United States and by ICI with the trademark Upilex. There are also several Japanese producers of polyimide-type films.

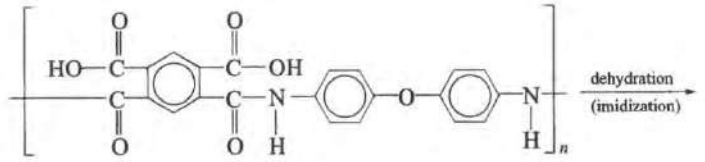
Chemistry

Polyimide film is the condensation product of pyromellitie dianhydride (PMDA) with an aromatic diamine:

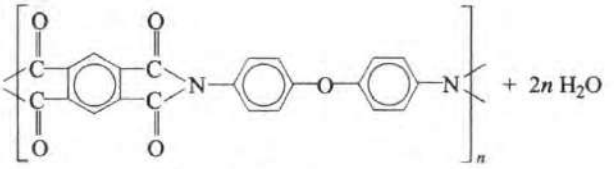


pyromellitic dianhydride (PMDA)

aromatic diamine (4,4'-diamino-diphenyl ether)



poly(amide-acid)



polyimide resin

The polymer is said to be cast into a film from solvent solution before the imidization step. After imidization, the film is usually biaxially oriented.

Federal Specification

The governing military specification for polyimide film is MIL-P-46112, *Plastic Sheet and Strip, Polyimide*. This specification covers polyimide sheet and strip with or without heat sealable FEP-fluorocarbon coatings. The following types and grades are designated:

Type I—General purpose
Type II—Heat sealable
  Grade A—One side coated
  Grade B—Two sides coated.

Requirements are listed for Type I sheet and strip, including tensile strength, elongation, shrinkage, moisture absorption, dielectric strength, volume resistivity, dielectric constant, and dissipation factor. Requirements for Type II sheet and strip include dielectric strength and minimum heat seal strength.

ASTM Standards for PI Films

The American Society for Testing and Materials (ASTM) has developed the following standards for polyimide films:

- D 5213, *Specification for Polyimide Resin Film for Electrical Insulation and Dielectric Applications*
- D 5214, *Test Method for Polyimide Resin Film for Electrical Insulation and Dielectric Applications*

Grades

There are three principal types of Kapton commercially available:

- Type HN, an all-purpose film that can be laminated, metallized, and adhesive coated.
- Type VN, similar to Type HN but with better dimensional stability.

• Type FN, a Type HN film coated on one or both sides with Teflon™ FEP fluorocarbon resin to impart heat sealability, provide a moisture barrier, and enhance chemical resistance.

Properties

Kapton film has no melting point and remains useful over the temperature range of –450 to 660°F (–269°–350°C). It will function continuously at 465°F (240°C). Physical attributes include high tensile strength, and high resistance to creep, cut-through, and abrasion. Dielectric properties are generally good, although except for dielectric strength, they decrease significantly with increasing temperature. Radiation resistance and resistance to ultraviolet light are outstanding. However, the film is vulnerable to attack by alkalis and strong inorganic acids, and moisture absorption rate is among the highest for all dielectric films.

Key property values are shown in Table 10-1.

Electrical/Electronic Uses

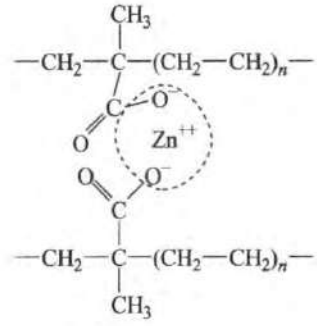
Because of its relatively high price, Kapton film is used principally where its unique properties make it the only suitable film, and also where its use permits economies in design which offset its high price. Typical applications include use in motors, where it replaces thicker dielectrics, permitting more powerful, cooler running motors with no increase in frame size; use in aerospace electrical equipment subject to temporary overloads; use in high-performance wire and cable constructions where it provides significant savings in space and weight; use as a substrate for flexible printed circuits and flat cables; and use as a capacitor dielectric.

Ionomer (Film)

Ionomer resins were introduced in the middle 1960s with the trademark Surlyn by Du Pont, and have since found extensive use in molded products such as cut-resistant golf balls and automotive bumper components. Powdered resins are fused by heat or infrared radiation to no-return glass beverage bottles, making them shatter-resistant and permitting 25 percent savings in glass with quieter processing. By far the largest use for inomer, however, is in packaging applications, usually in combination with paper, foil, and other films.

Chemistry

The term ionomer, a contraction of ion and polymer, describes ethylene copolymers with methacrylic or acrylic acid, bonded together by ionic forces. Interchain bonding takes place through metallic ions, predominantly Zn^{++} formed as carboxylic groups on methacrylic or acrylic acid which are neutralized:



This type of crosslinking is thermally reversible, making it possible to process ionomers by conventional thermoplastic techniques.

Grades

Ionomer film is available in extruded grades, but is generally supplied in combination with paper, foil, and other films for specific end uses. Military purchases for extrusion grades are made to MIL-P-46124, *Plastic Molding and Extrusion Material, Ionomer Resins.*

Properties

The oustanding property of ionomer is its toughness and abrasion resistance, as exemplified by its use as a golf ball cover and for automotive bumper parts. Its low specific gravity of 0.9–1.0 permits high yields. Maximum use temperature of 190°F (90°C) is relatively low.

Key property values are shown in Table 10-1.

Electrical/Electronic Uses

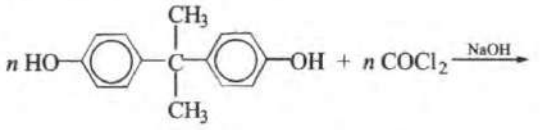
Although ionomer possesses good dielectric properties, its use is limited as electrical insulation since the polymers with which it competes (polyvinyl chloride, polyethylene) are much lower in price. However, this price disadvantage is offset in the case of polyvinyl chloride by its high yield and greater toughness, permitting thinner ionomer films to be substituted for thicker polyvinyl chloride films. Ionomer films also do not have plasticizer problems common to polyvinyl chloride films.

Polycarbonate (PC) (Film)

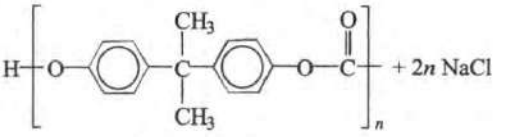
One of the more recently developed resins for extruded and solvent cast film, polycarbonate is used for a variety of electrical/electronic applications. Producers of electrical grade film include General Electric (extruded) and Kimberly-Clark (solvent cast).

Chemistry

Polycarbonate is made by reacting bisphenol A with phosgene in the presence of a caustic:



bisphenol A phosgene



polycarbonate

Polymerization may be in aqueous emulsion or in nonaqueous solution. Methylene dichloride is a preferred solvent in the solvent casting process.

Grades

Capacitor grades are made by solvent casting with Kimberly-Clark the sole producer. Grades for other electrical/electronic applications are made by General Electric, including a UV-stabilized grade. Films are usually biaxially oriented.

Properties

Polycarbonate film as good flexibility, heat resistance, dimensional stability, and thermoforming characteristics. Dielectric constant is virtually unaffected by temperature or frequency within the temperature range of –75° to 250°F (–60°–120°C). The film resists attack by oils, fats, and dilute acids, but is affected by alkalis, amines, ketones, esters, and aromatic hydrocarbons. Water vapor and gas transmission rates are relatively high. The film can be heat sealed.

Key property values are shown in Table 10-1.

Electrical/Electronic Uses

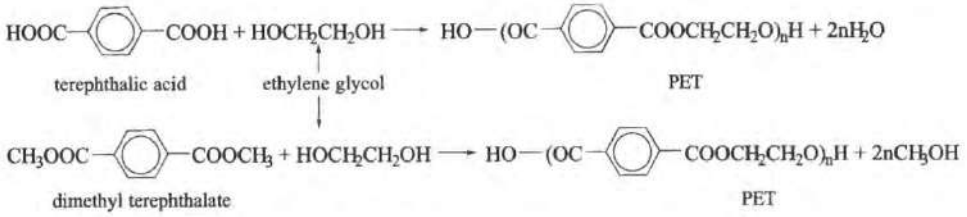
Solution cast film is used almost exclusively in capacitors. Extruded film is used for coil insulation, slot insulation, conductor insulation, and as a substrate for flexible printed circuits.

Polyester (PET) (Film)

Polyethylene terephthalate film is an exceptionally strong and durable film, used for a wide variety of industrial and packaging applications. Major producers for the merchant market are Hoechst Celanese (Celanar™), Du Pont (Mylar™), ICI (Melinex™), and 3M (Scotchpar™, Scotchpak™).

Chemistry

Polyester resin is produced by direct esterification of ethylene glycol and terephthalic acid, or by catalyzed ester exchange between glycol and dimethyl terephthalate, followed by polycondensation to a high-molecular-weight polymer:



Grades

Polyester film by itself is clear and slippery. It can be made heat-sealable by coating with polymers or laminating with polyethylene film. Friction-coated films are produced to eliminate slippage in wrapping operations. Film with a matte finish on one side is also available. Most polyester film is biaxially oriented.

Properties

Polyester film is characterized by outstanding tensile strength and flexibility, desirable dielectric properties, general chemical inertness, and useful temperature range of –80° to over 300°F (–20°–150°C). However, propagating tear strength is low and resistance to ultraviolet light is poor. Under humid conditions and high temperatures, the film has a tendency to hydrolyze. The film is designated Class 130 insulation.

ASTM Standards for PET Film

The American Society for Testing and Materials (ASTM) has developed the following standards for polyester film:

- D 3664, *Specification for Biaxially Oriented Polyethylene Terephthalate Film for Electrical Insulation and Dielectric Applications*. The material is biaxially oriented to improve the tensile properties in both the machine and transverse directions (MD and TD). For the purposes of this standard, film is defined as a piece of material not exceeding 0.250 mm (0.01 inch) in thickness and exceeding 100 mm (4 inches) in length and width. Tests for the properties covered are shown in Table 10–3.

  Key property values are shown in Table 10-1.

- D 5047, *Specification for Polyethylene Terephthalate Film and Sheeting*

Electrical/Electronic Uses

Polyester film is used extensively for flexible printed circuits and flat cables, for wrapping wire and cable, for slot-wedge and phase insulation in motors, as barrier and layer insulation in transformers, and as the dielectric in electronic capacitors.

Table 10-3 Property Tests and Test Methods for Biaxially Oriented Polyethylene Terephthalate Film (ASTM D 3664)

PROPERTY MEASURED	ASTM METHOD
Dielectric breakdown	D 149
Dielectric constant (permittivity)	D 150
Sampling	D 202
DC resistance of conductance	D 257
Thickness	D 374
Chemical resistance	D 543
Water absorption	D 570
Conditioning	D 618
Folding endurance	D 643
Basis weight	D 646
Grease resistance	D 722
Bursting strength	D 774
Tensile properties	D 882
Tear resistance	D 1004
Gas transmission rate	D 1434
Outdoor weathering	D 1435
Density	D 1505
Melting point	D 2117
Folding endurance	D 2176
Combustibility	D 2863
Impact resistance	D 3420
Water vapor transmission	E 96

Polyester Film Composites

Polyester film is often combined with other materials, including polyester mat. These composites, used primarily as dielectric barriers with thermal rating 130°C, are covered by military specification MIL-I-22834, *Insulation, Electrical, Dielectric Barrier, Laminated, Plastic Film and Synthetic Fiber Mat*. The following compositions are designated:

- Composition D100—One layer of polyethylene terephthalate fiber mat laminated to each side of a polyethylene terephthalate film or sheet (triplex). The mat is completely impregnated with epoxy resin.
- Composition D70—One layer of polyethylene terephthalate fiber mat laminated to each side of a polyethylene terephthalate film or sheet (triplex). The mat is 70 percent impregnated with epoxy resin.
- Composition D—One layer of polyethylene terephthalate fiber mat laminated to each side of a polyethylene film or sheet (triplex). The mat is heat bonded to the film.

Minimum requirements are listed for dielectric strength, volume resistivity, tensile strength, tear resistance, and absorbency.

See also MIL-I-19632 on paper-film composites, summarized (p. 324) in Chapter 11, *Dielectric Papers and Boards*.

Polyethylene (PE) (Film)

Polyethylene film is made from a wide variety of polyethylene densities, molecular weights, and melt indexes as described in "Ethylene Polymers" (p. 154) of Chapter 5, *Extrusion Compounds*. Principal electrical/electronic applications for polyethylene is as an extruded dielectric in wire and cable (q.v.). There is some usage for films as splicing tape after it has been coated with pressure-sensitive adhesive, and as a capacitor dielectric. The relatively low maximum service temperature of 80° to 90°C (176°–194°F) (depending on grade) limits use for other applications.

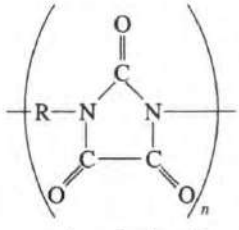
Key film property values of low-density polyethylene (LDPE) are shown in Table 10–1.

Polyparabanic Acid (PPA) (Film)

Polyparabanic acid (PPA) film was developed by Exxon Chemical, and became commercially available in 1979 with the trademark Tradlon. The film is no longer commercially available.

Chemistry

Polyparabanic acid film is made by solvent casting techniques. Known solvents include cyclic ketones, such as cyclohexanone. Polyparabanic acid has the following structure:



polyparabanic acid

Properties

Polyparabanic acid film has good dielectric properties, and is suitable for use in a temperature range from –200° to 170°C (–328°–338°F). It is resistant to attack by chlorinated hydrocarbons, alcohols, ethers, and acids, but is affected by strong bases.

Key film property values are shown in Table 10–1.

Electrical/Electronic Uses

Polyparabanic acid film is suitable for use in specialty applications as a wire and cable wrap, as motor insulation, and as a substrate for flexible printed circuits and flexible flat cable. When coated with suitable adhesive, it can be used in electrical grade pressure-sensitive tapes.

Polypropylene (PP) (Film)

Polypropylene film is relatively low priced with physical and dielectric properties suitable for many electrical and electronic applications. Electrical grades of film are produced by Himont and General Electric. Electrical grade resin is made by Himont and Rexene Polymers, Division of Dart Industries.

Chemistry

Polypropylene is formed by polymerizing high-purity propylene in the presence of a Ziegler-type catalyst, such as aluminum alkyl. Principal processes are discussed in "Propylene Polymers" (p. 160) of Chapter 5, *Extrusion Compounds*.

Grades

Capacitor grades and film grades for other electrical/electronic applications are available from Himont and General Electric. Swelling of polypropylene films with impregnation by dielectric liquids is much lower with tenter process grades than with bubble process grades.

Properties

Oriented polypropylene copolymer film attributes include low price, high dielectric strength, low and stable dielectric constant and dissipation factor over a wide frequency range, good resistance to short-term voltage overloads, and excellent resistance to moisture, greases, and oils.

Key property values are shown in Table 10-1.

Electrical/Electronic Uses

A major use for propylene film is as a dielectric for capacitors. It is also extensively used as a cable wrap and for layer and phase separators in rotating electrical equipment and transformers.

Polystyrene (PS) (Film)

Uniaxially oriented polystyrene film is used to some extent as a capacitor dielectric, which field is dominated by polypropylene and polyimide films. Low maximum service temperature (70°C) and high flammability limit its suitability for other electrical/electronic applications. The predominant producer of polystyrene film is Dow Chemical. HMC is the major supplier of capacitor grade film. See "Styrenics: Polystyrene (PS)" (p. 97) Chapter 3, *Thermoplastic Molding Compounds*.

Key film property values are shown in Table 10-1.

Polyvinyl Chloride (PVC) (Film)

The principal use of polyvinyl chloride film is in the form of pressure-sensitive tapes. This supject is covered in Chapter 12, *Tapes and Coated Fabrics*.

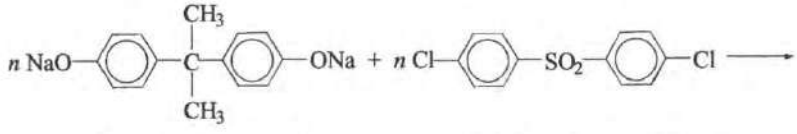
For comparison with other films, key property values for polyvinyl chloride films are shown in Table 10-1.

Sulfone Polymers: Polysulfone (Film)

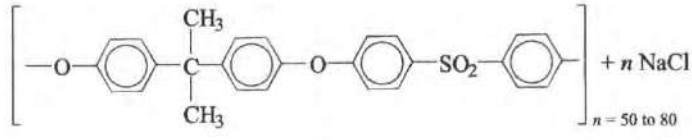
Polysulfone resins became commercially available in 1965. They possess the highest radiation resistance of all organic polymers. Union Carbide is the sole producer of the resin, using the trademark Udel. Film was made by Kimberly-Clark (solvent cast), Rowland (extruded), and Westlake (extruded), but no longer is commercially available.

Chemistry

Polysulfone is made by reacting the sodium salt of bisphenol A with 4,4'-dichlorophenyl sulfone in dimethyl sulfoxide or a similar polar solvent:



sodium salt of bisphenol A 4,4'-dichlorophenyl sulfone



polysulfone

Properties

Resistance of the film to radiation is outstanding. It has good resistance to attack by mineral acids, alkalis, salt solutions, alcohols, oils, and greases, but it is affected by esters, ketones, chlorinated hydrocarbons, and aromatic hydrocarbons. Useful temperature range is –150° to 300° (–100°–150°C). Dielectric properties are superior to those of polyethersulfone, but thermal, mechanical, and flammability values are lower.

Key property values are shown in Table 10-1.

Electrical/Electronic Uses

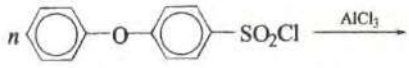
The film is used in flexible and rigid printed circuits, specialty laminates, and capacitors.

Sulfone Polymers: Polyethersulfone (Film)

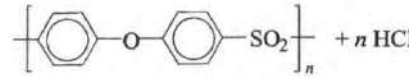
First produced in the United Kingdom, polyethersulfones became available in the United States in 1972–73. High-temperature properties are outstanding. Resins are produced by ICI Americas under the trademark Victrex. Film is made by Futurex, Kimberly-Clark (solvent-cast), and Westlake Plastics.

Chemistry

Polyethersulfone is made by Friedel-Crafts condensation of diphenyletherchlorosulfone using anhydrous aluminum chloride or similar metallic halide as a catalyst:



diphenyletherchlorosulfone



polyethersulfone

Grades

Both solvent cast from methylene chloride (for capacitors) and extruded grade films are commercially available.

Properties

Dielectric and mechanical properties of this film are largely retained up to 356°F (180°C). Dielectric values are somewhat lower than those of polysulfone, but thermal, mechanical, and flammability values are higher. Chemical resistance is similar to polysulfone.

Key property values are shown in Table 10-1.

Electrical/Electronic Uses

High price limits uses to specialized flexible circuits, flat cables, and integrated circuits. Other uses are justified by the film's high-temperature attributes.

11

Dielectric Papers and Boards

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MARKET TRENDS 321
DIELECTRIC PAPERS AND BOARDS 321
Cellulose Papers and Boards 321
Vulcanized Fibre and Fish Paper 325
Aramid Papers and Boards 326
Mica Paper 329
Other Papers and Boards 331

INTRODUCTION

Dielectric papers and boards may be produced from a variety of materials, including wood, cotton, organic fibers, glass, ceramics, and mica. The distinction between paper and board is not specific, but paper is thinner gauge, generally below 0.030 inch and boards are 0.030 inch and over. Above 0.25 inch, boards are laminated with adhesive to any desired thickness. Electrical insulating boards are referred to as pressboard, transformer board, fuller board, and presspan.

This chapter covers cellulose, vulcanized fibre, aramid, mica, glass, alumina-silica, and ceramic papers and boards.

DEVELOPMENT PROGRAMS

There is continuing emphasis among manufacturers to increase dielectric paper purity by eliminating all contaminants.

MARKET TRENDS

Because of the designation of asbestos as a toxic substance under the Toxic Substances Control Act (see Chapter 19, *Government Activities*) and publicity regarding health problems of asbestos workers, asbestos is rarely used for paper and board products. Substitute materials include aramid paper, especially the mica composite types, mica paper and composites, alumina-silica paper, ceramic paper and composites, and glass paper.

DIELECTRIC PAPERS AND BOARDS

The technology, chemistry, grades, properties, and electrical/electronic uses of principal types of dielectric papers and boards are described in the sections which follow in this order:

- Cellulose papers and boards
- Vulcanized fibre and fish paper
- Aramid papers and boards
- Mica paper
- Other papers and boards

Cellulose Papers and Boards

Cellulose base papers and boards may be made from a variety of materials, including wood pulp, cotton, hemp, ramie, jute, flax, bagasse (from sugar cane), straw, papyrus, and bamboo. The principal producers of cellulose insulating papers and boards include

Cottrell Paper, Dennison (crepe grades), Manning Paper, Mosinee, Riegel, Spaulding, Stevens, and Union Camp.

Technology

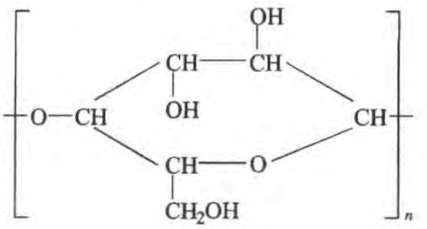
Dielectric grade paper is most often made from sulfate (kraft) wood pulp derived from coniferous, or softwood trees, such as spruce, hemlock, and pine. The first step in this process is to remove undesirable components in the wood, principally pentosans and lignin. Pentosans are complex carbohydrates which hydrolyze to sugar. Lignin is a phenylpropane polymer of amorphous structure comprising seventeen to thirty percent of wood. These materials are removed by boiling under pressure wood particles with a solution of sodium sulfite and sodium hydroxide. Sodium sulfate is then added to the caustic pulp liquors, where it is reduced to the sulfide, which then acts as a digesting agent.

This slurry, about 5 percent solids, is agitated in a tank, or "beater," by a rotating drum equipped with closely spaced sharp knives. Another set of knives is secured to the bottom of the beater. As the drum circulates the slurry, the fibers are disintegrated by the cutting and tearing action of the knives, rather than by any beating action, as the term "beater" implies. This is the most critical step in the process, requiring careful control of ingredient concentrations and time of beating, which varies with the type and quality of the paper being made. The higher the degree of beating, the greater the ability of the finished paper to absorb moisture.

The continuous paper sheet is formed on a Fourdrinier machine, where the pulp is first diluted to contain over 98 percent water. The mixture is then filtered through sand traps to remove grit, over magnets to remove magnetic particles, and through strainers to extract coarse fibers. It next pours onto a moving screen, where felting of the fibers is induced by lateral shaking. The water is screened out, with the assistance of suction boxes beneath the screen. The damp pulp is carried by the screen between felt-covered rollers, where excess water is squeezed out. The newly formed web is next transferred to a felt conveyor, which takes it through a pair of press rolls to remove more water. It then passes to another felt, and is finally dried on a series of steam-heated drums which increase in temperature from first to last, until the moisture content of the paper is reduced to 4–6 percent.

High-grade insulating papers are also made by an analogous process from hemp and cotton rags or linters, and combinations of these with wood pulp.

Cellulose $(C_6H_{10}O_5)_n$ is a high-molecular-weight polymer consisting of crystalline areas embedded in amorphous areas. The polymer is essentially linear, but with some crosslinking. The polymer unit may be represented as follows:



Through a process termed *cyanoethylation*, the moisture-absorbing tendency is reduced and dielectric properties of cellulose are significantly improved. This process introduces the group $—OCH_2CH_2CN$ into the cellulose molecule by reaction of acrylonitrile with a reactive hydrogen of a hydroxyl group, thereby changing the molecular structure to one with fewer troublesome hydroxyl groups. Cyanoethylation is done before the beating step.

ASTM Standards for Dielectric Papers and Boards

The American Society for Testing and Materials (ASTM) has developed these standards covering dielectric papers and boards:

- D 202, *Sampling and Testing Untreated Paper Used for Electrical Insulation.* These methods cover the procedures for sampling and testing untreated paper to be used as an electrical insulator or as a constituent of a composite material for electrical insulating purposes.
- D 1305, *Electrical Insulating Paper and Paperboard—Sulfate or Kraft Layer Type.* This specification covers electrical grade unsized, unbleached sulfate paper and paperboard for use as layer insulation in coils, transformers, and similar apparatus.
- D 2413, *Preparation and Electrical Testing of Insulating Paper and Board Impregnated with a Liquid Dielectric.* These methods have been found practicable for papers having nominal thickness of 0.05 mm (2 mils) and above. They have been used successfully for insulating board as thick as 6 mm ($^1/_4$ inch) when care is taken to assure the specimen geometry necessary for valid measurement of dielectric properties.
- D 3394, *Sampling and Testing Electrical Insulating Board.* These boards are fibrous, porous sheets used for dielectric and structural purposes in electrical apparatus. These methods are not intended for testing vulcanized fibre or molded laminated sheets.
- D 4063, *Electrical Insulating Board.* This specification covers electrical insulating board (pressboard) manufactured from kraft, cotton, or kraft and cotton pulps. This board is intended for dielectrical or structural purposes in transformer and other electrical apparatus.

Federal Specification for Paper and Pressboard

Following is the governing military specification for paper and pressboard:

- MIL-I-545, *Insulation Sheet, Electrical, Paper, Pressboard.* This specification is approved for use by all departments and agencies of the Department of Defense. This specification covers the requirements for paper, pressboard, electrical insulation sheet. The insulation is class O insulation with a continuous-operating temperature limit of 90°C. There are two grades:

  Grade B—Moderate dielectric strength, made from undyed and unbleached coniferous (kraft) wood pulp

  Grade C—High dielectric strength, made up of cotton or linen rag stock

Paper-Film Composites

Paper is often laminated to plastic film, primarily for use as dielectric barriers. This insulation type is covered by military specification MIL-I-19632, *Insulation, Electrical, Dielectric Barrier, Laminated, Plastic Film and Rag Paper*. These composites have thermal rating of 105°C. The following compositions are designated:

Composition FR—One layer of polyethylene terephthalate film or sheet laminated to one layer of 100 percent rag paper (duplex).

Composition RFR—One layer of 100 percent rag paper laminated to each side of a polyethylene terephthalate film or sheet (triplex).

Composition RoFRo—One layer of rope paper laminated to each side of a polyethylene terephthalate film or sheet (triplex).

Minimum requirements are listed for dielectric strength, volume resistivity, tensile strength, and tear resistance.

Grades

Available grades include:

- Capacitor tissue made solely of unbleached sulfate paper without additives, in thicknesses from 0.20 to 2.0 mils
- Paper grades made from kraft, cotton, hemp, and combinations of these, in thicknesses under 30 mils
- Crepe grades with controlled stretch from 20 to 300 percent, in thicknesses from 1.9 to 32 mils
- Board grades made from kraft, cotton, or kraft and cotton, in thicknesses 30 mils and over
- Composite grades to meet specification MIL-I-19632 and custom-made composites made with a variety of papers and films.

Properties

Untreated cellulosic insulating papers and boards have dielectric strength little better than air, dielectric loss factors which increase sharply with increasing frequencies, poor mechanical strength, and perhaps their greatest weakness, a high affinity for moisture. Thus, by themselves, they are not useful for dielectric applications except as a spacer. However, when treated or combined with other insulating materials, paper and boards become widely useful. Treatments include impregnation and coating with resins and varnishes for low-voltage applications, and impregnation with liquid dielectrics for higher voltage equipment. As an example of the improvement through impregnation with mineral oil, for 5 mil thick untreated paper, the dielectric strength is 200 volts per mil, but when impregnated with oil, the dielectric strength becomes 1340 volts per mil, a 5.7-fold increase. Samples were first dried at 240°F (115°C) and an absolute pressure of 0.02 torr or less for 16 hours. (1 torr is the pressure required to support 1 millimeter of mercury at 0°C.) The impregnating oil is dried and degassed by the same

process. Drying of paper and degassing of oil are essential procedures for good manufacturing practice as well. It has long been recognized that when these steps are taken, a significant improvement in all dielectric properties is obtained because of the elimination of moisture and air and their replacement with a dielectric liquid. Cellulose papers and boards have thermal index of 105.

Papers and boards may also be combined with dielectric films and resins, and even with mica flakes, to produce useful products with a wide range of properties.

Electrical/Electronic Uses

Typical applications include wire and cable wraps, capacitor dielectrics, coil wraps, separators and slot insulation for rotating equipment and transformers, panel boards, substrates for laminated plastics, fabricated and formed parts, and composites with other insulating materials. Creping reduces damage to paper in coil-winding operations and in wrapping structures involving curves, angles, and irregular contours.

Vulcanized Fibre and Fish Paper

Vulcanized fibre (the approved spelling), often referred to as fish paper in thicknesses under 0.10 inch, is one of the oldest types of electrical insulating materials. It is noted for its toughness and outstanding ability to absorb shock. The term *vulcanized* is applicable only to the extent that the process, which is unrelated chemically to the vulcanizing process for rubber, does enhance significantly the strength and stability of paper. Suppliers are NVF and Spaulding Composites.

Chemistry and Processing

Vulcanized fibre is made by saturating rag-base or wood pulp paper, layered to produce the desired thickness, in a bath of zinc chloride. This causes the paper to gelatinize and bond into a homogeneous sheet. The zinc chloride is then leached from the sheet with excess water. After the zinc chloride content has been reduced to a maximum of 0.1 percent (0.05 percent for electrical grades), the sheet is dried in a room with controlled temperature and humidity. Finally, the sheet is calendered to a smooth finish. Production time increases exponentially with sheet thickness so that several months are required to leach the zinc chloride from heavy-gauge sheets. Thin gauges have been produced continuously as the paper travels through a machine equipped with zinc chloride baths, leaching tanks with running water, and heated drying chambers.

Grades

There are three grades available as sheets, rods, tubes, and coils for dielectric applications. These grades are made to meet ASTM Standard D 710, *Specification for Vulcanized Fibre Sheets, Rods, and Tubes Used for Electrical Insulation:*

- Commercial Grade, a general purpose electrical and mechanical grade with good machineability, available in thicknesses from 0.010 inch to 2 inches.

- Bone Grade, a harder, stiffer grade with good machineability, available in thicknesses from $^1/_{32}$ to $^1/_2$ inch.
- Electrical Insulation Grade, the premier grade for dielectric applications involving difficult bending or forming operations, available in thicknesses from 0.004 to $^1/_8$ inch.

Standard sheet sizes (in inches) for the above grades are 25 × 40, 48 × 72, and 52 × 84.

A built-up, or laminated grade is also available in thicknesses from $^5/_{16}$ to $1^1/_2$ inches, with sheet size (in inches) of 48 × 82. Because it requires much less time to fabricate with adhesives, this grade is significantly less expensive than the equivalent thickness in standard grades.

Properties

Noteworthy characteristics of vulcanized fibre include:

- High values for impact strength and resilience
- Good arc-resistant and arc-quenching properties
- Light weight (one-half that of aluminum)
- Easy machineability

The weakness of vulcanized fibre which severely restricts dielectric applications is its affinity for moisture. In only 2 hours immersion in water, a $^1/_{16}$ inch thick specimen will increase weight 30–50 percent. UL use temperatures are limited to 115°C (239°F) electrical and 110°C (230°F) mechanical. The MIL-F-1148 operating temperature limit is 105°C (221°F).

Electrical/Electronic Uses

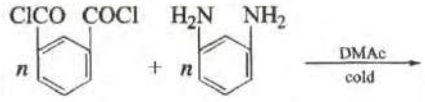
While many of the major applications of vulcanized fibre take advantage of its high mechanical strength, there are many traditional dielectric uses, where moisture is not a problem, such as arc barriers in air circuit breakers, lightning arrestors for heavy-duty transformers, switch and appliance parts, and slot liners for rotating equipment. As corrugated strips, fibre is used for ducts in oil-filled distribution transformers. Fish paper is widely used to insulate electrical coils and windings, and in slots of electrical equipment.

Aramid Papers and Boards

Aramid paper is the generic term for a wholly aromatic polyamide paper, most commonly known by the trademark NOMEX of Du Pont, its developer and principal producer. This paper and its fiber counterpart have been commercially available since 1962, and are primarily designed to serve the thermal range of 155° to 220°C (220°–428°F)—above that of polyester film used for similar applications at lower temperatures.

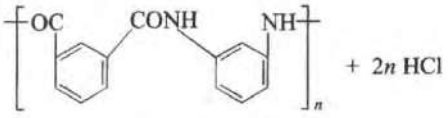
Chemistry and Processing

Aramid fibers (floc) and small binder particles (fibrids) are made by reacting isophthaloyl chloride and m-phenyl diamine in the presence of acid acceptor, such as dimethylacetamide (DMAc) containing 5 percent lithium chloride. The polycondensation is carried out in this solution:



isophthaloyl chloride

m-phenyl diamine



poly (*m*-phenylene isophthalamide)

Aramid paper is made from floc and fibrids in a Fourdrinier paper machine. No binders, sizes, or fillers are added in the process. The paper may then be calendered under high temperature and pressure to produce a dense, relatively nonporous sheet.

Aramid boards are made from the same materials as the papers, but are formed on commercial cylinder board-making machines, pressed and/or calendered to the required densities. In contrast to aramid paper, aramid pressboard is relatively porous and can be impregnated with mineral oil and various resins and varnishes.

Federal Specification

The governing Federal specification for aramid paper is MIL-I-24204, *Insulation, Electrical, High Temperature, Bonded, Synthetic Fiber Paper*. This specification is approved for use by the Naval Sea Systems Command and is available for use by all departments and agencies of the Department of Defense. Covered are calendered, flexible insulation used in the coils and slots of electrical machinery at temperatures up to 220°C (428°F). Required performance characteristics are listed (which are well below published values for commercially available products as shown in Table 11-1). Aramid papers also meet the requirements of NEMA, IEC, UL, and CSA standards.

Grades

Available commercial grades include:

- Standard, calendered NOMEX in thicknesses from 2 to 30 mils
- A higher tear strength calendered grade with greater conformability in thicknesses from 3.4 to 15 mils
- An uncalendered, porous grade in thicknesses from 5 to 23 mils

TABLE 11-1 Typical Property Values for Aramid Papers 5-Mil Specimens (23°C, 50% R.H.)

	ASTM TEST METHOD	ARAMID		ARAMID AND MICA
		CALENDERED	UNCALENDERED	
Pounds per square yard		0.21	0.08	0.27
Tensile strength, lb/in	D 828			
Machine direction		80	10	34
Transverse direction		40	5	23
Elongation, %	D 828			
Machine direction		16	3.0	2.4
Transverse direction		13	5.0	2.4
Elmendorf tear, grams	D 689			
Machine direction		240	130	190
Transverse direction		520	180	290
Dielectric strength ac rapid rise V/mil	D 149	635	230	1,000
Dielectric constant	D 150			
60 Hz, 23°C, 50% RH		2.4		3.6
10^3 Hz			1.3	
Dissipation factor	D 150			
60 Hz, 23°C, 50% RH		0.006		0.12
10^3 Hz			0.003	

- A blend of aramid polymer and mica flakes, combining the strong mechanical properties of aramid with the high corona resistance of mica, in thicknesses from 3 to 14 mils
- Several types of aramid and aramid-blend pressboards of varying surfaces, properties, and densities, made of 100 percent aramid or blends of aramid materials with mineral or glass fibers, in thicknesses up to approximately 400 mils.

Laminated Products

In cases where very high strength and tear resistance are required, commercially available laminates with polyester film are often used with loss of some thermal capability to about 180°C (356°F). If necessary, higher price polyimide film laminates may be used to provide the required thermal and dielectric properties.

Properties

Aramid paper possesses high-temperature durability, flame retardancy, excellent mechanical strength, and good dielectric properties. It has limiting oxygen index (LOI) of about 27 and UL flammability rating of 94 V-0. Dielectric constant and dissipation factor increase slightly up to 220°C (428°F). The paper has good resistance to acids, alkalis, refrigerants, ketones, alcohols, and oils. It is compatible with most wire enamels and insulating varnishes. Aramid paper is susceptible to moisture absorption, and

in fact requires 3–5 percent moisture content (based on dry weight) for the optimum balance of properties. Increasing the moisture content improves physical properties, but lowers insulating values, except dielectric strength, which remains essentially constant up to 95 percent relative humidity. This material is rated by Underwriters Laboratories for continuous use at 220°C (428°F).

Paper made with blends of aramid fibers with mica flakes has higher corona and arc resistance than unblended aramid paper, and is rated for continuous service at 220°C (428°F).

Typical property values are shown in Table 11-1.

Aramid boards exhibit the same thermal and electrical properties as aramid papers on a thickness basis.

Electrical/Electronic Uses

The first and still principal uses for aramid paper are in rotating electrical equipment for lead wire, coil, slot, phase, wedge, and end insulation; and in transformers for turn, layer, barrier, and tap insulation. Other applications include substrates for printed circuits, cable insulation, and spiral and convolute wound tubes and coil bobbins.

Mica Paper

Mica paper, or reconstituted mica, was first used for dielectric applications about 1950. Principal producers include Insulating Materials and Essex International.

For additional information on mica, see Chapter 14, *Mica and Mica Products*.

Technology

Mica paper is made from scrap mica. Mica muscovite splittings are broken up by heat at about 1470°F (800°C), followed by grinding particles into small platelets. Paper is formed in a modified Fourdrinier machine similar to that used in making kraft paper. The paper is then calendered to the desired thickness. The inherently low mechanical properties, moisture resistance, and dielectric strength of mica paper are improved by treatment with resins (shellac, epoxies, alkyds, polyesters, silicones) and by reinforcement (glass cloth, polyester mat and film, polyimide film).

Federal Specifications

The following Federal specifications cover mica paper products:

• MIL-I-19917, *Insulation Sheet, Electrical, Mica Paper, Silicone Bonded.* The following types are designated:

Type MPF-S—Mica paper, flexible, silicone bonded
Type MPR-S—Mica paper, rigid, silicone bonded

The nominal thickness range is 0.010–0.0625 inch for Type MPR-S and 0.010–0.030 inch for Type MPF-S.

• MIL-I-21070, *Insulating Sheet and Tape, Electrical, Reinforced Mica Paper.* The following classes are designated:

Class 130—With organic resin binder and organic varnish coating (if used) on glass fiber woven fabric reinforcement
Class 155—With epoxy or polyester resin binder and an epoxy or polyester coating (if used) on glass fiber woven fabric reinforcement
Class 180—With silicone resin binder and silicone varnish coating (if used) on glass fiber woven fabric reinforcement

The nominal thickness range for these composites is 0.005–0.025 inch. Requirements are specified for dielectric strength, volume resistivity, tensile strength, and tear resistance for each construction and thickness.

TABLE 11-2 Typical Property Values for Mica Paper Composites

CONSTRUCTION	BINDER	% BINDER BY WEIGHT	FINISHED THICKNESS (inches)	THERMAL CLASS	SHORT TIME DIELECTRIC STRENGTH (volts/mil)	TENSILE STRENGTH (lb/inch)
0.0017 in glass cloth 0.004 in mica paper	epoxy B-staged	27–33	0.0065– 0.0075	155°C	600	70
0.0008 in polyester mat 0.004 in mica paper 0.002 in glass cloth	epoxy B-staged	36–42	0.009	155°C	450	80
0.0017 in glass cloth 0.002 in mica paper 0.00025 in polyester film	epoxy fully cured	22–28	0.005– 0.006	155°C	750	70
0.0026 in glass cloth 0.002 in mica paper 0.00025 in polyester film both sides	polyester fully cured	20–25	0.005– 0.006	155°C	1,000	70
0.0017 in glass cloth 0.004 in mica paper 0.00025 in polyester film	polyester fully cured	25–30	0.007– 0.008	155°C	650	70
0.002 in mica paper 0.002 in glass cloth	silicone fully cured	20–25	0.0045– 0.0055	200°C	500	80
0.00025 in polyester film 0.0018 in mica paper 0.002 in glass cloth	silicone fully cured	20–25	0.005	200°C	700–900	84
0.001 in KAPTON 0.002 in mica paper	silicone fully cured	10–12	0.0035	200°C	2,220	30

Note: The above constructions are available in full width rolls 36 in wide by 36 yards long and in tapes $^1/_2$–$1^1/_4$ in wide by 36 yd long.

NEMA Standard for Untreated Mica Paper

The National Electrical Manufacturers Association (NEMA) has developed the following standard for untreated mica paper:

• FI 2, *Untreated Mica Paper Used for Electrical Insulation*. Covered are procedures, conditions, and methods of sampling and testing uncalcined and partially calcined or chemically treated mica paper.

Grades

Because of its fragility, mica paper is usually supplied in composite structures with glass cloth, polyester film and mat, and aramid (NOMEX) reinforcements. Typical composites are listed in Table 11-2.

Processing

Mica paper is receptive to impregnation, including vacuum pressure impregnation with insulating varnishes, and is also easily combined with reinforcing fabrics, films, mats, and other papers.

Properties

The outstanding attributes of mica paper, which it contributes to composites, are its arc and corona resistance and its high-temperature properties. Weak physical properties often make use difficult or dependent on reinforcement with other materials.

Property values of typical mica paper composites are shown in Table 11-2.

Electrical/Electronic Uses

Mica paper composites are used extensively for wrapping coils in electrical equipment, as cable wraps, and in other applications requiring flexibility and high-temperature service.

Other Papers and Boards

Commercially available papers made primarily from inorganic materials include the following:

• *Glass paper* is composed of glass microfibers. Because adhesion of these fibers is much lower than for other paper fibers, for adequate bonding the pulp requires special processing in an acid medium or with an inorganic binder. Glass paper is not dense, since calendering would crush the fibers. The outstanding feature of glass paper is its thermal stability up to 1,000°F (538°C). Other attributes include high thermal conductivity, low moisture absorption, and good chemical resistance. Manning Paper and Crane are suppliers. Paper is available in thicknesses of 0.005 inch up to 0.070 inch or more, and in widths up to 100 inches.

• *Alumina-silica paper* contains 51 percent alumina (Al_2O_3) and 47 percent silica (SiO_2). From 2–5 percent organic binder may be used to improve handling charac-

teristics. This paper can be used continuously at temperatures to 2,300°F (1,260°C). It is attacked by strong alkalis, hydrofluoric and phosphoric acids. It is furnished in thicknesses from 0.010 inch paper to 1/4 inch board. Carborundum is a producer.

• *Ceramic paper*, composed of a proprietary blend of "unfired ceramic-like material" with synthetic fibers and high-temperature binders, is produced by Quin-T Corporation as a substitute for asbestos-base papers in many applications. It is supplied in 0.005–0.060 inch thicknesses in rolls or sheets up to 48 inches wide. It is also furnished in laminates with polyester film and electrical grade fiberglass or improved mechanical strength. Dielectric properties depend on impregnation with many kinds of varnishes and resins. These materials are used in many applications at temperatures up to 428°F (220°C), depending on their organic binders.

12

Tapes and Coated Fabrics

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PRESSURE-SENSITIVE TAPES

INTRODUCTION

The original U.S. patents for pressure-sensitive adhesives were issued about 1845. Around 1900, pressure-sensitive tapes became widely used for first aid purposes. The first pressure-sensitive electrical tape, friction tape, was marketed in the late 1920s. During World War II, the shortage of natural rubber encouraged the development of synthetic rubber adhesives, and since that time, both products and markets for pressure-sensitive tapes have grown phenomenally as a wide variety of adhesives applied to every conceivable type of backing has become available.

Adhesive formulations are usually complex and proprietary with tape manufacturers, although some of the secretiveness has diminished in recent years, due in large part to the marketing efforts of basic material suppliers.

Standards and specifications have been developed covering virtually all commonly used pressure-sensitive tapes. These documents are summarized in this section including product descriptions, nominal sizes, and basic property requirements.

SUPPLIERS OF PRESSURE-SENSITIVE TAPES

Producers of pressure-sensitive tapes include the following:

- Acme
- Anchor Continental
- CHR Industries
- DeWal Industries
- 3M
- Mystic
- Nashua
- Norplex Oak
- Permacel Division of Fasson
- Plymouth Rubber
- Polyken Division, Kendall
- Taconic
- Tuck Industries

TECHNOLOGY

Pressure-sensitive tapes comprise three or four layers, each with its own specific function:

- A backing that provides the required physical, chemical, and dielectric properties. Commonly used backings include:

FILMS	INSULATION CLASS
– Polyester	130°C
– Polyester acrylic	130°C
– Polypropylene	85°C
– Polyimide	155°C, 180°C
– Polytetrafluoroethylene	155°C, 180°C
– Vinyl	80°C, 105°C
COMPOSITES	
– Polyester film/mat	130°C
– Polyester film/polyester nonwoven tape	130°C
– Polyester film/paper tape	130°C
– Polyester film/glass filament tape	130°C
OTHER BACKINGS	
– Glass cloth	155°C
– Silicone resin coated glass cloth	180°C
– Cotton cloth	105°C
– Acetate taffeta cloth	105°C
– Kraft paper	105°C
– Creped kraft paper	105°C
– Aramid nonwoven fabric	155°C
– Self-bonding silicone rubber	not available

• An adhesive layer provides the means of adhering the backing to the unit or to the back of the tape when layered. Adhesives for electrical grade tapes are activated either by pressure or by heat. Adhesives activated with water are not acceptable for dielectric applications. Adhesives activated with organic solvents are not widely used because of their inconvenience and fire and health hazards. Commonly used adhesives for electrical grade tapes include those based on natural rubber, synthetic rubber (SBR, butyl, Buna-N), silicone rubber, polyacrylate esters, and block copolymers (styrene-butadiene-styrene, styrene-isoprene-styrene) and combinations of these polymers. Rubber and silicone adhesives which are thermosetting crosslink with heat, thereby increasing solvent resistance and adhesion to the part. Thermosetting should be accomplished before impregnation with solvent-type varnishes.

• A release coating permits the tape to be unwound easily, an important feature where automated equipment is employed. The release coating is usually very thin, permitting the tape to adhere well under pressure to itself and other surfaces.

• A primer coat is sometimes used to bond the adhesive layer to the backing so that delamination does not occur.

Natural and Synthetic Rubber Adhesives

Natural rubber (polyisoprene) was the first elastomer used in pressure-sensitive tapes, and it is still widely used. Natural rubber must be masticated to break down the gel content and to reduce the molecular weight before it is suitable for pressure-sensitive

applications. This process also facilitates solution coating at reduced levels of solvent concentration.

Natural rubber becomes softer on oxidation aging because of chain scission, while styrene-butadiene rubber (SBR) rubber becomes harder with added crosslinking. Hence, by blending, aging properties of both materials can be significantly enhanced.

Improved dielectric, heat aging, solvent-resistant, and ozone-resistant characteristics are obtained in adhesives based on butyl and polyisobutylene elastomers. Butyl rubber is a copolymer of isobutylene with a small amount (3 percent) of isoprene which contributes double bonds to the macromolecule, thereby permitting the polymer to be crosslinked, or vulcanized:

$(CH_3)_2C{=}CH_2$ $\qquad$ $CH_2{=}C(CH_3)CH{=}CH_2$

isobutylene $\qquad$ isoprene

Other ingredients in natural, synthetic, and blended rubber pressure-sensitive adhesive formulations include:

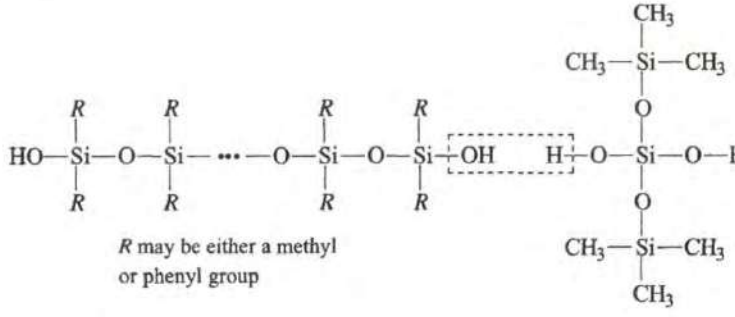
- Stabilizers and antioxidants, such as zinc dibutyl dithiocarbamate (0.20 or less percent by weight) and butylated hydroxytoluene (less than 0.1 percent by weight), are effective.
- Tackifiers, such as the polyterpenes, terpenephenolics, phenol-formal dehyde resins, modified rosins and rosin esters, and hydrocarbon resins, often in combination, impart tack in concentrations of 20–70 percent. Below 20 percent, addition of these resins has little effect on tack. Tack develops as concentration increases from 20 percent until it typically reaches a maximum at about 70 percent. Tack then falls precipitously to zero at about 80 percent concentration.
- Plasticizers, such as polybutene, paraffinic oils, petrolatum, and certain phthalates with long aliphatic side chains (e.g., ditridecyl phthalate) are used in combination with tackifiers to control cohesive strength.
- Fillers and pigments, such as zinc oxide (to increase tack and cohesive strength); clays, magnesium oxide, silica, hydrated silicas, calcium silicate, silicoaluminates (to increase stiffness); mica, graphite, and talc (to improve chemical resistance and gas permeability); aluminum hydrate, lithophone, whiting, and carbon black (to increase tack); and calcium carbonate (to lower cost), are among the multitude of materials used.
- Curing agents, such as active brominated phenolic resins, sulfur or sulfur-donor compounds, and p-quinone dioxime (QDO) or dibenzyl p-quinone dioxime (DBQDO), promote crosslinking, but reduce tack and solubility in hydrocarbon solvents, thereby limiting use. QDO and DBQDO should be combined with oxidizing agents such as MnO_2, PbO_2, Pb_3O_4, or benzothiazyl disulfide in curing butyl rubber adhesives. Zinc oxide or other metallic oxides are necessary to develop satisfactory cure in combination with sulfur or sulfur-donor compounds (not used in electrical tapes since they cause corrosion of copper wires).

Thus, the possible combinations of ingredients in a recipe are virtually limitless. The three critical parameters in formulating a pressure-sensitive adhesive are tack, peel

adhesion, and shear creep resistance (cohesive strength). Obtaining maximum value for one of these parameters is often at the expense of values for the other parameters. Different resins will produce different ratios for the optimum balance of properties. In blends of two elastomers, a resin may have a selective effect and tackify only one. Although the science of adhesion has developed significantly in recent years, there is still a large element of art in formulating effective pressure-sensitive adhesives.

Silicone Rubber Adhesives

Silicone adhesives have thermal Class 180 rating, the highest of all pressure-sensitive adhesives. They are based on a silicone gum and a silicone resin with the following structures:



The adhesive is formed by condensation reaction in which water is removed. The resin acts as a tackifier, with the resin-to-gum ratio determining the tack and adhesion characteristics. The higher the resin content, the lower the tack. In high-resin-content adhesives, it is necessary to induce tack with heat and pressure. High-gum-content adhesives are naturally tacky at room temperature. Phenyl-modified silicones are noted for their unique combination of high viscosity, high peel strength, and high tack, and for their incompatibility with methyl-modified silicones. Adhesives may be made to cure through crosslinking by addition of benzoyl peroxide for curing at temperatures over 150°C (302°F), or by addition of 2, 4-dichlorobenzoyl peroxide for curing at 140°C (284°F) with higher cohesive strength resulting. Curing improves high-temperature shear properties at the expense of a slight loss of peel adhesion compared with adhesive that is noncuring.

Acrylic Adhesives

Acrylic adhesives have grown in use in recent years. They may be formulated from basic raw materials to be inherently pressure sensitive without the need for compounding, although incorporation of tackifying resins improves further tack and adhesion. Thermosetting acrylic systems may also be synthesized that are initially pressure sensitive, but still capable of a later thermosetting reaction. Adhesives are formed from alkyl acry-

TABLE 12-1 Acrylic Monomers Used in Pressure-Sensitive Adhesives

Methylate acrylate	$CH_2=CH-COO-CH_3$
Ethyl acrylate	$CH_2=CH-COO-C_2H_5$
n-Butyl acrylate	$CH_2=CH-COO-C_4H_9$
2-Ethylhexyl acrylate	$CH_2=CH-COO-CH_2-CH(C_2H_5)-C_4H_9$
Methyl methacrylate	$CH_2=C(CH_3)-COO-CH_3$
Acrylic acid	$CH_2=CH-COOH$

late and methacrylate monomers of 4–17 carbon atoms, as shown in Table 12-1. Commonly used are n-butyl acrylate and 2-ethylhexyl acrylate, which are copolymerized in emulsion or solution polymerization with acrylic acid and/or one or more of a multitude of other functional monomers capable of undergoing vinyl polymerization.

Although acrylic pressure-sensitive adhesives do not require compounding as do other elastomers, their adhesive properties may be varied by inclusion in formulations of other ingredients used with other elastomers.

Shear resistance of acrylic pressure-sensitive adhesives may be improved by introduction of divinyl benzene in formulas to promote crosslinking.

Acrylic pressure-sensitive tapes with polyester backing are rated thermal Class 130. With suitable backing, they are rated Class 155.

Block Copolymer Adhesives

Block copolymer thermoplastic rubber adhesives are of two principal classes:

1. Block copolymers in which the rubbery midblock is an unsaturated rubber. The two main types in this class are polystyrene-polybutadiene-polystyrene (S-B-S) and polystyrene-polyisoprene-polystyrene (S-I-S).

2. Block copolymers in which the elastomeric midblock is a saturated olefin rubber. Examples are polystyrene-poly(ethylene/butylene)-polystyrene (S-EB-S) and polystyrene-poly(ethylene/propylene)-polystyrene (S-EP-S).

In reality, there are many variations in molecular structure possible, and commercial products may have additional endblock and midblock resins. Formulations are usually proprietary.

Endblock compatible resins are used to:

- Improve the specific adhesion of the endblock phase
- Adjust melt viscosity
- Control the degree of softness or stiffness (stiffness increases with higher concentration of these resins)

Commonly used endblock compatible resins include polyaromatics (e.g., poly-alphamethylstyrene/vinyl toluene copolymer) and coumarone-indene polymers.

Midblock compatible resins are used:

- To impart pressure-sensitive tack
- To improve the specific adhesion of the midblock phase toward substrates
- To control the degree of softness or stiffness (softness increases with higher concentrations of these resins)
- As processing aids

Midblock compatible resins include rosin esters, polyterpenes, terpene phenolic resins, and aliphatic olefin derived resins.

Formulations may also include plasticizing oils, which perform the following functions:

- Decrease hardness
- Increase pressure-sensitive tack
- Improve low temperature flexibility
- Reduce melt and solution viscosity
- Lower cost

The plasticizer oil ideally should be insoluble in the endblock phase, but miscible with the midblock phase. Plasticizer oils include aromatic, naphthenic, and paraffinic hydrocarbons and mixtures of these. Polybutenes with molecular weight between 300 and 600 are effective plasticizers. Volatility loss by weight after 22 hours at 225°F (107°C) should be not over 2 percent.

S-I-S polymers are miscible with polyisoprene and natural rubber. S-B-S polymers are compatible with SBR and polybutadiene rubbers. It is, therefore, possible to blend these miscible elastomers to produce adhesives with enhanced properties. By incorporating low concentrations of thermoplastic rubber into unvulcanized natural rubber, polyisoprene, and SBR, cohesive strength will be improved, solution viscosity will be lowered, and adhesive strength may be higher. Including a small amount of a conventional rubber in a thermoplastic rubber may increase solution or melt viscosity somewhat without significant loss in other properties.

Other ingredients in thermoplastic rubber adhesive formulations may include:

- Fillers, such as clay and talc, to pigment the adhesive and to lower cost.
- Antioxidants, such as zinc dibutyl dithiocarbamate (R. T. Vanderbilt's Butyl Zimate™, Uniroyal's Butazate™, and Pennwalt's Butyl Ziram™), tri (nonylated phenyl) phosphite (Uniroyal's Polygard™), and 2-(4-hydroxy-3,5-tertiary-butyl anilino)4,6-bis(n-octyl thio)-1,3,5-triazine (Ciba-Geigy's Irganox 565™) which are effective stabilizers in concentrations of 5 percent or less against attack by oxygen.
- Antiozonants, such as nickel dibutyl dithiocarbamate (Du Pont's NBC™), dibutyl thiourea (Pennwalt's Pennzone B™), and Reichhold's Ozone Protector 80™, which are effective. Pennzone B should not be used in hot melt formulations as it accelerates crosslinking.

• Ultraviolet light inhibitors, such as 2,4-dihydroxy-benzophenone (GAF's Uvinul 400™), substituted benzotriazole (Ciba-Geigy's Tinuvin P™), octylphenyl salicylate (Eastman's Eastman OPS™), and octadecyl 3-(3,5-ditertiary-butyl-4-hydroxyphenyl) propionate (Ciba-Geigy's Irganox 1076™) which will provide adequate protection at a concentration of about 0.5 parts per hundred parts of elastomer.

PROCESSING

The traditional, although not the only, method for applying adhesives to backing is by solution or dispersion coating to a substrate. All natural and synthetic rubber adhesives are applied from solution in hydrocarbon solvents such as mineral spirits, hexane, heptane, naphtha, cyclohexane, toluene, and perchloroethylene.

Natural rubber is solvated[1] by granulating the rubber and slowly milling in the solvent. This process can be accelerated by addition on the mill of peptizers, such as pentachlorothiophenol. Before coating, it is customary to apply primers to some backings. On glass backings, epoxy silanes have been effective. Isocyanate primers are used for other textile substrates. Certain silicone solution coatings are suitable primers for silicone adhesives when cured for 15–30 seconds at 150°C (302°F) on polyester film.

Butyl polymers do not require milling, and may be solvated by gradual addition into a mixer with agitated solvent. Other ingredients are added after the butyl rubber is solvated. The blend may then be processed on mills or Bamburys if desired.

Unlike rubbers, acrylic adhesives may be dissolved in ethyl or butyl acetate, or in ketones, as well as in commonly used rubber solvents. Polymers exhibiting the best tack are *n*-butyl acrylate and 2-ethylhexyl acrylate.

In addition to solvent systems, acrylic aqueous dispersions are also widely used to make pressure-sensitive adhesives. Emulsion polymerization in water is effective in the presence of emulsifiers such as alkali salts of long-chain aliphatic, carboxylic or sulfonic acids, or sulfated ethylene oxide adducts. Alkali persulfates in small amounts (0.05 percent of monomer weight) may be used as initiators, for example, potassium peroxide disulfate. A typical reaction pH obtained with aqueous caustic is 7–8. The reaction is carried out by heat and pressure, staring at 70° to 80°C (158°–176°F) and ending at 80° to 90°C (176°–194°F). The viscosity of the solids content determines the completion of the reaction. Residual monomers are removed by passing a stream of nitrogen over the surface of the emulsion for 30 minutes before reducing the temperature. Following emulsion polymerization, the polymer is coagulated, washed, and typically solvated to 25–40 percent solids, although higher solids or solventless coatings are suitable for application by hot melt processing. Primers are not required before applying acrylic adhesives to substrates.

Silicone rubber pressure-sensitive adhesives are polymerized by condensation reaction in solution and processed with other ingredients in a manner similar to butyl rubber.

[1]*Solvation* is the adsorption of a microlayer or film of solvent on individual dispersed particles of a dispersion.

Block copolymer thermoplastic rubbers are prepared by polymerization in solvent using an alkyl lithium catalyst such as butyl lithium ($CH_3(CH_2)_3Li$). S-B-S and S-I-S types may be synthesized by sequential (linear) polymerization of all three blocks, or by sequential polymerization of two blocks followed by coupling with the third block, forming either a linear or multiarmed polymer, depending on the functionality of the coupling agent, usually an ester- or halogen-containing molecule. Crosslinking is physical, rather than chemical in nature as with conventional vulcanized rubber. This physical crosslinking can be "unlocked" by solvation or by heat and shearing, making the elastomer thermoplastic.

Typically, in block copolymer pressure-sensitive adhesives, the rubber midblock phase is the continuous phase and is present in higher concentration (70–85 percent). The higher the styrene content, the greater the hardness, the higher the tensile strength and modulus, and the shorter the elongation. As the styrene content is increased, the polymer becomes more like high-impact polystyrene.

Thermoplastic rubbers require compounding with certain resins, described earlier, to impact tack. Plasticizers and other ingredients may also be added to obtain the desired balance of properties. Premastication of the thermoplastic rubbers is not required since they dissolve readily in many solvents to make low-viscosity solutions.

Solvent selection, however, significantly affects the characteristics of the dried fiber. Two solubility parameters are involved: one for the endblock and one for the midblock. Then, with the addition of resin and plasticizer, third and fourth parameters are implicated. It is common practice, therefore, to employ solvent blends since it is unlikely that a single solvent would be equally effective on all ingredients. Natural and butyl rubber solvents are all candidates. Final film properties are usually determined by the solvent which evaporates last. It is preferable, therefore, that the solvent for the rubbery midblock be the last to evaporate for optimum adhesive properties. A typical solvent system (15 percent by weight of polymer) would contain 20 percent or more toluene blended with *n*-hexane for a low-viscosity matrix. Below 20 percent, toluene content viscosity increases sharply because *n*-hexane is a nonsolvent for the styrene endblock, while toluene is a solvent for both midblock and endblock. Thermoplastic rubbers require significantly less solvent than natural rubber. In fact, thermoplastic rubbers may be hot melt processed. Temperatures above 220°C (428°F) will decompose the rubber phase. The proper range for mixing and application is 120° to 180°C (248°–356°F). Mechanical mixing decreases melt viscosity significantly, permitting the adhesive to be more readily applied.

Many coating methods have been used successfully in the manufacture of pressure-sensitive tapes. The most widely used are reverse roll, calendering, and knife-over-roll. These methods vary in speed, and in viscosity and coating weight range capability. The function of all methods is to apply a uniform coating to a substrate and make it adhere. The *reverse roll coater*, in its simplest form, employs a metering roll, an applicator roll separated from the metering roll by a gap which determines the amount of coating to be applied, and a backing roll which carries the backing. The roll surfaces are going in opposite directions where they nearly contact each other and roll speeds are different. This method deposits a uniform coating thickness that is independent of backing thickness variations.

Calendering is best suited for large-volume manufacture of products which require a heavy adhesive coating. The prewarmed adhesive is fed onto the substrate as it is dragged through a narrow gap between heated rolls turning to oppose the direction of motion of the substrate. Alternatively, the adhesive sheet is first formed by the rolls, and then adhered in line to the substrate by passing between other rolls.

In *knife-over-roll* coating, the coating thickness is determined by the gap between the knife edge and the roll which passes the substrate under the knife. The adhesive is placed in a trough, or is contained as a free puddle by side dams only. There are many variations of this method and a similar system in which the knife contacts the substrate between two rolls (floating knife coater), and still another variation employing a driven "blanket" which carries the substrate (knife-over-blanket).

After coating, the solvent must be evaporated from the adhesive by convection or infrared drying, or a combination of both. Various methods and devices are employed to convey the web through the drying process. The simplest technique is the use of idler rolls which support the web as it is pulled through the dryer. It has been found that arranging the rolls (idler or driven) in an arch prevents edge curl. The web may also be conveyed by numerous smaller rollers, or on a belt. The newest technique uses heated air from nozzles both above and below the web to float the web as it is pulled through the dryer. Thus, the web is heated from both sides and no mechanical support is needed.

The design and control of the drying process are critical to the production of high-quality pressure-sensitive tape. Inadequate drying can produce blow holes or blisters in the adhesive film, and air with too high velocity can disturb the adhesive surface. Dryers usually have at least three temperature zones, with the lowest temperature zone first and the highest temperature zone last. Strict limits should be placed on the concentration of flammable vapor in any zone. Recycling of exhaust may be used to conserve energy provided these limits are not exceeded. Concentration limits depend on the flammability of the solvent or solvent mixtures used.

ADHESION TESTS FOR PRESSURE-SENSITIVE TAPE

The property of tack lacks precise definition and has not yet been quantified by scientific test methods which give readily reproducible results. The thumb test is still regarded by some authorities as giving as good an indication of tack as any mechanical test. However, the thumb test applies only to tack between adhesive and skin. Mechanical tests in use include the following:

- A polished stainless steel ball 1.1 cm ($^{7}/_{16}$ inch) in diameter is rolled down an inclined track onto an upward-facing pressure-sensitive tape. The distance the ball rolls on the tape is an inverse measure of tack, but only between the adhesive and steel. Test conditions vary with the release height and how well the tape is held down. However, this method can be used for quality control in a plant where uniform conditions are maintained.
- Peel adhesion, commonly determined by applying the tape without pressure on a flat surface (which may be related to the end use for the tape). The tape is immedi-

ately peeled from the surface at 90 degrees at a rate of 30 centimeters per minute (12 inches per minute) employing a constant rate of extension tensile tester. A version of this method using a polished steel drum instead of a flat surface is described in ASTM D 1000, *Test Method of Testing Pressure-Sensitive Adhesive Coated Tapes Used for Electrical Insulation*.

- Peel adhesion, also determined by measuring the force necessary to strip a piece of tape adhered by a rubber covered steel roller at a 180 degree angle from a stainless steel plate at the same rate as in the above method. ASTM D 1000 describes this method also.
- Other tests for peel adhesion involve a rod of specified diameter and material which is brought into contact with the adhesive surface of a tape and then pulled away at a fixed rate using an Instron Tensile Tester or similar device.
- Shear creep resistance (cohesive strength), determined by applying a weight to the end of a strip of tape adhered to a specified vertical surface and measuring the amount of slippage in a given time, or the time for failure. In this test, it is essential that the tape make a 0 degree angle to vertical; otherwise, the tape will pull away from or toward the surface, or the weight will not apply an equal force across the tape.

These tests are suitable principally for comparing ostensibly identical tapes for a specific application. Variables which complicate adhesion tests include:

- Adhesive thickness
- Type and thickness of the backing
- Amount of pressure used to apply tape to test surface
- Type and condition of test surface
- Time of contact between adhesive and test surface before testing
- Test temperature
- Ambient humidity at time of test.

GRADES

Grades for all tapes covered by standards and specifications summarized in this section are commercially available.

ASTM STANDARDS FOR ELECTRICAL INSULATING PRESSURE-SENSITIVE TAPES

The American Society for Testing and Materials has developed the following standards for electrical insulating pressure-sensitive tapes:

SPECIFICATIONS

- Friction tape—D 69, D 4514
- Vinyl chloride backing—D 2301, D 3005

- Polyester film backing—D 2484
- Polytetrafluoroethylene backing—D 2686
- Glass cloth backing—D 2754
- Polyethylene backing—D 3006

TEST METHODS

- Pressure-sensitive tapes—D 1000
- Bondable silicone rubber—D 2148

The following pages provide a more detailed examination of these standards.

• D 69, *Friction Tape for General Use for Electrical Purposes.* This standard covers friction tape used for protecting and binding in place, insulation applied to joints of electrical wires and cables, and for other electrical and mechanical purposes. The fabric shall be thoroughly impregnated and evenly coated on both sides with the frictioning compound. This compound shall be a tacky adhesive compound containing practically no free sulfur or other substances that would have a deteriorating effect on copper or other metals, or on the fabric. The tape shall have the ability to stick to itself front to front, back to back, and back to front. The tape shall have a nominal thickness of 0.38 mm (0.015 inch) and shall be made in the following widths: 20, 25, 38, and 50 mm ($^3/_4$, 1, $1^1/_2$, and 2 inches). Each roll shall contain not less than 25 m (28 yards). Breakdown voltage shall not be less than 1,000 volts.

• D 1000, *Pressure-Sensitive Adhesive Coated Tapes for Electrical Insulation.* This standard describes methods of testing pressure-sensitive adhesive coated tapes used for electrical insulation. Two classes of tapes are identified:

Class 1—Nonelastic backings such as:
Paper, flat and creped
Fabric, uncoated and coated
Cellulose ester films
Polyethylene terephthalate films
Fluorocarbon polymer films
Combinations of the above

Class 2—Elastoplastic backings that are characterized by both high stretch and substantial recovery such as:
Vinyl chloride and copolymers
Vinylidiene chloride and copolymers
Polyethylene

Table 12-2 lists the test methods.

• D 2148, *Bondable Silicone Rubber Tapes Used for Electrical Insulation.* This standard covers test methods for adhesion, bond strength, breakdown voltage, hardness, length, thickness, and width.

• D 2301, *Vinyl Chloride Plastic Pressure-Sensitive Electrical Insulating Tape.* This standard covers electrical insulating tape consisting of an elastomeric backing

TABLE 12-2 Property Tests for Pressure-Sensitive Adhesive Coated Tapes for Electrical Insulation (ASTM D 1000)

PROPERTY MEASURED
Accelerated aging (high-temperature tape only)
Adhesion strength
Breaking strength and elongation
Conditioning
Dielectric breakdown
Flagging
Flammability
High-humidity insulation resistance
Length of tape in a roll
Low-temperature elongation for Class 2 tapes
Low-temperature testing Class 2 tapes only
Oil resistance
Precautions
Resistance to accelerated aging (heat and moisture)
Resistance to penetration at elevated temperatures
Sampling
Shear strength after solvent immersion (Class 1 only)
Thermosetting properties

made from vinyl chloride plastic coated on one side with a pressure-sensitive adhesive. Two types of material are identified:

Type I—General-purpose tape, nominal thickness 0.007 inch (0.18 mm)

Type II—General-purpose tape, nominal thickness 0.010 inch (90.25 mm). Standard widths range from 1/4 inch (6 mm) to 2 inches (50 mm). Standard lengths are 20 feet (6 m), 66 feet (20 m), and 108 feet (33 m).

The requirements for the tapes are shown in Table 12-3.

TABLE 12-3 Requirements for Vinyl Chloride Plastic Electrical Tapes (ASTM D 2301)

	TYPE I	TYPE II
Breaking strength, min, lb/in of width	18	26
(kg/25 mm of width)	(8.0)	(11.6)
Elongation, min, percent, average	125	150
Dielectric breakdown, min, volts, average		
Standard conditions	7,000	9,000
After conditioning 96 h at 23°C and 96 percent humidity	90% of original	90% of original
Adhesion, min, oz/in (g/25 mm) average		
On steel plate	22 (610)	22 (610)
On its own backing	18 (500)	18 (500)

Note: Tests are conducted in accordance with ASTM D 1000 procedures.

• D 2484, *Polyester Film Pressure-Sensitive Electrical Insulating Tape*. This standard covers electrical insulating tape consisting of polyethylene terephthalate film coated on one side with a pressure-sensitive adhesive. Five types of tape are identified:

Type 1—General purpose tape, nominal thickness 0.0025 inch (0.06 mm) and coated with a thermoplastic adhesive that is not chemically heat reactive

Type 2—General purpose tape, nominal thickness 0.0025 inch (0.06 mm) and coated with a heat-reactive thermosetting adhesive

Type 3—General purpose tape, nominal thickness 0.0035 inch (0.09 mm) and coated with a heat-reactive thermosetting adhesive

Type 4—General purpose thin tape, nominal thickness 0.0010 inch (0.025 mm) and coated with a heat-reactive thermosetting adhesive

Type 5—Oil-resistant tape, nominal thickness 0.0025 inch (0.06 mm) and coated with a heat-reactive thermosetting adhesive. Standard widths range from 1/4 inch (6 mm) to 2 inches (50 mm). Standard lengths are 108 feet (33 m), 164 feet (50 m), 180 feet (55 m), and 216 feet (66 m). Requirements for the tapes are shown in Table 12-4.

• D 2686, *Tetrafluoroethylene-Backed Pressure-Sensitive Electrical Insulating Tape*. This standard covers electrical insulating tape consisting of a polytetrafluoroethylene (PTFE) film coated on one side with a pressure-sensitive adhesive. Three types of tape are identified:

Type 1—Standard backing coated with a silicone adhesive:
Class A—0.002 inch (0.050 mm) backing thickness
Class B—0.005 inch (0.125 mm) backing thickness

Type II—Bondable backing tape coated with a silicone adhesive:
Class A—0.002 inch (0.050 mm) backing thickness
Class B—0.005 inch (0.125 mm) backing thickness

TABLE 12-4 Requirements for Polyester Plastic Pressure-Sensitive Tapes (ASTM D 2484)

	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5
Nominal thickness, inches (mm)	0.0025 (0.060)	0.0025 (0.060)	0.0035 (0.090)	0.0010 (0.025)	0.0025 (0.060)
Breaking strength, min, lb/in of width (N/m)	20 (3.5)	20 (3.5)	35 (6.1)	10 (1.7)	20 (3.5)
Dielectric breakdown, min, volts, average					
Standard conditions	4,500	4,500	6,000	3,000	4,500
After immersion in water	4,000	4,000	5,500	2,500	4,000
Adhesion, min, oz/in (N/m)					
On steel plate	20 (219)	35 (383)	35 (383)	20 (219)	20 (219)
On its own backing	15 (164)	15 (164)	15 (164)	10 (109)	15 (164)
On backing after thermosetting	—	35 (383)	35 (383)	35 (383)	30 (328)

Note: Tests are conducted in accordance with ASTM D 1000 and ASTM D 2305 procedures.

TABLE 12-5 Requirements for PTFE Pressure-Sensitive Adhesive Tapes (ASTM D 2686)

	CLASS A	CLASS B
Breaking strength, min, lb/in of width	10	20
(kN/m)	(1.7)	(3.5)
Elongation, min, percent	75	150
Adhesion, min, oz/in (N/m)		
On steel plate	15 (164)	20 (219)
On its own backing (Type II only)	15 (164)	15 (164)
Dielectric breakdown, min, volts, average		
Standard conditions	6,000	10,000
After immersion in water	6,000	10,000

Note: Tests are conducted in accordance with ASTM D 1000 procedures.

Type III—Standard backing coated with a special oil-resistant adhesive: Class A only—0.002 inch (0.050 mm) backing thickness.

Standard widths range from 1/4 inch (6 mm) to 2 inches (50 mm). Standard lengths are 108 feet (33 m), 164 feet (50 m), 180 feet (55 m), and 216 feet (66 m). Requirements for the tapes are shown in Table 12-5.

• D 2754, *High-Temperature Glass Cloth Pressure-Sensitive Electrical Tape.* This standard covers high-temperature electrical insulating tape consisting of glass cloth coated on one side with a pressure-sensitive adhesive. Two types of tape are identified:

Type I—Woven glass cloth, silicone adhesive
Class A—nominal thickness 0.007 in (0.18 mm)
Class B—nominal thickness 0.010 in (0.25 mm)
Type II—Woven glass cloth impregnated with polytetrafluoroethylene, silicone adhesive, nominal thickness 0.005 in (0.13 mm).

Standard widths range from 1/4 inch (6 mm) to 2 inches (50 mm). Standard lengths are 20 feet (6 m), 66 feet (20 m), and 108 feet (33 m). Requirements for the tapes are shown in Table 12-6.

• D 3005, *Low-Temperature Resistant Vinyl Chloride Plastic Pressure-Sensitive Electrical Insulating Tape.* This standard covers an electrical insulating tape for use at low temperature down to approximately 0°F (–18°C). The tape consists of a backing of vinyl chloride plastic, coated on one side with pressure-sensitive adhesive. Two types are identified:

Type I—nominal thickness 0.007 inch (0.178 mm)
Type II—nominal thickness 0.085 inch (0.216 mm)

Standard widths range from 1/4 inch (6 mm) to 2 inches (50 mm). Standard lengths are 20 feet (6 m), 66 feet (20 m), and 108 feet (33 m). Requirements for the tapes are shown in Table 12-7.

TABLE 12-6 Requirements for High-Temperature Glass Cloth Pressure-Sensitive Tapes (ASTM D 2754)

	TYPE I		
	CLASS A	CLASS B	TYPE II
Breaking strength, min, lb/in	120	120	50
(kg/25 mm)	55	55	23
Dielectric breakdown, min, volts	2,000	2,500	3,000
Adhesion min, oz/in (g/25 mm)			
On steel plate	25 (710)	25 (710)	20 (570)
On its own backing	15 (425)	15 (425)	—

Note: Tests are conducted in accordance with ASTM D 1000 procedures.

TABLE 12-7 Requirements for Low-Temperature Vinyl Chloride Plastic Electrical Tape (ASTM D 3005)

	TYPE I	TYPE II
Breaking strength, min, lb/in	15	17
(kN/m)	(2.6)	(2.9)
Elongation, min, percent	150	150
Dielectric breakdown, min, volts		
Standard conditions	7,000	8,500
After conditioning 96 h at 23°C and 96 percent humidity	90% of dry	90% of dry
Adhesion, min, oz/inch (N/m)		
On steel plate	16 (175)	16 (175)
On its own backing	16 (175)	16 (175)
On its own backing at –7°C (19°F)	16 (175)	16 (175)

Note: Tests are conducted in accordance with ASTM D 1000 procedures.

TABLE 12-8 Requirements for Polyethylene Plastic Electrical Tape (ASTM D 3006)

Breaking strength, min, lb/in (kN/m)	16 (2.8)
Elongation, min, percent	150
Dielectric breakdown, min, volts	
Standard conditions	10,000
After conditioning 96 h at 23°C and 96 percent humidity	90% of standard
Adhesion, min, oz/in (N/m)	
On steel plate	16 (175)
On its own backing	16 (175)
On its own backing at –7°C (19°F)	16 (175)

Note: Tests are conducted in accordance with ASTM D 1000 procedures.

• D 3006, *Polyethylene Plastic Pressure-Sensitive Electrical Insulating Tape.* This standard covers electrical insulating tape consisting of a backing made from polyethylene plastic, coated on one side with a pressure-sensitive adhesive. Standard widths range from 1/4 inch (6 mm) to 2 inches (50 mm). Standard lengths are 20 feet (6 m), 66 feet (20 m), and 108 feet (33 m). Thickness is 0.0095 inch (0.241 mm). Requirements for this tape are shown in Table 12-8.

• D 4514, *Friction Tape.* This specification presents requirements for adhesion, aged adhesion, breaking strength, breakdown voltage, parallelism, pinholes, tackiness, and thickness.

FEDERAL SPECIFICATIONS FOR ELECTRICAL INSULATING PRESSURE-SENSITIVE TAPES

The following Federal specifications have been developed for pressure-sensitive tapes:

- Nonelastic backings—MIL-I-15126
- Glass fiber backing—MIL-I-19166, MIL-I-22444
- Vinyl chloride—HH-I-595
- Polyethylene backing—MIL-I-15126
- Polyester film backing—MIL-I-15126
- Polytetrafluoroethylene backing—MIL-I-23594
- Silicone rubber tape—MIL-I-46852
- Unspecified backing—MIL-I-24391

The following pages provide a more detailed examination of these standards.

• HH-I-595, *Insulation Tape, Electrical, Pressure-Sensitive Adhesive, Plastic.* This specification was approved by the Commissioner, Federal Supply Service, General Services Administration, for the use of all Federal agencies. Covered are requirements of 80°C (176°F) polyvinyl chloride or copolymer of vinyl chloride and vinyl acetate, flame-retardant, cold- and weather-resistant, pressure-sensitive, electrical insulating tape. Standard widths of the tape are 1/2, 3/4, or 1 inch. The thickness of the tape shall be 0.007 inch. The length of tape in a roll shall be either 66 feet or 108 feet.

• Test procedures are described with reference, where appropriate, to applicable ASTM and UL standards. Property requirements include the following:

Flame retardant, cold and weather resistant
Low temperature
Adhesion strength to backing at 19.5°F (–7.0°C)
Unwind force at 19.5°F (–7.0°C)
Static elongation at 19.5°F (–7.0°C)
Breaking strength

• MIL-I-15126, *Insulation Tape, Electrical, Pressure-Sensitive Adhesive and Pressure-Sensitive Thermosetting Adhesive.* This specification has been approved by

the Department of Defense and is mandatory for use by the Departments of the Army, the Navy, and the Air Force. Covered are requirements for pressure-sensitive adhesive and pressure-sensitive thermosetting adhesive electrical insulation tapes intended for use in construction and repair of electrical and electronic equipment. The following types of tape are identified:

Type AFT—Acetate film backing, thermosetting adhesive
Type ACT—Acetate cloth backing, thermosetting adhesive
Type CFT—Cotton fabric backing, thermosetting adhesive
Type GFT—Glass fabric backing, thermosetting adhesive
Type PCT—Paper backing-crepe, thermosetting adhesive
Type PFT—Paper backing-flat, thermosetting adhesive
Type EF-7—Polyethylene backing—7 mils thick tape
Type EF-9—Polyethylene backing—9 mils thick tape
Type EF-20—Polyethylene backing—20 mils thick tape
Type MFT-2.5—Polyethylene terephthalate film backing, thermosetting adhesive—2.5 mils thick tape
Type MF-2.5—Polyethylene terephthalate film backing—2.5 mils thick tape
Type MFT-3.5—Polyethylene terephthalate film backing, thermosetting adhesive—3.5 mils thick tape

The adhesive used in types EF-7, EF-9, EF-20, and MF-2.5 shall be pressure sensitive, and shall not require heat, moisture, or other special manner of preparation. The adhesive employed in other types shall be a pressure-sensitive thermosetting, or heat-curing adhesive. Nominal widths shall be in the range of $^1/_4$–$1^1/_2$ inches, in $^1/_8$ inch increments. Rolls shall contain up to 72 yards. Thickness and other requirements are shown in Table 12-9.

• MIL-I-19166, *Insulation Tape, Electrical, High-Temperature, Glass Fiber, Pressure-Sensitive.* This specification has been approved by the Department of Defense and is mandatory for use by the Departments of the Army, the Navy, and the Air Force. Covered is glass fiber, silicone adhesive, pressure-sensitive tape for construction and repair of electrical equipment operating at high temperatures. The tape shall consist of glass fiber textile fabricated from continuous filament yarn, coated on one side with a silicone pressure-sensitive adhesive. The tape shall require no heat, moisture, or other preparation prior to or subsequent to application. The tape shall be natural in color, 0.007 or 0.010 inch thick, and in widths of 0.50, 0.75, and 1.00 inch. Rolls shall be 36 yards in length. Dielectric breakdown shall be as follows:

	NOMINAL THICKNESS	
CONDITIONING	0.010 in (volts, min)	0.007 in (volts, min)
96 h at 23°C and 0% humidity	4,000	2,000
96 h at 23°C and 96% humidity	3,000	1,500

TABLE 12-9 Requirements for Pressure-Sensitive Adhesive and Pressure-Sensitive Thermosetting Adhesive Tapes (MIL-I-15126)

TYPE	NOMINAL THICKNESS (inches)	TENSILE STRENGTH CONDITION 96/23/50* (lb/in width, min)	DIELECTRIC BREAKDOWN CONDITION 96/23/50* (volts, min)	DIELECTRIC BREAKDOWN CONDITION 96/23/96** (volts, min)
AFT	0.0035	15	4,500	3,500
ACT	0.0080	30	1,500	1,000
CFT	0.0105	40	1,000	500
GFT	0.0070	120	1,000	500
PCT	0.0105	15	1,000	500
PFT	0.0060	30	1,000	500
EF-7	0.0070	12	9,500	9,500
EF-9	0.0090	15	12,000	11,000
EF-20	0.020	25	15,000	12,000
MFT-2.5	0.0025	20	4,500	4,500
MF-2.5	0.0025	20	4,500	4,500
MFT-3.5	0.0035	30	7,000	7,000

*Conditioning for 96 h at 23°C and relative humidity 50 percent.

**Conditioning for 96 h at 23°C and relative humidity 96 percent.

• MIL-I-22444, *Insulation Tape, Electrical, Self-Bonding, Silicone Rubber Treated Bias Weave or Sinusoidal Weave Glass, Cable Splicing, Naval Shipboard.* The silicone rubber compound may be applied to the glass backing tape by an extrusion process and sealing the tape edge by extending the rubber compound $^{1}/_{32}$ of an inch beyond each edge of the glass tape. A separator tape shall be used between adjacent layers on the roll of tape to prevent bonding. Standard widths shall be $^{1}/_{2}$, $^{3}/_{4}$, 1, and $1^{1}/_{2}$ inches. Thickness shall be in the range of 0.015–0.050 inch. Rolls shall contain 20 yards of tape. Average dielectric strength after being conditioned for 96 hours at 23°C (73°F) and 96 percent relative humidity shall be 500 volts per mil.

• MIL-I-23594, *Insulation Tape, Electrical, High Temperature, Polytetrafluoroethylene, Pressure-Sensitive.* This specification is mandatory for use by all departments and agencies of the Department of Defense. Two types of tape are identified:

Type I—Smooth backing

Type II—Treated backing (for insulation varnish)

Backing shall be virgin fused polytetrafluoroethylene resin. Type II backing is treated to accommodate an insulation varnish. Backing thickness shall be at least 1.5 mil. The adhesive shall be a pressure-sensitive silicone polymer and shall not require heat treatment or other special means of preparation prior to application. Standard widths are $^{1}/_{2}$, 1, $1^{1}/_{2}$, and 2 inches. Standard roll length is 36 yards. This material is intended for use as splicing tape for electrical systems of underwater ordnance equipment, aircraft, missile, and other weapons systems. Tensile strength and dielectric breakdown values shall be in accordance with Table 12-10.

TABLE 12-10 Tensile Strength and Dielectric Breakdown Values for Polytetrafluoroethylene Pressure-Sensitive Tape (MIL-I-23594)

BACKING THICKNESS (mils)	TENSILE STRENGTH (lb/in width, minimum)	DIELECTRIC BREAKDOWN (volts, minimum)	
	TYPES I AND II	TYPE I	TYPE II
1.5–2.5	7.0	4,200	3,800
2.6–3.5	12.0	7,200	6,500
3.6–4.5	17.0	10,300	9,000
4.6–5.5	22.0	12,700	11,500
5.6–6.5	27.0	15,400	14,000
6.6–7.5	32.0	18,000	16,500

• MIL-I-24391, *Insulation Tape, Electrical, Pressure-Sensitive.* This specification is mandatory for use by all departments and agencies of the Department of Defense. Covered are requirements for one type of plastic, electric, pressure-sensitive, self-extinguishing insulating tape for use at any ambient temperature condition between 10°F (–12.2°C) and 150°F (65.6°C). The adhesive shall be water insoluble and shall require no solvent, heat, or any other preparation prior to application. Standard widths are $^1/_2$, $^3/_4$, or 1 inch. Tape thickness shall be 0.0085 inch and length of tape in a roll shall be a minimum of 36 yards. Minimum average dielectric breakdown after water immersion shall be 7,000 volts and after exposure for 4 hours at 158°F (70°C) shall be 6,000 volts. After aging for seven days at 150°F (65.6°C) and 90 percent relative humidity, adhesion shall be at least 75 percent of original value.

• MIL-I-46852, *Insulation Tape, Electrical, Self-Adhering Unsupported Silicone Rubber.* This specification is approved for use by all departments and agencies of the Department of Defense. Covered are requirements for an unsupported silicone rubber tape which will adhere to itself at room temperature. The tape is suitable for use at temperatures from –130° to +500°F (–90° to +260°C). The tape is intended to be used as electrical insulation and as a thermal protection barrier for components subjected to missile blast environments. The tape shall be furnished in two types:

Type I—Rectangular cross-section
Type II—Triangular cross-section with colored guidelines.

Dimensions for Type I shall be as follows:

Width—0.50 inch 1.5 inches in 0.25 inch increments
Thickness—0.010, 0.020, 0.030 inch
Roll length—12 yards

Dimensions for Type II shall be as follows:

Width—1, 1.25, 1.5 inches
Thickness—0.020–0.080 inch in 0.010 inch increments
Roll length—12 yards

Property requirements shall be in accordance with Table 12-11.

TABLE 12-11 Requirements for Unsupported, Self-Adhering Silicone Rubber Tape (MIL-I-46852)

PROPERTY	VALUE	TEST METHOD
Tensile strength, minimum lb/in^2	700	ASTM D 119
Elongation percent, minimum	300	ASTM D 119
Water absorption percent by weight, maximum	3	Fed. Test 601 Method 6215
Dielectric strength, volt/mil, minimum		
0.010, 0.020, 0.030 in thick	400	ASTM D 119
0.040 in thick	300	
0.050 in thick	275	
0.060 in thick	250	
0.080 in thick	200	
Volume resistivity Ω • cm minimum	3×10^{14}	ASTM D 1458
Bond strength, 1 in width, minimum pounds	2	MIL-I-46852

UL STANDARD FOR INSULATING TAPES

Underwriters Laboratories has developed the following standard for insulating tapes:

- UL 510, *Electrical Insulating Tapes*

PROPERTIES

The minimum requirements for all types of pressure-sensitive tapes are shown in the accompanying ASTM Standards and Federal specifications. Features of tapes with different elastomer bases are as follows:

- Natural rubber provides excellent adhesion and can be made to crosslink readily at varnish curing temperatures with improved chemical resistance. Premastication is required.
- Butyl and polyisoprene elastomers have inherently better dielectric, heat aging, solvent-resistant, and ozone-resistant properties than natural rubber. These adhesives may also be made to crosslink. Premastication is not required.
- Acrylic adhesives do not require premastication, tackifier resins, or fillers. These adhesives are rated thermal Class 155, versus Class 130 for natural and butyl rubbers. Oil and oxidation resistance is superior to rubbers, but adhesion is lower. Thermosetting versions can be made by introduction of functional groups.
- Silicone adhesives remain effective at 180°C (356°F), the highest of all commonly used adhesives. They are inorganic, and if burned, leave a nonconducting residue. Low-temperature flexibility is superior to all other adhesives, but adhesive properties are somewhat lower. Silicone adhesives may be applied to etched Teflon

films and unetched polyolefin films to which organic elastomers will not adhere adequately.

- Block copolymer adhesives do not require premastication. They dissolve readily, and because they are thermoplastic, they can be coated at 100 percent or high solids content using hot melt techniques.

TAPE SELECTION

In selecting a pressure-sensitive tape for a specific application, design engineers should consider the operating conditions to which the tape will be exposed:

- The required dielectric breakdown strength
- The operating and environmental temperature range
- Space limitations
- Exposure to solvents and other chemicals
- Required physical properties
- Conformance to customer, industry, or military specifications or standards (there is no UL 94 flammability rating for dielectric tapes)
- The surface to which the tape must adhere
- Esthetic requirements (color, printability)

ELECTRICAL/ELECTRONIC USES

Pressure-sensitive tapes are used to wrap and to hold down wires and wire harnesses, and for terminating and splicing wires and cables. Bus bars are wrapped with pressure-sensitive tapes for insulation. High-temperature applications are served by silicone rubber pressure-sensitive tapes on fluoropolymer or polyimide film backing.

Thermosetting pressure-sensitive tapes are used in the manufacture of electrical equipment subsequently treated with varnishes and baked at varnish-curing temperatures.

Polyester-backed pressure-sensitive tapes are used to mask printed circuit boards during plating operations.

DEVELOPMENT PROGRAMS

Because solvent systems are coming under increasing regulation aimed at protecting the environment and worker health and safety, development programs are principally focused on emulsion-based and hot melt adhesives. Acrylic and block copolymer adhesives are inherently better suited for these new systems than are rubbers, but rubbers are still unsurpassed in tack and low cost, even though they are the most energy intensive to process.

MARKET TRENDS

Pressure-sensitive tapes are firmly entrenched in electrical equipment manufacturing processes and in wire and cable wrapping applications. A wide range of products is offered to users who are cost and quality conscious, and are less concerned with adhesive recipes. While it is likely that rubber-base adhesives will lose market share to newer systems, the trend will be gradual.

NONADHESIVE TAPES AND COATED FABRICS

INTRODUCTION

Yellow and black varnished cambrics based on oleoresinous varnishes were among the earliest materials used to insulate electrical equipment. Although the largest volume use, as a tape wrap for power cables, has largely yielded most of its market share to extruded insulations, there has been an expansion of coating and substrate types for other electrical and electronic applications. Newer materials covered in this chapter include polyester, silicone, and polytetrafluoroethylene coatings; glass and dacron substrates; and synthetic and silicone rubber tapes.

SUPPLIERS OF NONADHESIVE TAPES AND COATED FABRICS

Producers of nonadhesive tapes and coated fabrics include the following:

- Acme
- CHR Industries
- Dewal Industries
- 3M
- Norplex Oak
- Permacel Division of Fasson

TECHNOLOGY

Electrical insulating coated fabrics and tapes, and unsupported tapes, come in a variety of types, among which the following are in common use:

- Black and yellow, straight-cut and bias-cut varnished cotton fabric and tape (ASTM D 373, MIL-I-3374)
- Silicone-varnished glass cloth and tape (ASTM D 1495, MIL-I-17205)
- Fully cured silicone rubber-coated glass fabric and tapes (ASTM D 1931)
- Varnished glass-polyester cloth and tapes (ASTM D 2400)

- Oleoresinous varnish-coated glass fabrics and tapes (ASTM D 3949, MIL-I-17205)
- Nonmetallic conducting and electrically insulating rubber tapes (ASTM D 4325)
- Polytetrafluoroethylene-coated glass fabric and tapes (ASTM D 4969, MIL-I-18746)
- Natural and synthetic rubber tapes (HH-I-553)
- Filler-type, flameproof insulation tape (MIL-I-17695)
- Semi-cured thermosetting resin-treated glass tape (MIL-I-24178).

The above ASTM standards and Federal specifications are summarized later in this chapter.

PROCESSING

Varnished fabrics are made by passing fabric through a tank containing varnish or resin, after which the film is formed and cured in a vertical tower with temperature controlled to suit the varnish or resin system employed. The desired film thickness is built up in several passes (usually two–four) through the tower. Typically, a machine consists of three or four adjacent units to permit the fabric to travel continuously through successive tanks and heating chambers.

Alternatively, the oven may be horizontal with the fabric passing through it on edge with edges held by tenters. With this method, much larger ovens may be used and significantly faster processing is made possible. Varnish or resin must be applied in such a way that it does not flow excessively or form droplets which would cure to make film imperfections. Top and bottom of rolls of material are reversed after each pass to prevent film from becoming wedge shaped. This process is best suited for long runs, and was used extensively when varnished cambric tape was the principal insulation for power cables.

Varnishes and resin systems are similar to those discussed in Chapter 8, *Insulating Coatings and Impregnants*. Substrates include cotton cloth, glass cloth, dacron-glass cloth, canvas, polyester mat, aramid mat, and composites of these. Kraft paper is also varnished for electrical applications.

In processing solvent systems, vapors must be burned or recycled so that emissions are in compliance with EPA, OSHA, and local government standards and regulations. See "Federal Air Pollution Program" (p. 517) of Chapter 19, *Government Activities*.

Rubber-coated glass tapes are made by methods described in "Pressure-Sensitive Tapes" section of this chapter. Extruded rubber processing is discussed in Chapter 5, *Extrusion Compounds*.

GRADES

Grades for all materials covered by standards and specifications summarized in this section are commercially available.

ASTM STANDARDS FOR NONADHESIVE TAPES AND COATED FABRICS

The American Society for Testing and Materials has developed the following standards for nonadhesive tapes and coated fabrics. For a listing of product types and related standards, see "Technology" (p. 356).

• D 295, *Varnished Cotton Fabrics Used for Electrical Insulation.* This standard describes methods for testing varnished cotton fabrics and varnished cotton fabric tapes to be used as electrical insulation. Table 12-12 lists the test methods applicable to both straight-cut and bias-cut materials.

TABLE 12-12 Property Tests for Varnished Cotton Fabrics (ASTM D 295)

PROPERTY MEASURED	ASTM METHOD
Breaking strength	D 295
Conditioning	D 295
Dielectric breakdown voltage	D 149
Dielectric breakdown voltage under elongation	D 149
Dissipation factor and permittivity	D 150
Elongation	D 295
Resistance to oil	D 92
Selection of test specimens	D 295
Tear resistance	D 689
Thickness	D 374
Thread count	D 295
Volume resistance	D 257
Weight	D 295

• D 373, *Black and Yellow Straight-Cut and Bias-Cut Varnished Cotton Cloth and Tape for Electrical Insulation.* Breaking strength and elongation requirements are specified. Dielectric breakdown requirements are shown in Table 12-13.

• D 902, *Flexible Resin-Coated Glass Fabrics and Glass Fabric Tapes Used for Electrical Insulation.* This standard describes methods of testing resin-coated glass fabrics and glass fabric tapes to be used as electrical insulation. Table 12-14 lists the following test methods.

• D 1458, *Fully Cured Silicone Rubber-Coated Glass Fabric and Tapes for Electrical Insulation.* This standard describes methods of testing fully cured silicone rubber-coated glass fabric and tapes to be used for electrical insulation. Table 12-15 lists the following test methods.

• D 1459, *Silicone Varnished Glass Cloth and Tape for Electrical Insulation.* This standard covers clear silicone varnished glass fabrics in the form of sheets, rolls, and tapes for use as electrical insulation. These materials shall conform to Class H (180) requirements. Two types of materials are identified:

TABLE 12-13 Dielectric Breakdown Requirements for Varnished Cotton Cloth (ASTM D 373)

NOMINAL THICKNESS, mm (mils)	CUT	AVERAGE DIELECTRIC BREAKDOWN, min, kV					
		BLACK			YELLOW		
		UNSTRESSED	UNDER 6% ELONGATION	AFTER HOT OIL	UNSTRESSED	UNDER 6% ELONGATION	AFTER HOT OIL
0.18 (7)	bias	7.7	4.2	7.7	7.0	3.2	7.0
	straight	7.7	—	—	6.3	—	—
0.25 (10)	bias	11.0	9.0	11.0	11.0	7.0	11.0
	straight	11.0	—	—	10.0	—	—
0.30 (12)	bias	13.8	11.0	13.8	13.2	10.0	13.2
	straight	13.8	—	—	12.0	—	—

Note: Tests are conducted in accordance with ASTM D 295 procedures.

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Type A—For use where maximum electrical properties are required
Type B—For use where maximum physical properties are required.

Nominal thicknesses range from 3 to 25 mils (0.076–0.635 mm).

Average breaking strength requirements range from 70 pounds per inch of width for 3 mil material to 300 pounds per inch of width for 20 mil Type A material (12.25 newtons per mm of width for 0.076 mm thick material to 52.54 newtons per mm of width for 0.508 mm thick material). For Type B material, the range is 100 pounds per inch of width for 5 mil thick material to 350 pounds per inch of width for 25 mil thick material (17.51 newtons per mm of width for 0.127 mm thick material to 61.29 newtons per mm of width for 0.635 mm thick material). Short-time dielectric strength val-

TABLE 12-14 Property Tests for Varnished Glass Fabrics (ASTM D 902)

PROPERTY MEASURED	TEST METHOD
Breaking strength	D 828
Conditioning	D 902
Dielectric breakdown voltage and dielectric strength	D 149
	D 295
Dissipation factor and relative permittivity	D 150
	E 104
Effect of elevated temperature	D 902
Resistance to oil	D 902
Sampling	D 902
Thickness	D 374
Thread count	D 902
Weight	D 902
Weight loss at elevated temperature	D 902

TABLE 12-15 Property Tests for Fully Cured Silicone Rubber-Coated Glass Fabrics (ASTM D 1458)

PROPERTY MEASURED	ASTM METHOD
Sampling	D 1458
Conditioning	D 1458
Thickness	D 1458
Breaking strength	D 1458
Breaking strength after creasing	D 1458
Dielectric breakdown	D 149
	D 295
	D 618
Dielectric proof-voltage	D 1389
Dissipation factor and relative permittivity	D 150
Volume resistivity	D 257
Weight	D 1458
Thread count	D 1458

ues using 1/4 inch (6.4 mm) electrodes shall be in the range of 1,300 volts per mil for 3 mil thick material to 400 volts per mil for 20 mil thick material (51.2 kilovolts per mm for 0.508 mm thick material). The range for Type B material shall be 1,000 volts per mil for 5 mil thick material to 300 volts per mil for 25 mil thick material (39.4 kilovolts per mm for 0.127 mm thick material to 11.8 kilovolts per mm for 0.635 mm thick material). Tests are conducted in accordance with ASTM D 902 procedures.

- D 1931, *Fully Cured Silicone Rubber-Coated Glass Fabric and Tapes for Electrical Insulation*. This standard covers fully cured silicone rubber-coated glass fabric in sheet form, full-width rolls, and tapes to be used as electrical insulation. Physical and electrical requirements are listed in Table 12-16.

- D 2400, *Varnished Glass-Polyester Cloth Used for Electrical Insulation*. This standard applies to black and yellow varnished woven cloth and tape having as a base fabric poly(ethylene terephthalate) yarns in the warp direction and glass yarns in the filler direction. The base fabric shall have a nominal thickness of 0.004 inch (0.10 mm). The varnish shall be of the oleoresinous type. Dielectric breakdown strength values are shown in Table 12-17.

- D 3949, *Coated Glass Fabrics Used for Electrical Insulation*. This standard covers woven glass fabric coated with fully cured oleoresinous varnish, epoxy resin, polyurethane resin, or polyester resin. This standard has been developed for materials using fabrics woven from relatively coarse-filament yarns, and in some cases from relatively open weave constructions. The following types of material are identified:

  Type 1—Black oleoresinous varnish
  Type 2—Yellow oleoresinous varnish
  Type 3—Epoxy resin
  Type 4—Polyurethane (isocyanate) resin
  Type 5—Polyester resin.

  Nominal thicknesses and dielectric requirements are shown in Table 12-18.

TABLE 12-16 Physical and Electrical Requirements for Silicone Rubber-Coated Glass Fabric and Tapes (ASTM D 1931)

Physical:				
Nominal thickness, mm	0.12	0.18	0.25	0.38
in	0.005	0.007	0.010	0.015
Thickness tolerance, mm	±0.01	±0.03	±0.03	±0.03
in	±0.0005	±0.001	±0.001	±0.001
Nominal fabric thickness, mm	0.08	0.10	0.10	0.18
in	0.003	0.004	0.004	0.007
Breaking strength (warp), min, avg:				
kN/m	12.3	21.9	21.9	43.8
lbf/in	70	125	125	250
Breaking strength (creased), min, avg:				
kN/m	3.5	15.8	15.8	35.0
lbf/in	20	90	90	200
Weight, kg/100 m^2	16 ± 1.6	26 ± 2.6	37 ± 3.7	49 ± 4.9
lb/100 yd^2	30 ± 3	48 ± 4.8	68 ± 6.8	90 ± 9
Electrical:				
Dielectric strength, kV/mm (V/mil), min, avg:				
Condition 96/23/50*	36 (900)	30 (750)	34 (850)	26 (650)
Condition 24/23/96**	—	19 (475)	23 (575)	—
Dissipation factor, 2 kV/mm (50 V/mil) stress, max, avg:				
at 23°C (73°F)	0.015	0.015	0.015	0.015
at 100°C (212°F)	0.020	0.020	0.020	0.020
Relative permittivity, 2 kV/mm (50 V/mil) stress, max, avg, at 23°C (73°F)	4	4	4	4

*96 h at 23°C and 50 percent humidity.

**24 h at 23°C and 96 percent humidity.

Note: Tests are conducted in accordance with ASTM D 1458 procedures.

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TABLE 12-17 Electrical Requirements for Varnished Glass-Polyester Cloth (ASTM D 2400)

	BLACK			YELLOW	
Nominal thickness inches (mm)	0.008 (0.20)	0.010 (0.25)	0.012 (0.31)	0.008 (0.20)	0.010 (0.25)
Dielectric breakdown voltage, min ave kV					
Unstressed	10.5	12.5	15.0	9.5	11.0
Under 6% elongation	8.5	10.0	12.5	8.0	9.5
After hot oil	10.5	12.5	15.0	9.5	11.0

TABLE 12-18 Dielectric Strength Requirements for Coated Glass Fabrics (ASTM D 3949)

NOMINAL THICKNESS, in (mm)		CONDITION 48/23/50,* AVERAGE MIN. V/mil[a]					CONDITION 90/23/90,* AVERAGE MIN. V/mil[a]				
TOTAL	FABRIC	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5
0.003 (0.08)	0.002 (0.05)	1,950	1,900	1,300	1,750	1,900	1,050	1,000	800	750	1,200
0.005 (0.08)	0.002 (0.05)	1,900	1,850	1,350	1,700	1,800	950	900	750	700	1,200
0.005 (0.13)	0.003 (0.08)	1,850	1,750	1,400	1,500	1,600	950	900	800	700	900
0.007 (0.18)	0.003 (0.08)	1,800	1,650	1,300	1,350	1,500	900	850	800	750	900
0.007 (0.18)	0.004 (0.10)	1,650	1,450	1,250	1,250	1,400	850	800	650	600	700
0.010 (0.25)	0.004 (0.10)	1,600	1,350	1,250	1,200	1,400	800	700	650	600	700
0.010 (0.25)	0.005 (0.13)	1,100	1,000	1,200	1,150	1,300	600	550	600	550	600
0.010 (0.25)	0.007 (0.18)	1,000	800	1,100	1,150	1,150	550	450	600	500	550
0.012 (0.30)	0.007 (0.18)	950	750	1,000	1,150	1,150	500	400	450	400	550
0.015 (0.38)	0.007 (0.18)	900	700	1,000	1,000	1,150	500	400	400	350	550
0.015 (0.38)	0.010 (0.25)	850	750	900	750	1,050	450	300	350	300	500
0.020 (0.51)	0.010 (0.25)	800	700	—	—	—	450	300	—	—	—
0.020 (0.51)	0.015 (0.38)	750	600	—	—	—	400	300	—	—	—
0.025 (0.64)	0.015 (0.38)	750	600	—	—	—	400	300	—	—	—
0.030 (0.76)	0.015 (0.38)	700	550	—	—	—	350	300	—	—	—

NOMINAL THICKNESS, in (mm)		DIELECTRIC STRENGTH AT ROOM TEMPERATURE AFTER BENDING 180° AVERAGE MIN. V/mil[a]					PERCENTAGE RETENTION OF BREAKDOWN VOLTAGE AFTER AGING 168 h AT TEMPERATURE[b] AND BENT 180° MIN. %
TOTAL	FABRIC	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	ALL TYPES
0.003 (0.08)	0.002 (0.05)	1,650	1,550	1,300	1,550	1,550	75
0.005 (0.13)	0.002 (0.05)	1,650	1,500	1,250	1,300	1,400	75
0.005 (0.13)	0.003 (0.08)	1,600	1,500	1,250	1,250	1,300	75
0.007 (0.18)	0.003 (0.08)	1,600	1,500	1,200	1,200	1,300	75
0.007 (0.18)	0.004 (0.10)	1,100	1,050	1,050	1,150	1,300	65
0.010 (0.25)	0.004 (0.10)	1,400	1,300	1,050	1,100	1,600	70
0.010 (0.25)	0.005 (0.13)	500	450	1,000	1,050	1,100	70
0.010 (0.25)	0.007 (0.18)	600	500	1,000	900	950	70
0.012 (0.30)	0.007 (0.18)	500	450	1,000	800	800	70
0.015 (0.38)	0.007 (0.18)	500	450	700	750	800	65
0.015 (0.38)	0.010 (0.25)	500	450	700	550	750	65
0.020 (0.51)	0.010 (0.25)	500	400	—	—	—	60
0.020 (0.51)	0.015 (0.38)	400	300	—	—	—	55
0.025 (0.64)	0.015 (0.38)	400	300	—	—	—	55
0.030 (0.76)	0.015 (0.38)	350	300	—	—	—	50

[a]Divide V/mil by 25.4 to obtain kV/mm.

[b]Temperature of aging: Types 1 and 2 = 130°C
Types 3 and 4 = 180°C
Type 5 = 200°C.

*Hours/temperature/percent relative humidity.

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• D 4325, *Nonmetallic Conducting and Electrically Insulating Rubber Tapes.* This standard describes methods of testing electrically insulating and nonmetallic conducting rubber tapes designed for splicing, terminating, and sheath repair of electrical wire and cable. Table 12-19 lists the test methods.

TABLE 12-19 Property Tests for Nonmetallic Conducting and Electrically Insulating Rubber Tapes (ASTM D 4325)

PROPERTY MEASURED	ASTM METHOD
Conditioning	D 4325
Dielectric strength	D 149
Dimensions	D 4325
Dissipation factor	D 150
Elongation	D 412
Heat resistance	D 4325
Fusion	D 4325
Ozone resistance	D 470
Permittivity	D 150
Sample requirements	D 4325
Tensile strength	D 412
Volume resistivity	D 257
Ultraviolet and weather resistance	D 750

• D 4388, *Nonmetallic Conducting and Electrically Insulating Rubber Tapes.* This standard covers nonmetallic conducting and electrical insulating tapes designed for the splicing and repair of electrical wire and cables operating at voltages up to 138,000 volts, phase to phase. Four types of tapes are identified:

Type I—A low-voltage rubber insulating tape designed for use on wires and cables operating up to 2,000 volts phase to phase in dry locations with temperatures up to 80°C (176°F) for continuous operation, to 95°C (203°F) for emergency overload conditions, and up to 150°C (302°F) for short-circuit conditions. This tape is not ozone resistant.

Type II—A medium-voltage, ozone-resistant, rubber insulating tape designed for use on wires and cables operating up to 35,000 volts phase to phase in either wet or dry locations with conductor temperatures up to 90°C (194°F) for continuous operation, to 130°C (266°F) for emergency overload conditions, and up to 250°C (482°F) for short-circuit conditions. This tape is not resistant to ultraviolet radiation.

Type III—A high-voltage, ozone-resistant, rubber insulating tape designed for use on wires and cables operating up to 138,000 volts phase to phase in either wet or dry locations with conductor temperatures up to 90°C (194°F) for continuous operation, to 130°C (266°F) for emergency overload conditions, and up to 250°C (482°F) for short-circuit conditions.

Type IV—A nonmetallic conducting tape designed for shielding various portions of joints and terminations in electrical wires and cables operating at any voltage under wet or dry conditions.

The tape shall consist of a noncrosslinked or partially crosslinked rubber nonmetallic conducting or insulating compound. Standard widths range from 0.75 inch (19 mm) to 2 inches (50 mm). Standard lengths range between 3 yards (2.7 m) and 10 yards (9.1 m). Thickness range is 0.020 inch (0.508 mm) to 0.040 inch (1.016 mm). Requirements for these tapes are shown in Table 12-20.

TABLE 12-20 Requirements for Nonmetallic Conducting and Electrically Insulating Rubber Tapes (ASTM D 4388)

REQUIREMENTS	TYPE I	TYPE II	TYPE III	TYPE IV
Tensile strength, min avg, psi (MPa)	250 (1.7)	250 (1.7)	250 (1.7)	>100 (0.69)
Elongation at break, min avg, %	300	500	700	300
Dielectric strength, min avg, V/mil (kV/mm):				
0.020 in (0.51 mm) thickness	—	—	700 (28)	—
0.030 in (0.76 mm) thickness	350 (14)	500 (20)	600 (24)	—
0.040 in (1.016 mm) thickness	—	400 (16)	—	—
Dissipation factor, max:				
24 h at 23°C[a]	—	0.05	0.05	—
168 h at 70°C[a]	—	0.05	0.05	—
Permittivity, max:				
24 h at 23°C[a]	—	4.5	4.0	—
168 h at 70°C[a]	—	4.5	4.0	—
Volume resistivity, (Ω · cm):				
96 h at 23°C and 50% RH	—	10^{14} min avg	10^{14} min avg	10^{3} max
96 h at 23°C and 96% RH	—	10^{13} min avg	10^{13} min avg	—
168 h at 90°C	—	—	—	5×10^{4} max
Fusion—Flags $^{5}/_{64}$ in (0.2 mm) max	200% elongation	300% elongation	300% elongation	300% elongation
Ozone resistance	–	No visible cracks or checking	No visible cracks or checking	—
Heat resistance	Pass at 95°C	Pass at 110°C	Pass at 130°C	—
UV resistance	—	—	Pass	Pass

[a]After immersion in distilled water prior to testing at 23°C in accordance with Test Methods D 4325.

Note: Tests are conducted in accordance with ASTM D 4325 procedures.

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• D 4969, *Specification for PTFE Coated Glass Fabric*. Type 1 of this standard covers glass fabric coated on both sides with polytetrafluoroethylene polymer. Table 12-21 lists the minimum dielectric requirements for this material.

TABLE 12-21 Dielectric Requirements for PTFE-Coated Glass Fabric (ASTM D 4969)

	COATED THICKNESS inches*	DIELECTRIC BREAKDOWN volts (min)
Type 1	0.002	1,000
	0.003	2,500
	0.004	3,300
	0.005	3,900
	0.006	4,300
	0.008	4,700
	0.010	5,200
	0.014	7,500

*There is no specification for coating thickness.

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The key requirement of this specification is that, after exposure to a temperature of 150°C (302°F) for 12 hours, the average dielectric breakdown value of five samples shall not be less than 80 percent of the value determined before exposure.

FEDERAL SPECIFICATIONS FOR NONADHESIVE TAPES AND COATED FABRICS

The following Federal specifications have been developed for nonadhesive tapes and coated fabrics. For a listing of product types and related specifications, see "Technology" (p. 356).

- HH-I-553, *Insulation Tape, Electrical (Rubber, Natural and Synthetic)*. This specification is for the use of all Federal agencies. Covered is rubber insulating tape for splicing wires and cables at both normal and high voltages. Two grades of tape are designated:

  Grade A—Ozone resistant, 130°C (266°F)

  Grade B—Regular, 600 volts maximum, 80°C (176°F)

Grade A tape shall consist of an unvulcanized self-amalgamating compound of natural rubber, synthetic rubber, or a mixture of the two. Grade B tape shall consist of an unvulcanized or partially vulcanized compound of natural rubber, synthetic rubber, or a mixture of the two. Nominal thickness of the tape shall be 0.030 inch with width according to ASTM D 119. Grade A tape shall not delaminate without rupture of the material after spiral wrapping and conditioning at 20° to 30°C (68°–86°F) for 24 hours. The fusion between layers of Grade B tape shall be in accordance with ASTM D 119.[1] Dielectric strength of both grades shall be in accordance with ASTM D 119.[1]

[1]Now discontinued by ASTM.

• MIL-I-3374, *Insulation Cloth and Tape, Electrical, Varnished Cambric.* This specification has been approved by the Department of Defense for use of the Departments of the Army, the Navy, and the Air Force. Covered is insulation intended for use as cable insulation, coil wrappers, and for insulating bus bars, joints and terminals of electric wires and cables. Insulation shall be of the following types and classes:

Type I—Cloth
Class 1—Bias cut
Class 2—Straight cut
Type II—Tape
Class 1—Bias cut
Class 2—Straight cut

The fabric shall be a closely knit cotton cloth with minimum thread count per inch of 60 for the warp and 55 for the filler. The coating shall be a high-grade yellow baking varnish, and the number of coats used shall be such that the finished material meets all dimensional and performance requirements of this specification. The varnish coating shall not crack when the cloth or tape is doubled upon itself, or when bent through 180 degrees over a $^1/_8$ inch mandrel after conditioning in an air oven at 125°C (257°F) for 150 hours. Requirements for these materials are shown in Table 12-22.

• MIL-I-17205, *Insulation Cloth and Tape, Electrical, Glass Fiber, Varnished.* This specification has been approved by the Department of Defense and is mandatory for use by the Departments of the Army, the Navy, and the Air Force. Insulation is classified as follows:

Form C—Cloth
Grade O—Varnished with yellow organic varnish
Grade S—Varnished with silicone varnish for use in motors, generators, and transformers.
Form T—Tape
Grade O—Varnished with yellow organic varnish
Grade S—Varnished with silicone varnish for use in motors, generators, and transformers.

Requirements for these materials are shown in Table 12-23.

• MIL-I-17695, *Insulation Tape, Electrical, Filler Type, Flameproof, Synthetic.* This specification covers the requirements for a filler type insulation in tape form intended for use as a filler material for splicing power and control cables. The unsupported material shall have application characteristics which are putty-like and capable of being easily moldable with reasonable finger pressure or applied winding pressure. It shall be able to maintain a continuity of material that will not crumble, flake, thin apart into stringiness or otherwise react to cause an unintended break in its normal application. The tape shall have maximum thickness of 0.125 inch and be $1^1/_2$ inches wide with a length of 5 feet. The material shall be flameproof in its stored form, in its application, and in use.

• MIL-I-18746, *Insulation Tape, Nonadhering, Glass Fabric Polytetrafluoroethylene Coated.* This specification covers one type of polytetrafluoroethylene-coated glass fabric for electrical insulation use at temperatures up to 260°C (500°F). The glass fabric shall be coated on both sides with polytetrafluoroethylene resin. Nominal widths

TABLE 12-22 Requirements for Varnished Cambric Cloth and Tape (MIL-I-3374)

			BREAKING STRENGTH				
			CONDITION[1] C-96/23/50				
			WARP OR LENGTH-WISE	FILLER	DIELECTRIC STRENGTH		TEAR STRENGTH ACROSS WRAP
					CONDITION[1] C-96/23/0	CONDITION[1] C-96/23/96	CONDITION[1] C-96/23/50
TYPE	CLASS	NOMINAL THICKNESS inch	lb/in width (min. avg.)	lb/in width (min. avg.)	volts/mil (min avg.)	volts/mil (min. avg.)	grams (min. avg.)
I—Cloth	1—Bias cut	0.007	38	—	1,000	250	—
		0.010	38	—	1,100	450	—
		0.012	38	—	1,000	500	—
I—Cloth	2—Straight cut	0.007	43	25	1,100	450	250
		0.010	43	25	1,100	600	250
		0.012	43	25	1,100	600	250
II—Tape	1—Bias cut	0.007	38	—	1,000	250	—
		0.010	38	—	1,100	450	—
		0.012	38	—	1,000	500	—
II—Tape	2—Straight cut	0.007	43	—	1,100	450	—
		0.010	43	—	1,100	600	—
		0.012	43	—	1,100	600	—

[1]Hours/°C/percent relative humidity.

are 1/2, 3/4, 1, and 1 1/2 inches. Nominal thicknesses, mechanical and electrical properties are shown in Table 12-24.

After exposure to a temperature of 150°C (302°F) for 12 hours, the average dielectric strength shall not be less than 80 percent of the value before exposure.

• MIL-I-24178, *Insulation Tape, Electrical, Semi-Cured Thermosetting Resin Treated Glass, Armature Banding, Naval Shipboard.* This specification covers semi-cured thermosetting resin treated, unidirectional glass electrical insulating tape intended for banding armatures of rotating electrical machines for shipboard use. Other applications may be banding of wound rotor coils, securing stator coils, surge rings, commutator string bands. There are two types of tape:

Type B—General Purpose, 130°C for continuous operation
Type H—High temperature, 180°C for continuous use

The insulating tape shall consist of nonwoven parallel glass yarns impregnated and bonded with a thermosetting resin. The tape shall be furnished in the semi-cured ("B" stage) state, and shall be flat, dry, and nonsticky. The surface may be slightly tacky, but shall unwind freely from the spool without transfer of resin or glass strands. The thermosetting resin shall be such that the treated tape may be completely cured

TABLE 12-23 Requirements for Varnished Glass Cloth and Tape (MIL-I-17205)

GRADE	FORM	NOMINAL THICKNESS OF VARNISHED MATERIAL	NOMINAL GLASS BASE FABRIC THICKNESS	TENSILE STRENGTH CONDITION C-96/23/50[1] WARP lb/in WIDTH (min. avg.)	TENSILE STRENGTH CONDITION C-96/23/50[1] FILL lb/in WIDTH (min. avg.)	DIELECTRIC STRENGTH CONDITION[1] C-96/23/0 volts/mil (min. avg.)	DIELECTRIC STRENGTH CONDITION[1] C-96/23/96 volts/mil (min. avg.)
		inch					
O	C	0.005	—	100	70	1,200	600
		0.007	—	100	70	1,200	600
		0.010	—	150	100	1,100	500
O	T	0.005	—	100	—	1,200	600
		0.007	—	100	—	1,200	600
		0.010	—	150	—	1,100	500
S	C	0.002	0.001	22	18	1,800	600
		0.004	0.002	70	40	1,400	1000
		0.007	0.003	100	70	1,300	900
		0.010	0.004	150	100	1,200	800
S	T	0.002	0.001	22	—	1,800	600
		0.004	0.002	70	—	1,400	1000
		0.007	0.003	100	—	1,300	900
		0.010	0.004	150	—	1,200	800

EFFECT OF ELEVATED TEMPERATURES

GRADE	FORM	POWER FACTOR AT 60 CYCLES Condition[1] C-96/23/0 (max. avg.)	POWER FACTOR AT 60 CYCLES Condition[1] C-96/23/96 (max. avg.)	DIELECTRIC CONSTANT AT 60 CYCLES Condition[1] C-96/23/0 (max. avg.)	DIELECTRIC CONSTANT AT 60 CYCLES Condition[1] C-96/23/96 (max. avg.)	CONDITION[1] C-168/23/50 Initial Bent Dielectric Strength volts/mil (min. avg.)	Condition[1] E-168/130 Percent Retention (min.)	Condition[1] E-168/250 Percent Retention (min.)
O	C	0.050	0.30	6.0	18.0	1,050	65	—
		0.050	0.30	6.0	18.0	1,050	65	—
		0.050	0.30	6.0	18.0	1,000	65	—
O	T	—	—	—	—	1,050	65	—
		—	—	—	—	1,050	65	—
		—	—	—	—	1,000	65	—
S	C	0.020	0.20	3.5	4.5	1,700	—	75
		0.020	0.20	4.5	6.0	1,300	—	75
		0.020	0.15	4.5	6.0	1,200	—	75
		0.020	0.20	4.5	6.0	1,100	—	75
S	T	—	—	—	—	1,700	—	75
		—	—	—	—	1,300	—	75
		—	—	—	—	1,200	—	75
		—	—	—	—	1,100	—	75

[1]Hours/°C/percent relative humidity.

TABLE 12-24 Mechanical and Electrical Properties of Polytetrafluoroethylene-Coated Glass Fabric (MIL-I-18746)

THICKNESS (inch)	BREAKING STRENGTH MINIMUM lb/in OF WIDTH	DIELECTRIC STRENGTH MINIMUM AVERAGE OF 5 TEST VALUES volts/mil
0.002	20	800
0.003	40	800
0.005	70	700
0.007	100	600
0.010	150	500
0.012	175	500
0.015	200	500

after baking for 3–5 hours after the equipment reaches a temperature of 150°C. Nominal thickness is 0.014 inch. Nominal widths are $^3/_8$, $^1/_2$, $^3/_4$, $^5/_8$, and 1 inch.

NEMA/ICEA STANDARD FOR VARNISHED CLOTH INSULATED WIRE AND CABLE

The following standard is applicable:

- NEMA WC4/ICEA S-65, *Varnished Cloth Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy.*

PROPERTIES

The minimum requirements for most widely used nonadhesive tapes and coated fabrics are described in the accompanying summaries of standards and specifications. In general:

- Oleoresinous varnishes on cotton fabric or kraft paper are limited to thermal Class 105 application. On glass fabric or dacron-glass fabric, varnishes may be formulated by addition of synthetic resins to meet thermal Class 130 operational requirements.
- Epoxy resin-coated glass fabric and polyester resin coated dacron-glass fabric qualify for thermal Class 155 with high chemical resistance.
- Polyurethane-coated glass cloth is rated thermal Class 155, and has outstanding abrasion resistance and toughness.
- High-temperature polyester and silicone resin-coated glass fabrics conform to thermal Class 180, and also have high resistance to moisture and solvents.

• Glass fabric-coated with silicone rubber carries thermal Class 200 rating with excellent flexibility and moisture resistance. Corona effect is minimal. Resistance to abrasion, aromatic solvents, and hot oils is low.

• Polytetrafluoroethylene resin-coated glass cloth has the highest thermal rating, and is designed for continuous use at 260°C (500°F). Moisture and chemical resistance are outstanding.

Dielectric strength for most varnished materials is in the range of 1,000–1,500 volts per mil for 10 mil specimens when tested under standard conditions. Breakdown strength for rubber tape and rubber-coated glass fabrics is in the range of 500–700 volts per mil for 30 mil specimens.

ELECTRICAL/ELECTRONIC USES

Nonadhesive tapes and coated fabrics are used primarily for coil and wire and cable wrapping, for phase and layer insulation in electrical and electronic equipment, and for slot-cell insulation (abrasion-resistant grades only).

DEVELOPMENT PROGRAMS

Even before EPA and OSHA standards and governmental regulations placed restrictions on solvent emissions, producers of varnish-coated fabrics have been trying to eliminate solvents from coatings. Although higher solids contents in varnishes have been achieved and there is much less use of toxic solvents, there is still no widespread use of solventless insulating varnishes for coating fabrics.

MARKET TRENDS

Usage of nonadhesive tapes and coated fabrics for electrical insulating applications should parallel production trends in the electrical equipment manufacturing industry.

13

TUBING AND SLEEVING

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INSULATING TUBING

INTRODUCTION

There is some confusion as to the distinction between the terms "tubing" and "sleeving." Military specifications MIL-I-7444, MIL-I-23053C, and MIL-I-85080 use the term *sleeving* to describe extruded, unreinforced tubular products. These products are referred to as *tubing* in MIL-R-46846 and MIL-I-47049. *Tubing* is the term used in all applicable ASTM standards for these products. However, the International Electrotechnical Commission (IEC) Standard 684 uses *sleeving* to include extruded, unreinforced tubular products.

General usage in industry in the U.S. refers to extruded, unreinforced products as *tubing*, and to tubular, braided yarn products, coated or uncoated, as *sleeving*. Both terms are used to refer to tubular products made by spiral or convolute winding of tape or sheet materials.

Extruded, unreinforced insulating *tubing* covered in this section is made in all degrees of flexibility from very flexible to rigid (called *pipe* in larger sizes).

ASTM standards and Federal specifications, summarized herein, contain requirements and test procedures for widely used tubings and are an essential part of this section.

PRODUCERS OF EXTRUDED TUBING UL APPROVED

Underwriters Laboratories (UL) Standard 224, *Extruded Insulating Tubing*, lists producers of UL-approved electrical grade and flame-retardant tubing showing company name, material, maximum voltage, and maximum operating temperature.

TECHNOLOGY

The term "flexible tubing" as used here includes tubing from extruded compounds, without reinforcement, whose characteristic constituents are thermoplastic, thermosetting, or elastomeric. Cross-sectional shapes are limited only by extrusion die configurations. All of the materials discussed in Chapter 5, *Extrusion Compounds*, can be extruded as insulating tubing. The more commonly used polymers and their useful temperature ranges include the following:

POLYMER	USEFUL TEMPERATURE RANGE °C (F°)
Butyl rubber	–46 to 150 (–51 to 300)
Neoprene	–70 to 120 (–94 to 250)
Polyolefin (ethylene and ethylene copolymers)	
High temperature	–55 to 135 (–67 to 275)
Low temperature	–75 to 125 (–103 to 257)
Polyvinyl chloride (PVC)	
High temperature	–10 to 105 (14 to 221)
Low temperature	–55 to 80 (–67 to 176)
General purpose	–30 to 90 (–22 to 194)
Silicone rubber	–75 to 200 (–103 to 392)
Fluoropolymers	
Fluorinated ethylene-propylene (FEP)	–55 to 200 (–67 to 392)
Perfluoroalkoxy (PFA)	–55 to 260 (–67 to 500)
Polychlorotrifluoroethylene (PCTFE)	–55 to 150 (–67 to 302)
Polytetrafluoroethylene (PTFE)	–55 to 260 (–67 to 500)
Polyvinylidene fluoride (PVDF)	–55 to 175 (–67 to 347)

Summaries of key ASTM standards and Federal specifications included in this section relate to the following tubing types:

- Chlorosulfonated polyethylene (MIL-I-85080/4)
- Neoprene (ASTM D 2903)
- Polychloroprene (MIL-I-23053/1, MIL-I-85080/5)
- Polyethylene terephthalate (MIL-I-23053/7)
- Polyolefin (ASTM D 3149, MIL-I-23053/4, /5, /6, /15)
- Polyurethane (MIL-I-85080/3)
- PVC (ASTM D 876, ASTM D 922, ASTM D 3150, MIL-I-7444, MIL-I-23053 /2, /3, MIL-I-85080/1)
- Silicone rubber (MIL-I-23053/9, /10, MIL-I-46846, MIL-I-47049, MIL-I-85080/2)
- Fluoroelastomer (MIL-I-23053/13)
- Fluoropolymers
  FEP (ASTM D 2902, MIL-I-23053/11)
  PFA (ASTM D 2902)
  PTFE (ASTM D 2902, MIL-I-23053/12, MIL-I-22129)
  PVDF (ASTM D 3144, MIL-I-23053/8)
  Ethylene-tetrafluoroethylene (MIL-I-23053/14)
- ASTM D 2671 covers testing methods for all types of heat-shrinkable tubing.

As can be noted in the accompanying summaries of standards and specifications, tubing is available both with fixed dimensions and shrinkable with applica-

tion of heat, infrared radiation, or by evaporation of solvent. A shrinkable capability permits tubing to encapsulate or bind securely the parts, wires, or terminations over which it is shrunk. Commonly used shrink ratios are 3–1, 2–1, $1^{3}/_{4}$–1, $1^{2}/_{3}$–1, and $1^{1}/_{3}$–1.

Heat-shrinkable tubing on expansion acts as though its molecules are frozen in the expanded state. On heating under controlled conditions, the strain is released and the tubing tends to recover to the original extruded dimensions (elastic memory). Tubing which shrinks by evaporation of solvent is useful where application of heat is undesirable.

Heat-shrinkable tubing may or may not be formulated to crosslink readily. Chemical crosslinking with application of heat or radiation crosslinking makes polymers no longer thermoplastic and improves chemical resistance, thermal endurance, and hardness. It also makes expansion possible at temperatures above the crystalline melt point in the fully elastic state.

Standard grades of irradiated PVC, polyolefin, PVDF, neoprene, butyl rubber, and fluoroelastomer tubings shrink to about one-half their extruded diameter with little or no longitudinal change. Uncrosslinked tubings may shrink in length considerably on heat activation. Recommended temperatures for shrinking range from 135°C (275°F) for PVC to 350°C (662°F) for PTFE, as shown in the accompanying summaries of standards and specifications.

In the manufacturing process, tubing is first extruded into a cooling bath from a horizontal extruder. It is to this extruded diameter that the shrinkable tubing returns after being expanded to the desired ratio by one of several suitable devices involving heat and air pressure, and cooling in the expanded state to "freeze" the molecules. The crosslinking process, when used, occurs following the extrusion process and before the expansion process.

Several methods are employed, sometimes in combination, to induce shrinkage, including infrared radiation units, hot air blowers, contact tools, heat transfer fluids, ovens, open flame torches, and electric blanket heaters.

Spiral and convolute wound tubing, one of the oldest forms of electrical insulations, is made by wrapping layers of substrate to the required thickness on a steel rod or mandrel of specified size. Spiral tubes can be made in continuous lengths as tubes are drawn from mandrels and supported on long troughs. Substrate materials include kraft paper, aramid paper, vulcanized fibre, polyester film, polyimide film, and composites of these materials. Layers of substrate are bonded with suitable adhesive, usually proprietary. The tubing is cut to length and usually impregnated with an insulating varnish and baked to cure. Commonly used cross-sectional shapes commercially available include round, square, and rectangular.

GRADES

Grades for all types of tubing covered by standards and specifications summarized in this section are commercially available.

ASTM STANDARDS FOR ELECTRICAL INSULATING TUBING

The American Society for Testing and Materials has developed the following standards for electrical tubing:

SPECIFICATIONS

- Neoprene—D 2903
- Polyolefin—D 3149
- Polyvinyl chloride—D 922, 3150
- Fluoropolymers
  FEP—D 2902
  PFA—D 2902
  PTFE—D 2902
  PVDF—D 3144

TEST METHODS

- Extruded PVC tubing—D 876
- Heat-shrinkable tubing—D 2671

The following pages provide a more detailed examination of these standards.

- D 876, *Nonrigid Vinyl Chloride Polymer Tubing Used for Electrical Insulation.* This standard describes methods of testing general purpose (Grade A, low-temperature, Grade B) and high-temperature (Grade C) nonrigid vinyl chloride polymer tubing, or its copolymers with other materials, for use as electrical insulation. Nonrigid tubing shall have an initial elongation in excess of 100 percent at break. Table 13-1 lists the test methods.

Table 13-1 Property Tests for Nonrigid Vinyl Chloride Polymer Tubing (ASTM D 876)

PROPERTY MEASURED	ASTM METHOD
Brittleness temperature	D 746
Corrosion tests	D 876
Dielectric breakdown at high humidity	D 876
Dielectric breakdown test	D 149
Dimensional tests	D 876
Effect of elevated temperatures	D 876
Flammability test	D 876
Oil resistance test	D 876
Penetration test	D 876
Sampling	D 876
Strain relief test	D 876
Tension test	D 876
Test conditions	D 876
Volume resistivity	D 257

• D 922, *Nonrigid Vinyl Chloride Polymer Tubing*. This standard specification covers nonrigid tubing of vinyl chloride or its copolymers with other materials for use in electrical insulation. Three grades are designated:

Grade A—General purpose
Grade B—Low temperature
Grade C—High temperature

Standard sizes are shown in Table 13-2.

Table 13-2 ASTM Standard Sizes for Nonrigid Tubing (ASTM D 922)

	INSIDE DIAMETER in.		WALL THICKNESS	
SPECIFIED SIZE	MAX	MIN	WALL THICKNESS in	TOLERANCES, PLUS OR MINUS, in
No. 24 (0.022 in)	0.027	0.020	0.012	0.002
No. 22 (0.027 in)	0.032	0.025	0.012	0.002
No. 20 (0.034 in)	0.039	0.032	0.016	0.003
No. 18 (0.042 in)	0.049	0.040	0.016	0.003
No. 16 (0.053 in)	0.061	0.051	0.016	0.003
No. 14 (0.066 in)	0.074	0.064	0.016	0.003
No. 12 (0.085 in)	0.091	0.081	0.016	0.003
No. 11 (0.095 in)	0.101	0.091	0.016	0.003
No. 10 (0.106 in)	0.112	0.102	0.016	0.003
No. 9 (0.118 in)	0.124	0.114	0.020	0.003
No. 8 (0.133 in)	0.141	0.129	0.020	0.003
No. 7 (0.148 in)	0.158	0.144	0.020	0.003
No. 6 (0.166 in)	0.178	0.162	0.020	0.003
No. 5 (0.186 in)	0.198	0.182	0.020	0.003
No. 4 (0.208 in)	0.224	0.204	0.020	0.003
No. 3 (0.234 in)	0.249	0.229	0.020	0.003
No. 2 (0.263 in)	0.278	0.258	0.020	0.003
No. 1 (0.294 in)	0.311	0.289	0.020	0.003
No. 0 (0.330 in)	0.347	0.325	0.020	0.003
5/16 in	0.334	0.312	0.025	0.003
3/8 in	0.399	0.375	0.025	0.003
7/16 in	0.462	0.438	0.025	0.003
1/2 in	0.524	0.500	0.025	0.003
5/8 in	0.655	0.625	0.030	0.003
3/4 in	0.786	0.750	0.035	0.005
7/8 in	0.911	0.875	0.035	0.005
1 in	1.036	1.000	0.035	0.005
1 1/4 in	1.290	1.250	0.040	0.005
1 1/2 in	1.550	1.500	0.045	0.006
1 3/4 in	1.812	1.750	0.055	0.008
2 in	2.070	2.000	0.060	0.010

[a]Multiply inches by 25.4 to get millimeters.

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Requirements for this tubing are shown in Table 13-3.

Table 13-3 Requirements for Nonrigid Vinyl Polymer Tubing (ASTM D 922)

Tensile strength, min, psi (MPa)			
Grades A&C		2,000 (15)	
Grade B		1,800 (13)	
Brittleness temperature, max, °C (°F)			
Grade A		–30 (–22)	
Grade B		–55 (–67)	
Grade C		–10 (+14)	
Volume resistivity, Ω · cm			
Grade A		10^{12}	
Grade B		10^{11}	
Grade C		10^{12}	
Dielectric breakdown, min, kvolts			
Wall thickness			
inches	mm	A & C	B
0.012	0.30	9.0	9.3
0.016	0.41	12.5	10.4
0.020	0.51	14.0	11.0
0.025	0.64	15.7	12.0
0.030	0.76	17.1	12.9
0.035	0.89	18.0	13.5
0.040	1.02	19.2	14.0
0.045	1.14	20.4	14.5
0.050	1.27	21.5	15.0
0.055	1.40	22.8	15.5
0.060	1.52	24.0	16.0
Breakdown at 96 percent humidity, percent of dry value			
Grade A		90	
Grade B		75	
Grade C		85	

Note: Tests are conducted in accordance with ASTM D 876 procedures.

• D 2671, *Heat-Shrinkable Tubing for Electrical Use*. This standard describes methods of testing heat-shrinkable tubing used for electrical insulation. Materials used include poly(vinyl chloride), polyolefins, fluorocarbon polymers, silicone rubber, and other plastic or elastomeric compounds. Table 13-4 lists applicable test methods.

• D 2902, *Fluoropolymer Resin Heat-Shrinkable Tubing*. This standard specification covers flexible heat-shrinkable tubing made from tetrafluoroethylene resin, copolymer of tetrafluoroethylene and hexafluoropropylene, and from perfluoroalkoxy resin for use as electrical insulation. Three types of tubing are identified:

Type I—Tubing made from tetrafluoroethylene polymer (TFE) and capable of being heat shrunk at a temperature of 327°C (621°F).

Table 13–4 Property Tests for Heat-Shrinkable Tubing (ASTM D 2671)

PROPERTY MEASURED	ASTM METHOD
Brittleness temperature	D 746
Color	D 1535
Color stability	D 1535
Conditioning	D 618
Corrosion testing	D 2671
Dielectric breakdown	D 149
Dimensions	D 2671
Flammability	D 876
Heat resistance	D 2671
Heat shock	D 2671
Low-temperature	D 2671
Restricted shrinkage	D 2671
Sampling	D 2671
Secant modulus	D 882
Shelf life	D 2671
Solvent resistance	D 2671
Specific gravity	D 792
Stress modulus	D 412
Tensile strength and ultimate elongation	D 2671
Thermal endurance	D 2671
Volume resistivity	D 257
Water absorption	D 570

Type II—Tubing made from a copolymer of tetrafluoroethylene and hexafluoropropylene (FEP) and capable of being heat shrunk at a temperature of 150°C (302°F).

Type III—Tubing made from perfluoroalkoxy resin (PFA) and capable of being heat shrunk at a temperature of 175°C (347F).

Dimensions for this tubing are shown in Table 13-5.

Tubing (all types) shall have low-temperature flexibility with no cracking at –55°C (–67°F). Dielectric breakdown after shrinkage shall not be less than the following values:

WALL THICKNESS (inches)	MINIMUM (kilovolts)
0.004–0.006	8
0.007–0.008	10
0.009	11.5
0.010–0.011	12.5
0.012–0.014	14.6
0.015	15
0.016–0.019	16.3
0.020 and larger	17

Note: Tests are conducted in accordance with ASTM D 2671 procedures.

Table 13-5 Dimension Ranges for Fluoropolymer Resin Heat-Shrinkable Tubing (ASTM D 2902)

AS SUPPLIED	AFTER SHRINKAGE		
ID MINIMUM inches (mm)	ID MAXIMUM inches (mm)	WALL THICKNESS inches (mm)	STOCK LENGTHS feet
	Type 1		
Heavy Wall			
0.166–1.330 (4.22–33.8)	0.130–1.020 (3.30–25.9)	0.030–0.050 (0.76–1.27)	1, 3
Standard Wall			
0.045–1.500 (1.14–38.1)	0.027–1.036 (0.69–26.3)	0.012–0.035 (0.30–0.76)	1, 2, 3
Thin Wall			
0.034–1.125 (0.86–28.6)	0.015–0.786 (0.38–20.0)	0.009–0.030 (0.23–0.76)	1, 2, 3
Very Thin Wall			
0.050–0.470 (1.27–11.94)	0.027–0.347 (0.69–8.81)	0.006–0.012 (0.15–0.30)	1, 2, 3
There are also special sizes for 2–1 shrink factor, 4–1 PTFE shrinkable tubing, and overexpanded tubing.			
	Types II and III		
1.33–1 and 1.20–1 Shrink Factor			
0.031–12.1 (0.79–307.3)	0.027–10.6 (0.69–269.2)	0.008–0.20 (0.20–0.51)	3–10
1.67–1 Shrink Factor			
0.093–2.00 (2.36–50.8)	0.056–1.20 (1.42–30.5)	0.008–0.030 (0.20–0.76)	3

Tubing shall shrink in accordance with the following schedule:

Type I—10 minutes at 350°C (662°F)
Type II—10 minutes at 175°C (347°F)
Type III—10 minutes at 204°C (400°F)

• D 2903, *Neoprene Heat-Shrinkable Tubing*. This standard specification covers electrical insulation grade flexible neoprene heat-shrinkable tubing that has been extruded, crosslinked, and then expanded to the required dimensions. Two types are identified:

Type I—Normal operating temperature (100°C (212°F))
Class 1—1.75:1 Shrink ratio
Class 2—2.0:1 Shrink ratio
Type II—Extended operating temperature (121°C (250°F))

Dimensions for this tubing are shown in Table 13-6.

• Type I tubing shall have low-temperature flexibility with no cracks at –55°C (–67°F). Type II tubing shall have low-temperature flexibility with no cracks at –70°C

Table 13-6 Dimension Ranges for Neoprene Heat-Shrinkable Tubing (ASTM D 2903)

AS SUPPLIED		AFTER SHRINKAGE	
NORMAL SIZE inches	ID MINIMUM inches (mm)	ID MAXIMUM inches (mm)	WALL THICKNESS inches (mm)
	Type I Class 1 and Type II		
1/4–4	0.250–4.00 (6.35–101.6)	0.143–2.280 (3.63–57.9)	0.035–0.140 (0.89–3.56)
	Type I Class 2		
	0.250–2.000 (6.4–50.8)	0.125–1.000 (3.2–25.4)	0.035–0.110 (0.89–2.8)

(–94°F). Dielectric breakdown for both types after shrinkage shall not be less than 300 volts/per mil for tubing sizes 1 3/4 inches ID and under, and 200 volts per mil for tubing sizes 2 inches and larger. Tests are conducted in accordance with ASTM D 2671 procedures. Tubing shall be shrunk at a temperature of 175°C (347°F) for 10 minutes.

• D 3144, *Poly(vinylidene Fluoride) Heat-Shrinkable Tubing for Electrical Insulation*. This standard specification covers semirigid, flame-retardant, crosslinked poly(vinylidene fluoride) heat-shrinkable tubing for electrical insulation applications. Dimensions for this tubing are shown in Table 13-7.

Tubing shall have low-temperature flexibility with no cracks at –55°C (–67°F). After 168 hours at 250°C (482°F), minimum elongation after shrinkage shall not be less than 50 percent. Dielectric breakdown after shrinkage shall not be less than 600 volts per mil. Tests are conducted in accordance with ASTM D 2671 procedures. Tubing shall be shrunk at a temperature of 392°F (200°C) for three minutes.

• D 3149, *Crosslinked Polyolefin Heat-Shrinkable Tubing for Electrical Insulation*. This standard specification covers crosslinked polyolefin heat-shrinkable tubing used for electrical insulating purposes. It is supplied in expanded form and will shrink to its extruded diameter when heated. Four types of tubing are identified:

Type I—Flexible, flame-retardant opaque polyolefin tubing with a secant modulus at 2 percent strain less than 25,000 psi (172 MPa) (ASTM D 882).

Table 13-7 Dimension Ranges for Poly(vinylidene Fluoride) Heat-Shrinkable Tubing (ASTM D 3144)

AS SUPPLIED		AFTER SHRINKAGE	
NOMINAL SIZE inches	ID MINIMUM inches (mm)	ID MAXIMUM inches (mm)	WALL THICKNESS inches (mm)
3/64–1	0.046–1.000 (1.16–25.4)	0.023–0.500 (0.59–12.7)	0.010–0.019 (0.25–0.48)

Type II—Flexible, nonflame-retardant, opaque or clear polyolefin tubing with a secant modulus at 2 percent strain less than 25,000 psi (172 MPa) (ASTM D 882).

Type III—Semi-rigid, flame-retardant, opaque polyolefin tubing with a secant modulus at 2 percent strain greater than 35,000 psi (241 MPa) (ASTM D 882).

Type IV—Semi-rigid, nonflame-retardant, opaque or clear polyolefin tubing with a secant modulus at 2 percent strain greater than 35,000 psi (241 MPa) (ASTM D 882).

Dimensions for this tubing are shown in Table 13-8.

Table 13-8 Dimension Ranges for Crosslinked Polyolefin Heat-Shrinkable Tubing (ASTM D 3149)

ALL TYPES AS SUPPLIED		AFTER HEAT SHRINKAGE		
		ALL TYPES	WALL THICKNESS	
NOMINAL SIZE inches	ID MINIMUM inches (mm)	ID MINIMUM inches (mm)	TYPES I, II inches (mm)	TYPES III, IV* inches (mm)
3/64–4	0.046–4.000 (1.16–101.6)	0.023–2.000 (0.59–50.1)	0.016–0.055 (0.41–1.40)	0.020–0.030 (0.56–0.76)

*Through nominal size 1/2 in only.

Tubing shall have low-temperature flexibility with no cracks at –55°C (–67°F). After 168 hours at 175°C (347°F), minimum elongation shall not be less than 150 percent. Dielectric breakdown after shrinkage shall not be less than 500 volts per mil. Tests are conducted in accordance with ASTM D 2671 procedures. Tubing shall be shrunk at a temperature of 175°C (347°F) for 3 minutes.

• D 3150, *Crosslinked and Noncrosslinked Poly(vinylchloride) Heat-Shrinkable Tubing for Electrical Insulation.* This standard specification applies to extruded, flexible, crosslinked, and noncrosslinked poly(vinylchloride) heat-shrinkable tubing for electrical insulating purposes. It is supplied in an expanded form and will shrink to its extruded diameter when heated. Two types of tubing are identified:

Type I—Flexible, noncrosslinked poly(vinyl chloride) tubing capable of being shrunk at 135°C (275°F) in 15 minutes.

Type II—Flexible, crosslinked poly(vinyl chloride) tubing capable of being shrunk at 175°C (347°F) in 15 minutes.

Dimensions for this tubing are shown in Table 13-9.

Tubing shall have low-temperature flexibility with no cracks at –10°C (14°F) as received. After 168 hours at 136°C (277°F), minimum elongation shall not be less than 150 percent. Dielectric breakdown after shrinkage shall not be less than 400 volts per mil. Tests are conducted in accordance with ASTM D 2671 procedures.

Table 13-9 Dimension Ranges for Crosslinked and Noncrosslinked Poly(vinyl Chloride) Heat-Shrinkable Tubing (ASTM D 3150)

AS SUPPLIED	AFTER SHRINKAGE	
ID MINIMUM inches (mm)	ID MAXIMUM inches (mm)	WALL THICKNESS inches (mm)
	Type I	
0.063–6.000 (1.60–152.5)	0.037–3.600 (0.94–91.5)	0.014–0.034 (0.35–0.86)
	Types I and II	
0.046–2.000 (1.16–50.1)	0.023–1.000 (0.59–25.4)	0.020–0.050 (0.51–1.27)

FEDERAL SPECIFICATIONS FOR ELECTRICAL INSULATING TUBING

The following Federal specifications have been developed for electrical insulating tubing:

- Butyl rubber—MIL-R-46846
- Chlorosulfonated polyethylene—MIL-I-85080/4
- Neoprene—MIL-R-46846
- Polychloroprene—MIL-I-23053/1, MIL-I-85080/5
- Polyethylene terephthalate—MIL-I-23053/7
- Polyolefin—MIL-I-23053/4/5/6/15, MIL-R-46846
- Polyurethane—MIL-I-85080/3
- Polyvinyl chloride—MIL-I-7444, MIL-I-23053/2/3, MIL-I-85080/1
- Silicone rubber—MIL-I-23053/9/10, MIL-R-46846, MIL-I-47049, MIL-I-85080/2
- Fluoroelastomer—MIL-I-23053/13, MIL-R-46846
- Fluoropolymers
  FEP—MIL-I-23053/11
  PTFE—MIL-I-23053/12, MIL-I-22129
  Ethylene-tetrafluoroethylene—MIL-I-23053/14

The following pages provide a more detailed examination of these standards.

- MIL-I-7444, *Insulation Sleeving, Electrical, Flexible*. This specification is mandatory for use by all departments and agencies of the Department of Defense. It covers flexible, extruded, vinyl plastic tubing (sleeving). The tubing shall be identified as follows:

Type I—Colorless and transparent
Type II—no longer listed
Type III—Colored
Class 1 (applicable to both types)—Cold brittle point at –90°F (–67°C) and flame resistance of 45 seconds.
Class 2 (applicable to both types)—Cold brittle point at –67°F (–55°C) and flame resistance of 15 seconds.

The material shall be a vinyl chloride or vinyl chloride acetate copolymer. Nominal inside diameter shall be in the range of 0.022 inch (AWG No. 24)–$2^1/_2$ inches. Nominal wall thicknesses shall range from 0.012 inch for 0.022 inch ID tubing to 0.070 in for $2^1/_2$ inch ID tubing. Tubing under 1 inch ID shall be wound on spools in lengths not less than 100 feet. Tubing 1 inch ID and over shall be wound on spools in lengths not less than 50 feet. Testing for brittle points is done both before aging and after aging for 168 hours at 158°F (70°C). Minimum dielectric strength of tubing shall be not less than 200 volts per mil when specimens are either dry or after immersion in water for 24 hours at 77°F (25°C).

• MIL-I-23053C, *Insulation Sleeving, Electrical, Heat Shrinkable, General Specification For*. This specification is approved for use by all departments and agencies of the Department of Defense. This is a general specification covering heat-shrinkable types listed in Table 13-10. The individual requirements for each type, including dimensions, are detailed in the specification sheet for that type.

Test procedures for all sleeving types are described with reference, where appropriate, to applicable ASTM standards. Property requirements after unrestricted shrinkage include the following:

Color
Color stability
Specific gravity
Dielectric constant
Odor
Fungus resistance
Tensile strength
Ultimate elongation
Dielectric strength
Volume resistivity
Low-temperature flexibility
Corrosion
Heat resistance
Water absorption
Flammability
Fluid resistance
Flow of inner wall

Table 13-10 Heat-Shrinkable Insulation Sleeving Types Covered by MIL-I-23053C

SPECIFICATION SHEETS	
MIL-I-23053/1	Insulation Sleeving,* Electrical, Heat Shrinkable, Polychloroprene, Flexible
MIL-I-23053/2	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyvinyl Chloride, Flexible, Crosslinked and Noncrosslinked
MIL-I-23053/3	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyvinyl Chloride, Semi-Rigid, Crosslinked and Noncrosslinked
MIL-I-23053/4	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyolefin, Dual-Wall, Rigid Outer Wall, Crosslinked
MIL-I-23053/5	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyolefin, Flexible, Crosslinked
MIL-I-23053/6	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyolefin, Semi-Rigid Crosslinked
MIL-I-23053/7	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyethylene Terephthalate, Noncrosslinked
MIL-I-23053/8	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyvinylidene Fluoride, Semi-Rigid, Crosslinked
MIL-I-23053/9	Insulation Sleeving,* Electrical, Heat Shrinkable, Fluorosilicone Rubber, Flexible (Cancelled)
MIL-I-23053/10	Insulation Sleeving,* Electrical, Heat Shrinkable, Silicone Rubber, Flexible
MIL-I-23053/11	Insulation Sleeving,* Electrical, Heat Shrinkable, Fluorinated Ethylene Propylene, Noncrosslinked
MIL-I-23053/12	Insulation Sleeving,* Electrical, Heat Shrinkable, Polytetrafluoroethylene
MIL-I-23053/13	Insulation Sleeving,* Electrical, Heat Shrinkable, Fluoroelastomer, Flexible
MIL-I-23053/14	Insulation Sleeving,* Electrical, Heat Shrinkable, Ethylene-Tetrafluoroethylene Fluoropolymer, Semi-Rigid
MIL-I-23053/15	Insulation Sleeving,* Electrical, Heat Shrinkable, Polyolefin, Heavy Wall, Coated, Flexible, Outer Wall Crosslinked

*Generally considered tubing.

• MIL-R-46846, *Rubber, Synthetic, Heat-Shrinkable*. This specification covers the requirements for flexible electrical insulating extruded tubing, molded parts, and extruded shapes whose dimensions will reduce to a predetermined size upon the application of heat. The following types and classes of material are identified:

Type I. Crosslinked, modified polychloroprene (Neoprene) tubing, molded parts, and extruded shapes, flexible general purpose cable-jacketing, cable harness, boots and transitions, service temperature range of −55 to 90°C.

Class 1. Tubing-cable-jacketing material, 1.75× expansion ratio

Class 2. Molded parts and extruded shapes, cable harness boots and transitions, 2.5× expansion ratio

Type II. Crosslinked modified flame-retarded silicone rubber tubing, molded parts and extruded shapes, highly flexible, ablative-resistant.

Class 1. Tubing, expansion ratio 1.75×, service temperature range of −70 to 180°C.

Class 2. Molded parts and extruded shapes, expansion ratio 2 to 4×, service temperature range –75 to 135°C.

Type III. Crosslinked, modified viton tubing, molded parts and extruded shapes, flexible for materials exposed to extended periods of high temperature and solvent attack.

Class 1. Tubing 2× expansion ratio, service temperature range –55 to 200°C

Class 2. Molded parts and extruded shapes, 3.5× expansion ratio, service temperature range of –55 to 200°C

Type IV. Crosslinked, modified, propellant-resistant butyl rubber tubing, molded parts and extruded shapes flexible, for protection of cable assemblies exposed to hypergolic fuels.

Class 1. Tubing, 2× expansion ratio, service temperature range of –55 to 125°C

Class 2. Molded parts and extruded shapes 2.5× expansion ratio, service temperature range of –55 to 125°C

Type V. Crosslinked, modified, flame-resistant elastomeric polyolefin tubing, highly flexible airborne harnessing or jacketing material where low weight, high flame resistance, and thin walls are required, low shrinkage temperature, 2–4× expansion ratios, service temperature range of –55 to 135°C.

Type VI. Crosslinked, modified, flame-resistant ethylene-propylene rubber tubing, molded parts, and extruded shapes, flexible, ozone resistant, mechanically tough.

Class 1. Tubing, 2× expansion ratio, service temperature of –70 to 115°C

Class 2. Molded parts and extruded shapes, 4× expansion ratio, service temperature range of –75 to 125°C

Type 1 synthetic rubber shall be fabricated from a crosslinked, stabilized, modified polychloroprene (Neoprene) composition. Type II synthetic rubber shall be fabricated from a crosslinked, stabilized, flame-retarded, modified silicone rubber composition. Type III synthetic rubber shall be fabricated from a crosslinked, stabilized, flame-resistant, modified Viton composition. Type IV synthetic rubber shall be fabricated from a crosslinked, stabilized, propellant-resistant, modified butyl rubber composition. Type V material shall be fabricated from a crosslinked, stabilized, flame-resistant, modified elastomeric polyolefin composition. Type VI synthetic rubber shall be fabricated from a crosslinked, stabilized, flame-resistant, modified ethylene-propylene rubber composition. These expanded synthetic rubbers shall shrink to predetermined dimensions upon the application of heat as follows:

Types I, IV, VI—Heat in excess of 135°C (275°F)
Types II, III—Heat in excess of 175°C (347°F)
Type V—Heat in excess of 90°C (194°F)

Types I–VI tubing shall have the sizes, tolerances, and properties specified in Tables 13-11 and 13-12.

Table 13-11 Heat-Shrinkable Synthetic Rubber Tubing Sizes (MIL-R-46846)

	EXPANDED—AS SUPPLIED						RECOVERED DIMENSIONS—AFTER HEATING											
	MINIMUM INSIDE DIAMETER, inches						MAXIMUM INSIDE DIAMETER, inches						WALL THICKNESS, inch					
SIZE, inches	TYPE I	TYPE II	TYPE III	TYPE IV	TYPE V	TYPE VI	TYPE I	TYPE II	TYPE III	TYPE IV	TYPE V	TYPE VI	TYPE I	TYPE II	TYPE III	TYPE IV	TYPE V	TYPE VI
3/64	—	—	—	—	.046	—	—	—	—	—	.023	—	—	—	—	—	.016 ± .003	—
1/16	—	—	—	—	.063	—	—	—	—	—	.031	—	—	—	—	—	.017 ± .003	—
3/32	—	—	—	—	.093	—	—	—	—	—	.046	—	—	—	—	—	.020 ± .003	—
1/8	—	—	—	—	.125	—	—	—	—	—	.062	—	—	—	—	—	.020 ± .003	—
3/16	—	—	—	—	.187	—	—	—	—	—	.093	—	—	—	—	—	.020 ± .003	—
1/4	0.250	0.250	0.250	0.250	0.250	0.250	0.143	0.143	0.125	0.125	0.125	0.125	.035 ± .010	.035 ± .010	.030 ± 0.10	.035 ± .010	.025 ± .003	.030 ± .010
3/8	0.375	0.375	0.375	0.375	0.375	0.375	0.214	0.214	0.187	0.187	0.187	0.187	.040 ± .010	.040 ± .010	.035 ± .010	.040 ± .010	.025 ± .003	.035 ± .010
1/2	0.500	0.500	0.500	0.500	0.500	0.500	0.286	0.286	0.250	0.250	0.250	0.250	.048 ± .010	.048 ± .010	.043 ± .010	.050 ± .015	.025 ± .003	.043 ± .010
5/8	0.625	0.625	0.625	—	—	0.625	0.357	0.357	0.312	—	—	0.312	.052 ± .015	.052 ± .015	.047 ± .012	—	—	.047 ± .012
3/4	0.750	0.750	0.750	0.750	0.750	0.750	0.428	0.428	0.375	0.375	0.375	0.375	.057 ± .015	.057 ± .015	.052 ± .015	.060 ± .015	.030 ± .003	.052 ± .015
7/8	0.875	0.875	0.875	—	—	0.875	0.500	0.500	0.437	—	—	0.437	.065 ± .015	.065 ± .015	.060 ± .015	—	—	.060 ± .015
1	1.00	1.00	1.00	1.00	1.00	1.00	0.570	0.570	0.500	0.500	0.500	0.500	.070 ± .015	.070 ± .015	.069 ± .015	.075 ± .020	.035 ± .005	.065 ± .015
1 1/4	1.25	1.25	1.25	—	—	1.25	0.714	0.714	0.625	—	—	0.625	.087 ± .020	.087 ± .020	.070 ± .020	—	—	.070 ± .020
1 1/2	1.50	1.50	1.50	1.50	1.50	1.50	0.857	0.857	0.750	0.750	0.750	0.750	.095 ± .020	.095 ± .020	.075 ± .020	.100 ± .020	.040 ± .006	.075 ± .020
1 3/4	1.75	1.75	—	—	—	—	1.00	1.00	—	—	—	—	.107 ± .020	.107 ± .020	—	—	—	—
2	2.00	2.00	2.00	2.00	2.00	—	1.14	1.14	—	1.00	1.00	—	.110 ± .020	.110 ± .020	—	.110 ± .020	.045 ± .007	—
2 1/2	—	—	—	2.50	—	—	—	—	1.00	1.25	—	—	—	—	.110 ± .020	.130 ± .020	—	—
3	3.00	—	—	3.00	3.00	—	1.71	—	—	1.50	1.50	—	.125 ± .020	—	—	.140 ± .020	.050 ± .008	—
4	4.00	—	—	4.00	4.00	—	2.28	—	—	2.00	2.00	—	.140 ± .020	—	—	.150 ± .020	.055 ± .009	—

Table 13-12 Requirements for Heat-Shrinkable Synthetic Rubber Tubing (MIL-R-46846)

PROPERTY	REQUIREMENT						METHOD
	TYPE I	TYPE II	TYPE III	TYPE IV	TYPE V	TYPE VI	
Longitudinal change, percent, maximum	10	10	20	15	5	15	MIL-R-46846
Tensile strength, psi, minimum	1,500	600	1,200	1,200	1,500	1,400	ASTM D 412, (See 4.5.1)
Tensile stress at 100 percent elongation, psi, maximum	1,500	500	1,400	1,200	1,000	1,000	ASTM D 412, (See 4.5.1)
Elongation, percent, minimum	200	200	250	250	200	200	ASTM D 412, (See 4.5.1)
Specific gravity, maximum	1.50	1.35	2.0	1.40	1.35	1.25	ASTM D 792
Hardness, shore A	80 ± 5	60 ± 5	82 ± 5	85 ± 5	85 ± 5	80 ± 5	ASTM D 2240
Low temperature	Pass or fail	Pass or fail	Pass or fail	Pass or fail	Pass or fail	Pass or fail	ASTM D 2671
Heat shock				No dripping, flowing, or cracking			MIL-R-46846
Heat aging, followed by tests for:							MIL-R-46846
Tensile strength, psi, minimum	1,200	500	1,200	1,000	1,500	1,200	ASTM D 412, (See 4.5.1)
Elongation, percent, minimum	150	120	200	100	200	100	ASTM D 412, (See 4.5.1)
Dielectric, strength volts/mil, minimum	200	300	150	100	500	220	ASTM D 876
Volume resistivity, $\Omega \cdot$ cm, minimum	1×10^{10}	1×10^{11}	1×10^{9}	1×10^{10}	1×10^{14}	1×10^{11}	ASTM D 257
Flammability, seconds, maximum	15; self-exting.*	60; self-exting.** (See Note 1)	15; self-exting.*	—	15; self-exting.*	15; self-exting.* Sec. 67–72	*ASTM D 876 **ASTM D 2671,
Fungus resistance			Rating of 0				ASTM D 1924
Water absorption, percent, maximum	1.0	1.0	0.5	0.5	0.5	1.0	ASTM D 570 Procedure A
Solvent resistance, followed by tests for:							MIL-R-46846
Tensile strength, psi, minimum	900	400	1,200	1,000	750	500	ASTM D 412, (See 4.5.1)
Elongation, percent, minimum	125	120	250	200	200	100	ASTM D 412, (See 4.5.1)
Eccentricity, percent, minimum	60	60	60	60	60	60	ASTM D 2671 (Sec. 6–11)

Note 1: Not more than 25 percent of indicator flag burned; no dripping or flowing.

• MIL-I-47049, *Insulation Tubing, Silicone Rubber, Heat Shrinkable*. This specification is approved for use by all departments and agencies of the Department of Defense. Covered are requirements for one type of silicone rubber heat-shrinkable tubing. The material shall be silicone rubber heat-shrinkable tubing supplied in an expanded form capable of being shrunk by the application of heat. The inside diameter and wall thickness of tubing shall be in accordance with Table 13-13.

Table 13-13 Inside Diameter and Wall Thickness of Heat-Shrinkable, Silicone Rubber Tubing (MIL-I-47049)

EXPANDED AS SUPPLIED		RECOVERED DIMENSIONS AFTER HEATING	
SIZE NO.	INSIDE DIMATER (inches) MINIMUM	INSIDE DIAMETER (inches) MAXIMUM	WALL THICKNESS (inches) NOMINAL
1	0.125	0.067	0.020
2	0.250	0.125	0.035
3	0.375	0.187	0.040
4	0.500	0.250	0.048

Test procedures are described with reference, where appropriate, to applicable ASTM standards. Key requirements are shown in Table 13-14.

Table 13-14 Requirements for Heat-Shrinkable, Silicone Rubber Tubing (MIL-I-47049)

PROPERTY	REQUIREMENT
Dielectric strength, $^1/_{16}$ in thick wall	400 V/mil minimum
Dielectric constant	3.10 maximum
Volume resistivity	1×10^{14} minimum
Tensile strength	1200 psi minimum
Ultimate elongation	450% minimum
Specific gravity	1.20 maximum
Water absorption	0.5% maximum

Tubing shall be shrunk at 150° to 180°C (302°–356°F) for 2 minutes minimum.

• MIL-I-85080, *Insulation Sleeving,* Electrical, Shrinkable Without Heat, General Specification For*. This specification is approved for use by the Naval Air Systems Command, Department of the Navy, and is available for use by all departments and agencies of the Department of Defense. This specification establishes requirements for chemically expanded, flexible, electrical insulating sleeving that shrinks to a predetermined size upon solvent evaporation. This is a general specification covering shrinkable types listed in Table 13-15. The individual requirements for each type including dimensions are detailed in the specification sheet for that type.

Table 13-15 Insulation Sleeving Shrinkable Without Heat Types Covered by MIL-I-85080

SPECIFICATION SHEETS	
MIL-I-85080/1	Insulation Sleeving,* Electrical, Shrinkable Without Heat, Polyvinyl Chloride, Flexible, Noncrosslinked
MIL-I-85080/2	Insulation Sleeving,* Electrical, Shrinkable Without Heat, Silicone, Rubber, Flexible
MIL-I-85080/3	Insulation Sleeving,* Electrical, Shrinkable Without Heat, Polyurethane, Flexible
MIL-I-85080/4	Insulation Sleeving,* Electrical, Shrinkable Without Heat, Chlorosulfonated Polyethylene, Flexible
MIL-I-85080/5	Insulation Sleeving,* Electrical, Shrinkable Without Heat, Polychloroprene

*Generally considered tubing.

Test procedures for all sleeving types are described with reference, where appropriate, to applicable ASTM standards. Property requirements after unrestricted shrinkage include the following:

Water absorption
Dielectric strength
Volume resistivity
Fungus resistance
Color
Voltage withstand
Low-temperature flexibility
Heat shock
Heat resistance
Corrosion
Fluid resistance
Odor
Modulus
Tensile strength
Ultimate elongation
Flammability
Color stability

PROPERTIES

Properties of commonly used materials for extruded tubings are described in Chapter 5, *Extrusion Compounds*, and in standards and specifications summarized in this chapter. In general:

• Polyvinyl chloride and polyolefin tubings can be made with the widest range of flexibility and are low in cost.

• Butyl and neoprene tubings have good flexibility and have good resistance to fuels and oils (aerospace environments).

• Silicone rubber has high thermal rating (Class 200) and low-temperature brittleness point. Tubing is fungus resistant and exhibits excellent aging characteristics.

• Fluoropolymers are chemically inert and are highly moisture resistant. Polytetrafluoroethylene and perfluoroalkoxy have the best thermal rating (260°C (500°F)) of all polymers. Tubings from these polymers are the highest price.

ELECTRICAL/ELECTRONIC USES

The major electrical/electronic uses are to identify and bind wires together, to cover and insulate splices and terminations, as an outer jacket of covered wiring harnesses, and as protective packaging for electronic parts.

DEVELOPMENT PROGRAMS

Properties of existing tubings are adequate for virtually every tubing requirement. Therefore, development programs are aimed primarily at product refinements.

MARKET TRENDS

While usage of nonshrinkable tubing is tied to traditional applications in the electrical industry, shrinkable tubing should find new uses in the more rapidly expanding electronics industry.

INSULATING SLEEVING

INTRODUCTION

Insulating sleeving is similar to tubing in many applications. In construction, flexible tubing is made from unsupported extruded polymers and elastomers, while sleeving consists of coated or uncoated braided fabric.

ASTM and Federal specifications for sleeving, summarized herein, contain requirements and test procedures for widely used sleevings and are an essential part of this section.

PRODUCERS OF COATED SLEEVING UL APPROVED

Underwriters Laboratories (UL) Standard 1441, *Coated Electrical Sleeving*, lists producers of UL-approved materials.

TECHNOLOGY

Coated sleeving consists of a tubular braided fiber product impregnated and/or coated with a resinous or elastomeric material. The various types of coated sleeving are described in the accompanying ASTM standards and Federal specifications. Commonly used products include the following, arranged by coating type (all on braided glass fiber sleeving):

- Acrylic thermal Class 155
- Oleoresinous varnish (ASTM D 372, MIL-I-3190C), thermal Class 105
- Polyimide (MIL-I-3190C), thermal Class 220
- Polytetrafluoroethylene (ASTM D 372), thermal Class 220
- Polyurethane thermal Class 130
- Polyvinyl chloride (ASTM D 372, MIL-I-3190, MIL-631, MIL-I-21557), F thermal Class 105
- Silicone resin (ASTM D 372, MIL-I-3190C), thermal Class 200
- Silicone rubber MIL-I-3190C, MIL-I-18057), thermal Class 200

Chemistry of the coatings is described in Chapter 8, pp. 244–257, *Insulating Coatings and Impregnants*. Substrates are made from braided fibers of glass (the predominant material), cotton, rayon, nylon, and dacron. E glass yarns used for most coated sleeving is useful up to 1,200°F (650°C). Special glass yarns retain life up to 1,600°F (870°C).

The traditional coating method consists of drawing lengths of sleeving onto wire mandrels, singeing off the hairs, dipping in varnish, draining, and baking. Dipping, draining, and baking steps are repeated until the desired number of varnish coats have been applied. The finished sleeving is then removed from the mandrels and trimmed to the specified length.

In another process, a steel ball is inserted in the untreated sleeving, which is then passed through a heated die constructed so the ball will not pass through. The sleeving is thus formed with circular cross section, after which it is wound under tension on a rectangular frame. The wound frame is dipped in varnish and baked the desired number of times, after which straight lengths of sleeving are cut from the frame.

In a process which produces continuous lengths, sleeving is coated in much the same manner as varnished cambric—by traveling through tanks of varnish and curing in vertical ovens. The tubing thus produced tends to be oval in cross section, caused by passing around rollers at the top of the oven. 2–12 return passes are required.

As well as being coated, sleeving may be used without any or with little impregnant, usually prior to subsequent varnish treatment and baking for a complete assembly. Sleeving provides better protection against mechanical abuse than extruded tubing, but it cannot be made to conform to wires and parts by shrinking action.

Polyvinyl chloride coatings are applied as plastisols, typically with 50 parts of plasticizer to 100 parts of resin. *Acrylics* are applied as water emulsions. *Silicone rubber* coatings are applied by extrusion directly over braided fabric or as solvent base elastomers. *Other resin* coatings are applied in organic solvents.

GRADES

Grades for all sleeving covered by standards and specifications summarized in this section are commercially available.

ASTM STANDARDS FOR ELECTRICAL INSULATING SLEEVING

The American Society for Testing and Materials has developed the following standards for electrical insulating sleeving. For a listing of sleeving types and related standards, see "Technology" (p. 394).

• D 350, *Flexible Treated Sleeving Used for Electrical Insulation*. This standard describes methods of testing flexible treated sleeving used as electrical insulation. Table 13-16 lists test methods:

• D 372, *Flexible Treated Sleeving Used for Electrical Insulation*. This standard covers six types of flexible treated sleeving as follows:

Table 13-16 Property Tests for Flexible Treated Sleeving (ASTM D 350)

PROPERTY MEASURED	ASTM METHOD
Brittleness temperature	D 746 D 876
Compatibility with magnet wire	D 350 D 2307
Dielectric breakdown voltage	D 149
Dimensions	D 350
Flammability	D 350
Flexibility after heat aging	D 350
Oil resistance	D 350
Sampling	D 350
Test conditions	D 618
Thermal endurance	D 350

Type 1—A flexible treated sleeving made from organic-base materials such as cotton, rayon, nylon, or other organic fibers and impregnated or coated with an organic substance capable of operation at 105°C (221°F).

Type 2—A flexible treated sleeving made from inorganic-base materials such as fibrous glass and impregnated or coated with a thermosetting organic substance capable of operation at 130°C (266°F).

Type 3—A flexible treated sleeving made from inorganic-base materials such as fibrous glass and impregnated or coated with a poly(vinyl chloride) plastic compound capable of operation at 105°C (221°F).

Table 13-17 ASTM STANDARD SIZES FOR FLEXIBLE SLEEVING (ASTM D 372)

	INSIDE DIAMETER, in (mm)	
SIZE	MAX	MIN
1 in.	1.036 (26.3)	1.000 (25.4)
7/8 in.	0.911 (23.2)	0.875 (22.2)
3/4 in.	0.786 (20.0)	0.750 (19.1)
5/8 in.	0.655 (16.7)	0.625 (15.9)
1/2 in.	0.524 (13.3)	0.500 (12.7)
7/16 in.	0.462 (11.7)	0.438 (11.1)
3/8 in.	0.399 (10.1)	0.375 (9.5)
No. 0	0.347 (8.8)	0.325 (8.3)
No. 1	0.311 (7.9)	0.289 (7.3)
No. 2	0.278 (7.1)	0.258 (6.6)
No. 3	0.249 (6.3)	0.229 (5.8)
No. 4	0.224 (5.7)	0.204 (5.2)
No. 5	0.198 (5.0)	0.182 (4.6)
No. 6	0.178 (4.5)	0.162 (4.1)
No. 7	0.158 (4.0)	0.144 (3.7)
No. 8	0.141 (3.6)	0.129 (3.3)
No. 9	0.124 (3.2)	0.114 (2.9)
No. 10	0.112 (2.8)	0.102 (2.6)
No. 11	0.101 (2.6)	0.091 (2.31)
No. 12	0.091 (2.31)	0.081 (2.06)
No. 13	0.082 (2.08)	0.072 (1.83)
No. 14	0.074 (1.88)	0.064 (1.63)
No. 15	0.067 (1.70)	0.057 (1.45)
No. 16	0.061 (1.55)	0.051 (1.30)
No. 17	0.054 (1.37)	0.045 (1.14)
No. 18	0.049 (1.25)	0.040 (1.02)
No. 20	0.039 (0.99)	0.032 (0.81)
No. 22	0.032 (0.81)	0.025 (0.64)
No. 24	0.027 (0.69)	0.020 (0.51)

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Table 13-18 Grade Designations and Requirements for Flexible Treated Sleeving (ASTM D 372)

		DIELECTRIC BREAKDOWN VOLTS C-48/23/50*		COMPATIBILITY WITH MAGNET WIRE: DIELECTRIC BREAKDOWN % OF ORIGINAL AFTER EXPOSURE TO TEMPERATURE FOR 672 h		THERMAL ENDURANCE EXTRAPOLATED TEMPERATURE
TYPE	GRADE	MINIMUM AVERAGE	MINIMUM INDIVIDUAL	°C	PERCENT	°C 20,000 h
1	A	7,000	5,000	130	50	105
	B	4,000	2,500	130	50	105
	C-1	2,500	1,500	130	50	105
	C-2	800	800	130	50	105
2	A	7,000	5,000	155	50	130
	B	4,000	2,500	155	50	130
	C-1	2,500	1,500	155	50	130
	C-2	1,500	800	155	50	130
3	A	8,000	6,000	155	50	105
	B	4,000	2,500	155	50	105
	C-1	2,500	1,500	155	50	105
	C-2	1,500	800	155	50	105
4	A	7,000	5,000	225	50	200
	B	4,000	2,500	225	50	200
	C-1	2,500	1,500	225	50	200
	C-2	1,500	800	225	50	200
5	A	8,000	6,000	225	50	200
	B	4,000	2,500	225	50	200
	C-1	2,500	1,500	225	50	200
	C-2	1,500	800	225	50	200
6	A	7,000	5,000	180	50	155
	B	4,000	2,500	180	50	155
	C-1	2,500	1,500	180	50	155
	C-2	1,500	800	180	50	155

*Conditioned for 48 h at 23°C and 50% relative humidity.

Note: Tests are conducted in accordance with ASTM D 350 procedures.

Type 4—A flexible treated sleeving made from inorganic-base materials such as fibrous glass and impregnated or coated with silicone resin or polytetrafluoroethylene materials capable of operation at 200°C (392°F).

Type 5—A flexible treated sleeving made from inorganic-base materials such as fibrous glass and impregnated or coated with silicone elastomer capable of operation at 200°C (392°F).

Type 6—A flexible treated sleeving made from inorganic-base materials such as fibrous glass and impregnated or coated with an insulating

material such as some epoxies, polyesters, or acrylics capable of operation at 155°C (311°F).

Standard sizes for flexible sleeving are shown in Table 13-17.

Grade designations and required properties for flexible treated sleeving are shown in Table 13-18.

FEDERAL SPECIFICATION FOR ELECTRICAL INSULATING SLEEVING

The following Federal specification has been developed for sleeving. For a listing of sleeving types and related specifications, see "Technology" (p. 394).

• MIL-I-3190C, *Insulation Sleeving, Electrical, Flexible, Coated, General Specification For*. This is a general specification covering flexible coated sleeving in the classes, types, and categories shown below. The individual requirements for each type are detailed in the specification sheet for each type. The base material of the sleeving shall be glass fiber braid or other synthetic base braids as specified in the applicable specification sheet.

THERMAL CLASS °(C)	
130 155 200 220	
TYPE	COATING
A	Nonchlorinated organic resins, singly or in admixture
B	Polyvinyl chloride, homo- or copolymer
C	Silicone resin
D	Silicone rubber
E	Polyimide

CATEGORY	HUMIDITY RESISTANCE	PERCENT RETENTION OF DIELECTRIC BREAKDOWN (MINIMUM) 96/23/96*
a	low	30
b	medium	50
c	high	80

*Hours/temperature °C/percent relative humidity.

Standard sizes for sleeving are shown in Table 13-19.

Nominal lengths of sleeving shall be 30-42 inches.

Table 13-19 Standard Sizes for Insulation Sleeving (MIL-I-3190C)

SIZE	INSIDE DIAMETER[1] MAXIMUM inch	INSIDE DIAMETER[1] MINIMUM inch	INSIDE DIAMETER[1] NOMINAL inch	WALL THICKNESS MAXIMUM inch
No. 24	0.027	0.020	0.022	0.030
No. 22	0.032	0.025	0.027	0.030
No. 20	0.039	0.032	0.034	0.030
No. 18	0.049	0.040	0.042	0.030
No. 17	0.054	0.045	0.047	0.030
No. 16	0.061	0.051	0.053	0.030
No. 15	0.067	0.057	0.059	0.030
No. 14	0.074	0.064	0.066	0.045
No. 13	0.082	0.072	0.076	0.045
No. 12	0.091	0.081	0.085	0.045
No. 11	0.101	0.091	0.095	0.045
No. 10	0.112	0.102	0.106	0.045
No. 9	0.124	0.114	0.118	0.045
No. 8	0.141	0.129	0.133	0.045
No. 7	0.158	0.144	0.148	0.045
No. 6	0.178	0.162	0.166	0.045
No. 5	0.198	0.182	0.186	0.045
No. 4	0.224	0.204	0.208	0.045
No. 3	0.249	0.229	0.234	0.045
No. 2	0.278	0.258	0.263	0.055
No. 1	0.311	0.289	0.294	0.055
No. 0	0.347	0.325	0.330	0.055
3/8 in	0.399	0.375	0.387	0.055
7/16 in	0.462	0.438	0.450	0.065
1/2 in	0.524	0.500	0.512	0.065
5/8 in	0.655	0.625	0.640	0.065
3/4 in	0.786	0.750	0.768	0.075
7/8 in	0.911	0.875	0.893	0.075
1 in	1.036	1.000	1.018	0.075

[1]The minimum inside diameters for sizes No. 20–0, inclusive, are the same as the diameters of copper wire for corresponding AWG or Brown and Sharpe gage sizes.

Test procedures for all sleeving types are described with reference, where appropriate, to applicable ASTM standards. Property requirements include the following:

- Visual examination
- Dimensional measurement
- Dielectric breakdown
  - Straight
  - 90° bend
- Resistance to potting temperature
- Cold brittleness
- Flammability
- Oil and solvent resistance

Hydrolytic stability
Push back after heat aging
Thermal endurance
Thermal stability
Fungus resistance

PROPERTIES

Property values for commonly used sleeving types are shown in the accompanying summary of ASTM Standard D 372, *Specification for Flexible Treated Sleeving Used for Electrical Insulation.*

In general:

- Oleoresinous varnish and polyvinylchloride coated sleevings are low cost, flexible, and resistant to attack by hot oil (105°C (221°F)), but limited to 105°C (221°F) use.
- Polyurethane-coated exhibits outstanding toughness and is unaffected by hot oil (105°C (221°F)). It is useful up to 130°C (266°F).
- Acrylic and modified acrylic (more flexible) coated sleevings have high resistance to acids, organic solvents, and water. Films are tough and compatible with most magnet wire enamels. These sleevings are useful up to 155°C (311°F).
- Silicone rubber coated sleeving is very flexible, has excellent aging characteristics, and is useful up to 200°C (392°F).
- Silicone resin and polytetrafluoroethylene resin coated sleevings are high priced and are for use at temperatures higher than those for which other sleevings are qualified.

ELECTRICAL/ELECTRONIC USES

Insulating sleevings are used primarily over wires where other insulation has been stripped away or where additional insulation or mechanical protection is needed.

DEVELOPMENT PROGRAMS

Since sleevings are available in all thermal Classes and degrees of flexibility, the requirements of design engineers can usually be met with existing products, and development is focused on product refinements.

MARKET TRENDS

Sleeving usage is directly tied to production trends in the electrical industry. There is growing usage of silicone and other high-temperature coatings at the expense of vinyl and traditional varnish coatings.

14

Mica and Mica Products

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INTRODUCTION

Mica, a term derived from the Latin word *micare* (to shine or glitter), was mined in India for medicinal purposes as early as 2000 B.C. In medieval times, it was used for windows in houses because of its transparency, and later in stoves because of that property plus its resistance to fracture and heat. Mica has been used as a dielectric since the earliest days of the electrical industry. Principal manufacturers of mica products include Asheville-Schoonmaker, Cleveland Mica Insulating Materials, Macallen, Midwest Mica, Spruce Pine Mica, Tar Heel Mica, and U.S. Samica.

TECHNOLOGY AND GRADES

Micas are complex silicates of several types, of which two are used commercially as dielectrics:

- Muscovite mica, also referred to as India white, or ruby mica, mined primarily in India and Brazil, and in smaller amounts in Angola, Tanganyika, Argentina, and the United States
- Philogopite mica, also referred to as amber mica, mined in Madagascar, with small deposits in Canada and Mexico.

Table 14-1 compares the ranges of principal compounds in these mica types.

TABLE 14-1 Composition Ranges of Muscovite and Phlogopite Mica

	MUSCOVITE (%)	PHLOGOPITE (%)
SiO_2	45–47	38–43
Al_2O	30–38	12–17
K_2O	9–12	9–11
MgO	trace	23–29

There are also present traces of oxides of iron, calcium, lithium, sodium, titanium, and barium.

Mica is mined as blocks, plates, or slabs (7 mils and over thick), as films (0.8–4 mils thick), and as splittings (thin laminae split from blocks). After mining, blocks are trimmed to remove worthless layers and ragged edges. Full-trimmed mica is mica trimmed on all sides with all cracks, reeves (pockets), and cross grains removed. Mica has virtually perfect basal cleavage, permitting it to be split to exceptional thinness. Mica is often contaminated with impurities which render it unsuitable for dielectric applications.

The grading of muscovite mica, the most widely used as electrical insulation, is covered by ASTM Standard D 351, *Natural Muscovite Block Mica and Thins Based on Visual Quality*, and includes these categories:

V-1 Clear—Hard, of uniform color, flat, free from all stains and foreign inclusions, waves, cracks, buckles, and other similar defects.

V-2 Clear and Slightly Stained—Hard, of uniform color, nearly flat, free from all vegetable and mineral stains, cracks, buckles, and other similar defects, and foreign inclusions, except for a few tiny air inclusions in not more than one-fourth of the usable area. Slight crystallographic discoloration is permitted to a limited extent.

V-3 Fair Stained—Hard, of uniform color, free from all vegetable and mineral stains, cracks, buckles, and other similar defects, and foreign inclusions, except may be slightly wavy, and may contain slight air inclusions in not more than one-half of the usable area. These inclusions should not be concentrated. Slight crystallographic discoloration is permitted to a limited extent.

V-4 Good Stained—Hard, free from vegetable or mineral stains, cracks, buckles, and other similar defects, and foreign inclusions, except may be medium wavy but not rippled, and may contain medium air inclusions in not more than two-thirds of the usable area, but may not have heavily concentrated air inclusions in any of the usable area. Slight crystallographic discoloration is permitted to a limited extent.

V-5 Stained A Quality—Hard, free from cracks and other similar defects and foreign inclusions, except may be medium wavy and may contain slight vegetable stains, and the entire area may have air inclusions if not heavily concentrated. Crystallographic discoloration is permitted.

V-5.1 Stained A1 Quality—Hard, free from cracks and other similar defects and foreign inclusions, except may be wavy and may contain slight vegetable stains, slight mineral stains not exceeding two specks within the usable area, and the entire area may have air inclusions if not heavily concentrated over more than area equivalent to $^1/_4$ inch square (6.4 mm square) for grade 5 and up and over more than an area equivalent to $^1/_8$ inch square (3.2 mm square) for grade $5^1/_2$ and below. Crystallographic discoloration is permitted.

V-6 Stained B Quality—Hard, free from cracks, and other similar defects and foreign inclusions, except may be wavy and slightly buckled, and may contain heavy inclusions of air, medium vegetable, clay, and mineral stains. Crystallographic discoloration is permitted.

V-7 Heavy Stained—Hard, free from cracks and other similar defects and foreign inclusions, except may be wavy and buckled, and may contain heavy air inclusions, heavy vegetable and medium mineral stains. Crystallographic discoloration is permitted.

V-8 Densely Stained—May be soft and may contain heavy stains and inclusions, waves, cracks, buckles, and other defects. Crystallographic discoloration is permitted.

V-9 Black Dotted—Hard, free from cracks and other similar defects, but may be medium wavy, and may contain heavy air inclusions, vegetable stains, and dispersed black dots. Crystallographic discoloration is permitted.

V-10 Black Spotted—Hard, free from cracks and similar defects and foreign inclusions, except may be medium wavy and contain slight buckles and vegetable stains, black spotted or red dotted mineral stains, and heavy air inclusions. Crystallographic discoloration is permitted.

V-11 Black Stained—Hard, may contain medium waves, heavy air inclusions, smoky stains, black stains and red dots (mineral), green stains (vegetable type), and sand blast, medium black stains (mineral), slight red stains (mineral), and clay stains. Crystallographic discoloration is permitted.

V-12 Black/Red Stained—V-11 Quality, but may be soft and have black lines and/or short red bars or connected stains.

Federal Specification HH-I-536 also defines mica grades. Table 14-2 lists equivalent HH-I-536 and ASTM D 351 grades.

TABLE 14-2 Equivalent Grades of Mica

ASTM STANDARD D 351	FEDERAL SPECIFICATION HH-I-536
V-1	NMC_1
V-2	NMS_s
V-3	NMF_s
V-4	NMG_s
V-5	NMSA
V-6	NMSB
V-7	NMH_s
V-8	NMBD
V-9	$NMBS_p$
V-10	$NMBS_t$

TABLE 14-3 Grade Sizes of Muscovite Uncut Mica Block and Thins (ASTM D 351)

ASTM GRADE SIZES	AREA OF MINIMUM RECTANGLE		MINIMUM DIMENSION OF ONE SIDE	
	in^2	cm^2	in	mm
OOEE Special	100	650	4	100
OEE Special	80	520	4	100
EE Special	60	390	4	100
E Special	48	310	4	100
A-1 (Special)	36	235	$3\frac{1}{2}$	89
No. 1	24	155	3	76
No. 2	15	97	2	51
No. 3	10	65	2	51
No. 4	6	40	$1\frac{1}{2}$	38
No. 5	3	20	1	25
No. $5\frac{1}{2}$	$2\frac{1}{4}$	15	$\frac{7}{8}$	22
No. 6	1	6.5	$\frac{3}{4}$	19

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For critical dielectric applications, grades used are V-6 or better.

ASTM D 351 also establishes grade sizes based on the area of a rectangular surface of the mica containing the maximum usable surface within the specimen, and specifies the minimum dimension of one side for each grade as shown in Table 14-3.

Splittings may be loose or book packed. Loose packed splittings are irregular in shape and are randomly boxed, whereas book-packed splittings are consecutive laminae split from the same block and stacked as pages in a book. The size and thickness range of muscovite splittings are covered by ASTM D 2131, *Natural Muscovite Mica Splittings*, as shown in Table 14-4.

TABLE 14-4 Requirements for Size and Average Thickness of Muscovite Mica Splittings (ASTM D 2131)

ASTM GRADE	FORM	SIZE in^2 (cm^2)	MINIMUM DIMENSION OF USABLE RECTANGLE in (mm)	THICKNESS OF TEN SPLITTINGS in (mm)
4	bookform	6–10 (39–65)	1 1/2 (38)	0.006–0.009 (0.15–0.23)
5	bookform	3–6 (19–39)	1 (25)	0.006–0.009 (0.15–0.23)
5 1/2	bookform	2–3 (13–19)	7/8 (22)	0.006–0.009 (0.15–0.23)
6	bookform	1–2 (7–13)	1/4 (19)	0.006–0.10 (0.15–0.25)
4	loose with powder	6–10 (39–65)	1 1/2 (39)	0.006–0.009 (0.15–0.23)
5	loose with powder	3–6 (19–39)	1 (25)	0.006–0.009 (0.15–0.23)
5 1/2	loose with powder	1 1/2–3 (10–19)	7/8 (22)	0.007–0.010 (0.18–0.25)
6	loose with powder	1–1 1/2 (6–10)	3/4 (19)	0.007–0.010 (0.18–0.25)
6—1st	loose	1–1 1/2 (70% min) (6–10) (70% min)		0.007–0.010 (0.018–0.25)
6 inter	loose	1–1 1/2 (60% min) (6–10) (60% min) 3/4–1 (25% min) (5–6) (25% min)		0.007–0.010 (0.18–0.25)
6—2nd	loose	1–1 1/2 (50% min) (6–10) (50% min)		0.007–0.011 (0.18–0.28)
6—3rd	loose	3/4 (65% min) (5) (65% min)		0.007–0.011 (0.18–0.28)
6—4th	loose	1/2 (30% min) (3.2) (30% min)		0.007–0.012 (0.18–0.30)

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SYNTHETIC MICA

Mica may also be grown electrothermally with a composition similar to natural mica, except without water content. A modified mica, fluorophlogopite, has excellent dielectric properties and higher thermal endurance than natural mica. With natural mica, when a temperature is reached where its water content is driven off (1,000°F for muscovite, 1,400°F for phlogopite), mica calcines, or crumbles, and is no longer useful unless bonded with high-temperature inorganic binders such as silicates, borates, and phosphates.

Synthetic mica splittings are used exclusively for glass-bonded mica insulations and are not available as splittings. (See "Glass-Bonded Mica," p. 412 in this chapter.)

PROPERTIES

The outstanding dielectric and thermal endurance, inertness, and nonflammable characteristics of mica separate it from virtually all other insulating materials. Mica is also highly resistant to the harmful effects of corona and radiation. However, without further fabrication into composites, splittings are usually limited to no more than 10 square inches in size.

Key property values for muscovite ruby, phlogopite amber, and fluorophlogopite synthetic micas are shown in Table 14-5.

TABLE 14-5 Key Property Values for Natural and Synthetic Micas (High Quality)

	MUSCOVITE RUBY NATURAL	PHLOGOPITE AMBER NATURAL	FLUORO-PHLOGOPITE SYNTHETIC
Specific gravity	2.8	2.8	2.9
Specific heat, cal/gm	0.207	0.207	0.194
Hardness (mohs)	2.8–3.1	2.5–3.0	3.0–3.5
Dielectric strength*			
3 mils thick, volts/mil	3,000	3,000	3,000
Dielectric constant*			
10^6 Hz	6.5–8.7	5–6	6.5
Dissipation factor*			
10^6 Hz	—	—	0.0002
Maximum use temperature, °F	1,000	1,400	1,800
(°C)	(540)	(760)	(980)

*At room temperature.

ELECTRICAL/ELECTRONIC USES

Block mica and mica films are used extensively as dielectrics in electronic capacitors (ASTM D 748). Mica provides a transparent path for microwaves, and is used in microwave windows. Other dielectric applications include stamped washers and other shapes for electrical/electronic equipment. There is still some use as spacers in the vacuum tubes which remain in the market.

BUILT-UP MICA

To make mica more useful, layers of splittings are bonded together with a variety of resins, including shellac, epoxy, alkyd, alkyd-vinyl, polyester, and silicone. The layering of splittings, originally done by hand, is now also done mechanically. This process consists of fluttering down mica flakes in a tower, much like snowflakes in a snowstorm. The mica flakes form a fairly uniform layer on a tray or moving belt. The desired amount of bonding agent is applied and the process is repeated, or when a belt is used, it carries the composite under another tower. Alternatively, powdered resin may be interspersed with the mica flakes in the tower. A still newer method involves a rectangular cowl fitting over a box of splittings. The mouth of the cowl is covered by a wire screen. Suction over the screen pulls splittings up against the screen. The mica box is drawn to one side and a perforated tray is substituted. The suction is released, and the layer of splittings is deposited on the tray. As this tray is withdrawn, it passes under a varnish sprinkler. The process is repeated to build the desired number of layers. There are many variations of these methods. After build-up, the composite is then cured in a multiple-opening, heated, hydraulic press. Milling of the cured mica plates brings them to the specified thickness.

Molding plate, although rigid at room temperature, softens when heated, and the splittings are able to slip relative to each other. The plate then becomes readily moldable. Binders include shellac, epoxy, silicone, and alkyd-vinyl. Binder content for this type of plate is relatively high, up to 25 percent for silicone binder. Uses include commutator V-rings, motor slot cells, bushings, washers, coil forms, sleeves, and transformer coil forms. Molding plate is available in thicknesses from 0.015 through 0.062 inch. Sheets are 36 × 36 inches.

Segment plate is made by laminating several layers of machine-laid mica splittings. Binders are the same as for molding plate, but binder content is less than 10 percent and the plate is fully cured, featuring maximum density combined with minimum compression when subjected to high temperatures and pressures. This material is used primarily in commutators for insulation between copper bars. Segment plate is available in thicknesses from 0.015 through 0.062 inch. Sheets are 36 × 36 inches.

Flexible plate contains binders of polyester, epoxy, and silicone. Binder contents is 10–15 percent. Sheets are cured to have optimum flexibility for up to six months or more. Flexible plate features high resistance to moisture, heat, and cut-through, high dielectric strength, and imperviousness to attack by oil. Uses include armature end-turn

insulation, slot liners, field coil separators, and commutator core insulation. It is also used for transformer coil insulation, and insulating collars, channels, and rings. Flexible plate is available in thicknesses from 0.005 through 0.030 inch. Sheets are 36 × 36 inches and 36 × 72 inches.

Flexible composites use mica splittings backed and/or faced with reinforcing materials such as woven glass, glass mat, polyester film, polyester mat, polyimide film, polyamide paper, and electrical grade paper. Binder content is 10–20 percent with binders of alkyd, alkyd modified with pine tar, epoxy, polyester, and silicone. These composites are used where the high dielectric strength and high heat resistance of mica and the physical properties of the backing and facing materials are required. Applications include motor slot liners, coil and cell wrappers, and phase, layer, and core insulation. The governing military specification is MIL-I-3505, *Insulation Sheet and Tape, Electrical, Coil and Slot, High Temperature*. Flexible composites are available in thicknesses from 0.007 to 0.030 inch. Sheets are 36 × 36 inches.

Mica splittings tape is made by hand laying splittings selected for quality, large size, and uniformity in thickness and shape. Machine-laid tapes are also produced with B-stage epoxy binder. Because of limited shelf life, these tapes require cold storage if they are not to be used immediately. Woven glass cloth, typically 0.002 inch thick, is used as reinforcement on one or both sides of the mica, or on one side with 0.00025 inch polyester film on the other side to increase slipping property. Mica thickness is 0.002–0.008 inch. The product is available in rolls 36 inches wide by 36 or 50 yards long, or slit in widths from $^1/_2$ inch to 36 inches by 36 yards long.

MICA PAPER PRODUCTS

The manufacture of mica paper, commonly referred to as reconstituted mica, is described in Chapter 11, *Dielectric Papers and Boards*. In addition to flexible composites used as wrappers and tapes and covered in that chapter, these mica paper products are produced in forms similar to mica splittings products:

Mica paper molding plate contains up to 25 percent B-stage epoxy or silicone binder. Available in thicknesses from 0.010 through 0.062 inch.

Mica paper segment plate contains 7–14 percent fully cured epoxy or inorganic binder. Available in thicknesses from 0.010 through 0.062 inch.

Heater plate, a fully cured, rigid laminate of either mica paper or mica splittings, contains 5–12 percent silicone or inorganic binder. Available in thicknesses from 0.006 through 0.125 inch. Sheets are 36 × 36 inches. The principal use for heater plate is for the mechanical support and insulation of the heating elements of appliances such as toasters, hot combs, hair driers, irons, and space heaters where temperatures can reach 1,400°F (760°C).

Mica paper tubes, round, square, and rectangular, contain 16–22 percent fully cured epoxy or silicone binder. Minimum wall thickness is 0.020 inch, minimum ID is 0.125 inch, maximum length is 36 inches.

THERMAL CLASSIFICATION OF MICA PRODUCTS

In general, binders determine the thermal Class of mica products:

BINDER	THERMAL CLASS
Shellac	130
Epoxy	155
Alkyd-vinyl	155
Polyester	155
Silicone	180 and 200

ASTM STANDARD FOR BONDED MICA PRODUCTS

The American Society for Testing and Materials has developed the following standard for testing bonded mica products:

• D 352, *Pasted Mica Used in Electrical Insulation.* Covered are methods of testing bonded mica splittings and bonded mica paper. The following tests are described:

Compressive creep
Stability under heat and pressure
Mica or binder content
Molding test
Dielectric strength
Resistivity

FEDERAL SPECIFICATIONS FOR MICA PRODUCTS

The governing Federal specifications for mica products include the following:

• HH-I-538, *Insulation, Electrical, Pasted-Mica.* This specification was approved by the Commissioner, Federal Supply Services, General Services Administration, for the use of all Federal agencies. This specification covers pasted-mica electrical insulation for molded armature slot bases, commutator insulation, shells, heating elements, and other similar insulating purposes. Types and forms are designated as follows:

Type PMR—Pasted mica, rigid
  Form S—Sheets (plates)
Type PMM—Pasted mica, moldable
  Form R—Rings
  Form S—Sheets (plates)

Form T—Tubes
Form X—Special shapes
Type PMF—Pasted mica, flexible
Form S—Sheets (plates)
Type PMH—Pasted mica, heat resistant
Form S—Sheets (plates)

Pasted-mica electrical insulation shall consist of, or contain, muscovite mica conforming to the requirements of ASTM D 2131 unless phlogopite mica is specifically required (which shall conform to the minimum standards for muscovite mica). The pasted mica shall consist of layers of overlapping mica splittings held together by a suitable binding material, which shall be chemically inert with respect to materials normally used in electrical equipment under conditions of rated operating temperature and the presence of humid salt atmosphere.

• MIL-I-3505, *Insulation Sheet and Tape; Electrical, Coil and Slot, High Temperature*. This specification has been approved by the Department of Defense and is mandatory for use by the Departments of the Army, the Navy, and the Air Force. This specification covers high-temperature mica-glass electrical insulation used in the coils and slots of rotating electrical machinery. The following classifications are employed:

Class B (130°C)—With organic varnish
Class H (180°C)—With silicone varnish
Form S—Sheet
Form T—Tape
Type Mg—Pasted mica laminated with one layer of glass fiber fabric
Type Pmg—Pasted mica laminated with one layer of paper on one side and one layer of glass fabric on the other side
Type Gmg—Pasted mica sandwiched between single layers of glass fabric insulation.

The binding material shall be high-quality insulating material used in the minimum amount needed to obtain specified properties, including tensile strength, flexibility, and dielectric strength.

• MIL-I-21070, *Insulating Sheet and Tape, Electrical, Reinforced Mica Paper*. This specification covers reinforced mica paper electrical insulation used in the coils and slots of electrical machinery. There are three Classes of this material supplied as flat sheets, rolls, and tapes:

Class 130—With organic resin binder and organic varnish coating (if used) on glass fiber woven fabric reinforcement
Class 155—With epoxy or polyester resin binder and an epoxy or polyester coating (if used) on glass fiber woven fabric reinforcement
Class 180—With silicone resin binder and silicone varnish coating (if used) on glass fiber woven fabric reinforcement

Constructions include mica paper backed and faced with woven glass or varnished woven glass fabric, or polyester film. Required performance characteristics for various constructions include dielectric strength, volume resistivity, tensile strength, and tear resistance.

GLASS-BONDED MICA

Finely ground mica, either natural or synthetic, may be bonded with a low-melting electrical grade glass to produce ceramic insulations that are both machinable and moldable. These materials are made by Mykroy/Mycalex Ceramics, with trade name Mykroy/Mycalex.

Glass-bonded mica products are covered by ASTM standard D 1039, *Standard Methods of Testing Glass-Bonded Mica Used as Electrical Insulation*.

The governing military specification for glass-bonded mica is MIL-I-10, *Insulating Materials, Ceramic*.

Commercially available Mykroy/Mycalex grades and their property values are shown in Table 14-6. Noteworthy characteristics include:

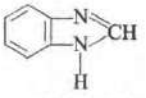
- Exceptionally high-dimensional stability
- Service temperatures up to 1,200°F (650°C)
- Good dielectric properties
- Nonflammable
- No arcing, tracking, or outgassing
- Impervious to moisture
- High mechanical properties
- Close tolerance molding and machining
- Thermal expansion coefficient close to that of steel used for molds

Typical electrical/electronic uses include circuit breakers, switchgear, arc barriers, connectors, relays, bushings, brush holders, coil forms, and printed circuit substrates.

DEVELOPMENT PROGRAMS

Because binders limit the maximum operating temperatures for mica composites, the search continues for higher thermal class bonding agents. Improved thermal properties would permit greater output from rotating electrical equipment using the same frame, an attribute of special importance for traction equipment.

Scientists at Bharat Heavy Electricals Limited, Bhopal, India, have developed a resin and mica composite system ascribed Class 275 and reported to be useful at temperatures up to 350°C (662°F).[1] The resin, comprised of linear chains, is polybenzimidazole (PBI or PBMI), formed by polymerizing benzimidiazole. Hydrogen bonding is pronounced in the polymer.



benzimidiazole

[1]M. V. Dalal and V. K. Ganpate, "A new 275 Class non-silicone micaceous insulation system," in *Proceedings of the 16th Electrical/Electronics Insulation Conference*, p. 32.

TABLE 14-6 Typical Property Values for Glass-Bonded Mica (Mykroy/Mycalex Grades)

GENERAL PROPERTIES	ASTM METHOD	UNITS	MACHINING/GRADES SHEET/POD 400	500	1100	MOLDING GRADES 410/751	555/761	620/1301	371
Specific gravity	C 373		2.5	2.7	2.8	0.38	3.7	3.9	4.8
Density		lb/in^3	0.09	0.10	0.10	0.14	0.13	0.14	0.17
Thermal conductivity		cal/s/cm^2/°C/cm	0.00100	0.00120	0.00140	0.00120	0.00130	0.00125	0.00136
		BTU/h/ft^2/ft/°F	0.24	0.29	0.39	0.29	0.31	0.30	0.31
Moisture absorption			Nil	Nil	Nil	Nil	Nil	Nil	Nil
Coefficient of thermal expansion ($\times 10^{-6}$)		in/in/°C	10.5	11.2	9.4	11.2	11.0	10.3	11.5
		in/in/°F	5.8	6.0	5.2	6.0	6.0	5.5	6.3
Specific heat		cal/gm/°C	0.12	0.12	0.11	0.24	0.24	0.23	0.25
Max continuous Operating temp.		°F	700	700	1100	750	750	1300	700
		°C	370	370	595	400	400	700	371
Flammability						Does not burn			
Mica filler			Natural	Synthetic	Synthetic	Natural	Synthetic	Synthetic	Natural
Radiation resistance (3×10^{10} rads-cobalt)			Good	Better	Excellent	Good	Better	Excellent	Good
ELECTRICAL PROPERTIES									
Dielectric strength	D 149	V/mil $^1/_8$ in thick	400	400	380	375	375	375	350
Arc resistance	D 495	s	300	300	325	325	325	350	300
Permittivity	D 150	1MHz	6.7	6.9	6.8	9.3/8.4	8.8/8.2	9.5/8.8	—
Dissipation factor	D 150	1MHz	0.0018	0.0013	0.0017	0.0012	0.0013	0.0015	0.006
Loss index	D 150	1MHz	0.012	0.009	0.012	0.0115	0.0110	0.0150	—
Surface resistivity	D 257	dry Ω · cm (70°F)	10^{16}	10^{16}	10^{16}	10^{15}	10^{15}	10^{15}	10^{15}
Volume resistivity	D 257	Ω · cm (70°F)	10^{12}	10^{13}	10^{14}	10^{13}	10^{14}	10^{14}	10^{14}
Surface resistivity	D 257	wet Ω · cm (70°F)	10^{6}	10^{10}	10^{11}	10^{9}	10^{9}	10^{10}	10^{9}
Dielectric constant	D 150	1MHz	6.7	6.9	6.8	6.6	8.8	9.0	12.5

(continued)

TABLE 14-6 (*Continued*)

GENERAL PROPERTIES	ASTM METHOD	UNITS	MACHINING/GRADES SHEET/POD 400	500	1100	MOLDING GRADES 410/751	555/761	620/1301	371
MECHANICAL PROPERTIES									
Tensile strength	D 651	psi	6,000	6,000	5,000	6,500	6,000	6,000	6,500
Flexural strength	D 790	psi	15,000	15,000	12,000	12,000	10,000	10,000	11,000
Compressive strength	D 695	psi	45,000	40,000	32,000	33,000	34,000	30,000	35,000
Modulus of elasticity (in tension)		psi	11.0×10^6	12.0×10^6	10.6×10^6	7.0×10^6	7.2×10^6	9.0×10^6	—
Hardness—Rockwell H		H	90	90	90	90	90	90	90
Hardness—Brinell		H	56	56	56	56	56	56	56
Impact strength—IZOD (notched)		ft · lb/in	1.8	1.7	1.3	0.7	0.7	0.6	0.65

(Table courtesy of Mykroy/Mycalex.)

PBI is derived by the condensation of 3,3'-diaminobenzidien with dicarboxylic aromatic acids, such as a mixture of isophthalamide and terephthalamide. A solution of PBI resin is obtained by dissolving the resin in a complex solvent system, for example, dimethylformamide and dimethylacetamide in the presence of lithium chloride solution and triboronate catalyst. This solution is suitable for preparation of prepregs and flexible to rigid composites.

The composite consists of mica paper or splittings sandwiched between PBI saturated glass fabric layers and film. With mica paper, 35–40 percent by weight of PBI is required. Mica splittings require only 10–15 percent PBI. The amount of catalyst determines the degree of flexibility or stiffness after curing at 300°C.

MARKET TRENDS

Because of the Toxic Substances Control Act, inorganic bonded mica paper laminates are now widely used in high-temperature applications to replace asbestos products. It is forecast that this trend will continue.

15

Ceramic and Glass Insulations

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INTRODUCTION

Ceramics and glasses are among the oldest dielectrics used in electrical equipment and in the transmission and distribution of power. A variety of ceramic and glass materials is available from several manufacturers, including the following:

MATERIALS	SUPPLIERS
Alumina	Alcoa, Kaiser, Ormet, Reynolds, Brush Wellman, Star
Aluminum nitride	Karamont
Aluminum silicate	Saxonburg
Beryllia	Brush Wellman
Boron nitride	General Electric (Borazon™), Carborundum (Combat™)
Cordierite	Saxonburg, Star, D. M. Stewart
Diamond	Norton
Magnesia	Dow Chemical
Porcelain	Southern Porcelain, Star, Coors
Sapphire	Crystal Systems, Tyco Laboratories, Union Carbide
Silica (fused)	Amersil, Corning Glass, General Electric, Raytheon, Thermal American, U.S. Fused Quartz
Steatite	D. M. Stewart, Saxonburg, Star
Zircon	Corning Glass, 3M

This chapter covers ceramics and glasses used for electrical insulation other than glass-bonded mica (see "Glass-Bonded Mica," p. 412 of Chapter 14, *Mica and Mica Products*) and substrates for printed circuits (see "Substrates for Printed Circuits," p. 285 of Chapter 9, *Unclad and Clad Structures*).

TECHNOLOGY

Ceramic structures are characterized by outstanding resistance to normal aging and the ability to withstand high operating temperatures, heat shock, and electrical degradation. However, it is to be noted that the structural strength of ceramics holds to much higher temperatures than do dielectric properties. The point at which there is a rapid increase in dielectric loss is referred to as the dielectric transition temperature. Above this temperature, dielectric breakdown occurs rapidly, typically accompanying localized heating and the establishment of high thermal gradients within the ceramic body, which may cause structural destruction.

CHEMISTRY

Early ceramics were composed of natural clays (hydrated aluminum silicates) with the generalized formula $Al_2O_3SiO_2 \cdot xH_2O$. Several materials used as dielectrics are now classed as ceramics. In general, they are crystalline structures bonded together by a smaller amount of a vitreous matrix formed during the firing process. The ratio of crys-

talline and amorphous phases significantly affects the dielectric and physical properties of the ceramic. The formation and rate of growth of the crystalline phase is determined by the temperature versus time profile of the firing operation. The firing temperature for most ceramics is in the range of 1,200° to 1,700°C (2,192°–3,092°F). By contrast, glass is technically an amorphous liquid of extremely high viscosity, composed of silica (75 percent), soda ash (20 percent), and lime (5 percent), often combined with metallic oxides such as those of calcium, lead, lithium, and cerium. The principal ceramics used in electrical insulations include:

- *Alumina*, or aluminum oxide (Al_2O_3), occurs naturally as the mineral corundum and in hydrated form in bauxite. Virtually all commercially produced alumina involves a caustic leach of the bauxite at elevated temperature and pressure. Lime is added to control the phosphorus content and to increase the solubility of alumina. The resulting slurry, 40–50 percent solids, is pumped to pressurized digesters, where high-pressure steam is used to raise the temperature. Alumina and some of the silica are dissolved during this step, soluble sodium aluminate is formed, and a complex sodium aluminum silicate is precipitated. The resulting slurry containing sodium aluminate in solution is cooled to atmospheric boiling temperature, and a coarse sand fraction is removed by gravity separators or wet cyclones. The liquor is clarified and cooled until it becomes supersaturated, and then is seeded with crystals of alumina trihydrate. Alumina is precipitated as the trihydrate. It is then filtered and washed, after which it is calcined (heated below the melting point) to drive off the water or hydration. High-grade ceramic shapes with melting point of 2,040°C (3,700°F) are made from alumina calcined at 1,480° to 1,590°C (2,700°–2,900°F).

- *Aluminum nitride* (AlN) powders are sintered at very high temperatures in nitrogen atmosphere to avoid its oxidation to alumina.

- *Aluminum silicate* ceramics contain varying amounts of alumina (Al_2O_3) and silica (SiO_2). They are made synthetically by heating aluminum fluoride at 1,000° to 1,200°C (1,830°–2,200°F) with silica and water vapor.

- *Beryllia*, or beryllium oxide (BeO), is derived from beryl ($Be_3Al_2Si_6O_{18}$), the ore of beryllium. the ore is wet-ground and screened to form a slurry that is transported to a processing plant, where it is leached with a 10 percent sulfuric acid solution. The insoluble residue is filtered and discarded. The remaining beryllium sulfate solution is treated by a solvent-extraction process using di-2-ethylhexyl phosphoric acid in kerosene. The beryllium in solution is subsequently converted to beryllium hydroxide, which is then calcined to form beryllia. Beryllium is the lightest structural metal known. The Occupational Safety and Health Administration (OSHA) has designated beryllium and its compounds highly toxic with a worker exposure limit of 0.002 milligram per cubic meter of air for an 8 hour time-weighted average.

- *Boron nitride* (BN) is formed at very high pressure (85,000 atmospheres) and temperatures (1,800°C, 3,270°F) from mixtures of boron and nitrogen, or from hexagonal boron nitride in the presence of catalysts such as lithium, calcium, magnesium, or their nitrides. Boron occurs in nature as sodium borate (borax), $Na_2B_4O_7 \cdot 10\ H_2O$. Boron is derived by several processes, including reduction by heating boric oxide with powdered metals (sodium, magnesium, aluminum); by vapor phase reduction of boron

trichloride with hydrogen over hot filaments; and by electrolysis of fused salts. Boron dust ignites spontaneously in air, presenting a severe fire and explosion hazard.

- *Cordierite* is a naturally occurring magnesium aluminum silicate ($2\ MgO \cdot 2\ Al_2O_3 \cdot 5\ SiO_2$).
- *Diamond* films are produced by mixing methane and hydrogen in a plasma environment and depositing pure diamond films on a substrate.
- *Magnesia*, or magnesium oxide (MgO), is produced by calcining magnesium carbonate or magnesium hydroxide; by treating magnesium chloride with lime and heating; and from sea water via the hydroxide. Two forms are produced. A light, fluffy material is prepared by a relatively low-temperature dehydration of the hydroxide. The other form is a dense material made by high-temperature furnacing of the oxide after it has been formed from the carbonate or hydroxide. Magnesia is toxic by inhalation of fumes. OSHA has placed a worker exposure limit of 15 milligrams per cubic meter of air for an 8 hour time-weighted average.
- *Porcelain*, or potassium aluminum silicate ($4\ K_2O \cdot Al_2O_3 \cdot 3\ SiO_2$), is formed by sintering mixtures of clays, quartz, and feldspar (potassium alumino-silicate). Ultra porcelain, the highest mechanical and dielectric grade, is composed of aluminum oxide, barium oxide, and clay.
- *Quartz*, or crystallized silicone dioxide (silica, SiO_2), is produced by crystal growth from molten silica under carefully regulated conditions. For a discussion of crystal growth, see "Semiconductor Silicon" (p. 286) in Chapter 9, *Unclad and Clad Structures*. Fused silica is obtained by the electric-arc fusion of high-purity quartz sand. Ingots thus formed are then crushed to silica grains for casting and kiln bonding.
- *Sapphire*, or corundum (Al_2O_3), is a crystalline variety of alumina. Purified, synthetic sapphire is made by crystal-growing techniques. For a discussion of these techniques, see "Semiconductor Silicon" (p. 286) in Chapter 9, *Unclad and Clad Structures*. In a proprietary EFG process, Saphikon (a Division of Tyco Laboratories) produces continuous lengths of sapphire crystal in almost any cross-sectional configuration from furnaces operating at almost 2,200°C (4,000°F).
- *Steatite* is a mixture of hydrous magnesium silicate, clay, and alkaline oxides.
- *Zircon*, or zirconium silicate ($ZrSiO_4$, or $ZrO_2 \cdot SiO_2$), used in ceramics is a purified form of a naturally occurring mineral.

A new process for making ceramic multilayer circuit boards is based on co-firing alumina layers. Du Pont offers a system called *Green Tape*. Mixtures of alumina, glass, and other powders are combined with a plastic and a solvent, producing an uncured flexible tape. Tapes are cut, punched, and etched, and then holes are interconnected. The stack is pressed in a plastic press to make a multilayer laminate. The laminate is then fired at 800°C (1,472°F) which fuses the ceramic and burns out the plastic.

GRADES

Grades are available with varying degrees of basic mineral content with over 99.99 percent purity for single crystals such as quartz, and with up to 99.9 percent purity for other ceramic powders. Manufacturers of ceramic parts, including custom fabricators,

often formulate compositions to meet their own special requirements by blending ceramic powders with binders and other additives.

PROCESSING

Ceramic powders are usually wet blended with enough water to wet the particles. Excess water causes the slurry to settle and should be avoided. It is important to use deionized water and lined tanks to minimize powder contamination. The slurry may then be vibro-energy-milled using ultrasonics, or ball-milled. This process breaks up agglomerates and produces a narrow size range of discrete particles. After milling, lubricants and organic binders, such as sodium lignum sulfonate, may be added during agitation. Moisture may then be completely removed by spray drying. The resulting particles flow freely to fill dies evenly with minimum voids and pits. The "green" parts thus obtained are then sintered, or fused, in high-temperature electric kilns with precise process controls. Organic components are burned out during this operation.

A wet process commonly used to manufacture large ceramic pieces is similar to that above, but omits the organic lubricants and binders. A portion of the water in the slurry is removed by filter press to make a putty or paste. The putty or paste is then formed into the desired shape, and subsequently dried to a sufficiently low moisture content so that it can be kiln fired without cracking.

In a simpler process, the ceramic powder is mixed with just enough water to make a stiff paste or putty, after which the desired shape is formed, dried, and fired at high temperature with exposure to air.

A "dry" process uses less water and produces parts with good dimensional properties. Mechanical and dielectric properties, however, are inferior to those obtained by the wet process.

During the kiln firing, crystalline growth proceeds at a rate which depends on the basic constituents, the temperature, and the duration of firing. Insulator porcelain is fired at 1,250°C (2,280°F), steatite at 1,400°C (2,550°F), and alumina and beryllia at 1,700°C (3,090°F).

ASTM STANDARDS FOR ELECTRICAL INSULATING CERAMICS

The American Society for Testing and Materials has developed the following standards for electrical insulating ceramics:

- D 116, *Vitrified Ceramic Materials for Electrical Appliances*. This standard outlines procedures for testing samples of vitrified ceramic materials that are to be used as electrical insulation. They are equally suited for both unglazed and glazed specimens. Test methods are described in Table 15-1.
- F 356, *Beryllia Ceramics for Electronic and Electrical Applications*. This specification covers fabricated beryllia parts suitable for electronic and electrical applications. Specified are limits and methods of test for electrical, mechanical, thermal, and

TABLE 15-1 Property Tests and Test Methods for Vitrified Ceramic Materials (ASTM D 116)

PROPERTY MEASURED	ASTM METHOD
Compressive strength	C 773
Dielectric constant and dissipation factor	D 2149, D 150, D 2520
Dielectric strength	D 149
Elastic properties	C 623
Electrical resistivity	D 257, D 1829
Flexural strength	C 674, F 417
Hardness	C 730, E 18
Porosity	C 373
Specific gravity	C 329, C 20
Thermal conductivity	C 408, C 177
Thermal expansion	F 228, C 539
Thermal shock resistance	D 116

general properties of the bodies used for these fabricated parts. Three types of materials are identified:

TYPE	BERYLLIA CONTENT WEIGHT PERCENT MINIMUM
I	95
II	98
III	99

Requirements for beryllia ceramics are shown in Table 15-2.

• D 2442, *Alumina Ceramics for Electrical and Electronic Applications*. This specification covers the requirements for fabricated alumina parts suitable for electronic and electrical applications, and ceramic-to-metal seals as used in electron devices. Specified are limits and methods of test for electrical, mechanical, thermal, and general properties of the bodies used for these fabricated parts. Four types of materials are identified:

TYPE	ALUMINA CONTENT WEIGHT PERCENT MINIMUM
I	82
II	93
III	97
IV	99

TABLE 15-2 Requirements for Beryllia Ceramics to be Used as Electrical Insulations (ASTM F 356)

	TYPE I	TYPE II	TYPE III	ASTM METHOD
Electrical				
Dielectric constant, max, 25°C				D 150
at 1 MHz	7.0	7.0	7.0	
at 10 GHz	6.8	6.8	6.9	
Dissipation factor, max, 25°C				D 150
at 1 MHz	0.0005	0.0005	0.0004	
at 10 GHz	0.001	0.001	0.001	
Volume resistivity, min, Ω · cm				D 257
at 25°C	10^{14}	10^{15}	10^{15}	D 1829
at 300°C	10^{11}	10^{12}	10^{12}	
at 500°C	10^{10}	10^{11}	10^{11}	
at 700°C	10^{8}	10^{9}	10^{9}	
at 900°C	10^{6}	10^{8}	10^{8}	
Dielectric strength, min, 125 mils				D 149
volts/mil	300	300	300	
Mechanical				
Density, g/cm^3, min	2.80	2.80	2.85	F 77
Flexural strength, min, avg psi	20,000	24,000	25,000	F 417
Compressive strength, min, avg psi	200,000	222,000	240,000	C 773
Modulus of elasticity, min, psi	44×10^6	45×10^6	49×10^6	C 623
Thermal				
Mean coef. of linear thermal expansion, μm/m/°C				E 228
25°–1,000°C	9.0 min 10.0 max	8.7 min 9.4 max	9.4 min 9.7 max	
Thermal conductivity, (min) cal/s/cm^2 °C/cm				C 408
at 25°C	0.35	0.52	0.60	
at 100°C	0.30	0.40	0.41	
at 400°C	0.14	0.15	0.15	
at 800°C	0.05	0.05	0.06	
Specific heat at 100°C				C 351
cal/g/°C	0.30	0.30	0.31	
Thermal shock resistance*	pass	pass	pass	

*To be agreed upon between manufacturer and purchaser.

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TABLE 15-3 Requirements for Alumina Ceramics to Be Used as Electrical Insulation (ASTM D 2442)

	TYPE I	TYPE II	TYPE III	TYPE IV	ASTM METHOD
Electrical					
Dielectric constant, max, 25°C					D 150
at 1 MHz	8.8	9.6	9.8	10.1	
at 10 GHz	8.7	9.6	9.8	10.1	
Dissipation factor, max, 25°C					D 150
at 1 MHz	0.002	0.001	0.0005	0.0002	
at 10 GHz	0.002	0.001	0.0005	0.0002	
Volume resistivity, min, Ω · cm					D 257
at 25°C	10^{14}	10^{14}	10^{14}	10^{14}	D 1829
at 300°C	1×10^{10}	1×10^{10}	1×10^{10}	7×10^{10}	
at 500°C	4×10^{7}	2×10^{7}	8×10^{7}	1×10^{8}	
at 700°C	4×10^{6}	2×10^{6}	6×10^{6}	1×10^{7}	
at 900°C	4×10^{5}	1×10^{5}	8×10^{5}	1×10^{6}	
Dielectric strength, min,					D 149
125 mils volts/mil	250	250	250	250	
Mechanical					
Density, g/cm^3, min	3.37	3.57	3.72	3.78	F 77
Flexural strength, min, avg psi	35,000	40,000	40,000	40,000	F 417
Modulus of elasticity, min, psi	31×10^{6}	40×10^{6}	45×10^{6}	50×10^{6}	C 623
Thermal					
Mean coef. of linear thermal expansion μm/m/°C					E 228
25°–1,000°C	7.4 min	7.5 min	7.6 min	7.5 min	
	8.2 max	8.3 max	8.3 max	8.4 max	
Thermal conductivity, cal/s/cm^2 °C/cm					C 408
at 100°C	0.023 min	0.031 min	0.048 min	0.052 min	
	0.049 max	0.077 max	0.073 max	0.090 max	
at 400°C	0.015 min	0.014 min	0.022 min	0.023 min	
	0.022 max	0.036 max	0.033 max	0.047 max	
at 800°C	0.009 min	0.009 min	0.014 min	0.014 min	
	0.018 max	0.021 max	0.021 max	0.025 max	
Thermal shock resistance*	pass	pass	pass	pass	

*To be agreed upon between manufacturer and purchaser.

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Requirements for alumina ceramics are shown in Table 15-3.

• D 2757, *Impervious Steatite Ceramics for Electrical and Electronic Applications*. This specification covers the requirements for impervious steatite ceramics having low electrical loss characteristics. These ceramics are designated as Type I, Type II, Type III, and Type IV. There is no further description of these types other than the values appearing in the table of requirements Table 15-4.

TABLE 15-4 Requirements for Impervious Steatite Ceramics to Be Used for Electrical and Electronic Applications (ASTM D 2757)

	TYPE I	TYPE II	TYPE III	TYPE IV	ASTM METHOD
Physical					
Specific gravity, min	2.5	2.6	2.7	2.7	C 20
Flexural strength,					D 116
min avg psi	18,000	18,000	20,000	20,000	
Dye penetration	none	none	none	none	D 116
Thermal expansion,					D 116
25–700°C					
cm/cm · °C × 10^{-6}	7–10	7–10	7–10	7–10	
Hardness, Rockwell 45N	45	45	50	50	E 18
Impact strength,					
min, in · lbf	4.0	4.5	5.0	5.5	D 116
Electrical					
Dielectric strength,					D 116
1/4 in thick					
volts/mil min	220	230	230	230	
Volume resistivity,					D 116
min Ω · cm					
at 25°C	10^{14}	10^{14}	10^{14}	10^{14}	
at 100°C	1×10^{12}	1×10^{13}	5×10^{13}	5×10^{13}	
at 300°C	1×10^{7}	1×10^{10}	5×10^{10}	5×10^{10}	
at 500°C	1×10^{5}	5×10^{7}	1×10^{8}	1×10^{9}	
at 700°C	1×10^{4}	1×10^{6}	1×10^{6}	1×10^{7}	
at 900°C	1×10^{3}	1×10^{5}	1×10^{5}	1×10^{6}	
Dielectric constant,					
at 25°C, max					
at 1 MHz	6.0	6.0	6.2	6.5	D 150
at 4 GHz	5.8	5.8	6.0	6.3	D 2520
Loss index, 25°C, max					
at 1 MHz	0.035	0.016	0.008	0.004	D 150
at 4 GHz	0.038	0.018	0.015	0.007	D 2520

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PROPERTIES

Thermal Properties

Thermal conductivity is the principal property that determines the dissipation of local heating. Of all electrical insulating ceramics, beryllia has by far the highest thermal conductivity. Where ceramics are used in conjunction with other materials, it is often important that rates of expansion be compatible. That is, the coefficients of linear thermal expansion should be as close as possible.

Thermal properties of selected ceramic materials are shown in Tables 15-5–15-8.

TABLE 15-5 Thermal Conductivities of Electrical Insulating Ceramics

	TEMPERATURE		
	°F	°C	Btu/(h)(ft²)(°F/ft)*
Beryllia	200	93	104
Magnesia	200	93	18
Alumina	212	100	16.4
Sapphire	200	93	15–16
Boron nitride	212	100	13.3–25.5
Porcelain	not stated		8.2
Aluminum silicate	77	25	4.8
Quartz	200	93	3.0–5.4
Zircon	200	93	2.4
Steatite	77	25	1.5
Cordierite	77	25	1.2
Silica (fused)	1,000	538	0.33

*To convert to cal/(s)(cm²)(°C/cm), multiply by 0.00413.

Note: Because of variance in composition and processing methods, the actual value for a specific material in the above table may vary significantly from the value shown.

Sources: Handbook of Physics and Chemistry and others.

TABLE 15-6 Coefficient of Linear Expansion of Electrical Insulating Ceramics

	TEMPERATURE RANGE °C	inch/inch/°C × 10^{6}*
Magnesia	25–400	12.8
Aluminum silicate	25–400	8.1
Quartz	0–80	8.0
Beryllia (99% BeO)	not stated	7–9
Alumina (99.9% Al_2O_3)	25–500	7.4
Porcelain	25–400	6.9
Steatite	25–400	6.6
Sapphire	25–400	4.5–7.0
Zircon	25–400	4.5
Cordierite	25–400	3.1
Boron nitride	25–350	0.18–3.1
Silica (fused)	0–800	0.55

*To convert to °F, divide by 1.8.

Note: Because of variance in composition and processing methods, the actual value for a specific material in the above table may vary significantly from the value shown.

Sources: Various.

TABLE 15-7 Maximum Operating Temperatures of Electrical Insulating Ceramics

	TEMPERATURE	
	°C	°F
Magnesia	2,200	4,000
Sapphire	2,000	3,630
Zircon	1,870	3,400
Alumina	1,700	3,100
Beryllia	1,700	3,100
Aluminum silicate	1,425	2,600
Silica (fused)	1,370	2,500
Steatite	1,315	2,400
Cordierite	1,300	2,380
Porcelain	1,200	2,200
Boron nitride (in oxidizing atmosphere)	985	1,805
Quartz	na	na

Note: Because of variance in composition and processing methods, the actual value for a specific material in the above table may vary significantly from the value shown.

na—not available.

Sources: Various.

TABLE 15-8 Thermal Shock Resistance of Electrical Insulating Ceramics

CERAMIC	RATING
Alumina	Good
Aluminum silicate	Excellent
Beryllia	Excellent
Boron nitride	Excellent
Cordierite	Good
Magnesia	Excellent
Porcelain	Poor
Quartz	Poor
Sapphire	na
Silica (fused)	Excellent
Steatite	Poor
Zircon	Good

Note: Because of variance in composition and processing methods, the actual value for a specific material in the above table may vary significantly from the value shown.

na—not available.

Sources: Various.

Physical Properties

Parts made of ceramics are characteristically hard, dense, and incombustible. Values for compressive strength are eight–ten times tensile strength values, indicating better performance under compression than under tension. Most ceramic bodies have low

impact strength and tend to fracture when struck sharply with a hard object, although there are noteworthy exceptions. For example, beryllia can be fabricated into armor for both vehicles and personnel.

Ceramic parts are not affected by long exposure to the atmosphere, even at high operating temperatures. Densities and mechanical properties of electrical insulating ceramics are shown in Table 15-9.

TABLE 15-9 Densities and Mechanical Properties of Electrical Insulating Ceramics

	DENSITY g/cm³*	FLEXURAL STRENGTH psi (000)*	COMPRESSIVE STRENGTH psi (000)*	TENSILE STRENGTH psi (000)*
Alumina (99.9% Al_2O_3)	4.0	41	370	30
Aluminum silicate	1.9	3	10	1.5
Beryllia (99% BeO)	2.9	34	240 min	21
Boron nitride	2.1	na	34–45	na
Cordierite	2.1–2.9	15	50	5.5
Magnesia	2.3–2.5	2–10	2–10	na
Porcelain	3.0	12.5	75	8.5
Quartz	2.7	na	na	na
Sapphire	4.0	na	450	60
Silica (fused)	2.0	1.5	5	na
Steatite	2.9	21	90	9
Zircon	3.6	4.6	27	2

*At room temperature

Note: Because of variance in composition and processing methods, the actual value for a specific material in the above table may vary significantly from the value shown.

na—not available.

Sources: Various.

Dielectric Properties

Dielectric strengths of most electrical grade ceramics are in the range of 100–400 volts per mil for 125 mil specimens. Dielectric constants are in the 4–10 range, with alumina near the high end of the range and fused silica at the low end. Dielectric constant values are often sensitive to temperature, and may rise, fall, or remain unaffected by temperature changes, depending on the type and density of the ceramic. The dissipation, or loss factor, also sensitive to temperature, is lowest for beryllia, followed by alumina.

Moisture accumulating on the surface or penetrating into the body of a ceramic significantly degrades all dielectric properties, and may also degrade mechanical properties via surface tension phenomena which can enhance crack propagation in highly stressed ceramics. Dust, or other deposits (as on transmission line insulators), worsens dielectric degradation and becomes conducting with high moisture content. Glazes reduce the ability of dust or other deposits to adhere to ceramic bodies and make their surfaces more washable, but they may incur significant power losses. Dielectric greases

have also been used to protect ceramic surfaces in contaminated environments, but greases often require periodic cleaning and replacement.

Values for dielectric properties of ceramics are shown in Table 15-10.

TABLE 15-10 Dielectric Properties of Electrical Insulating Ceramics

	DIELECTRIC STRENGTH 125 mils volts/mil* (ASTM D 149)	DIELECTRIC CONSTANT 1 MHz* (ASTM D 150)	DISSIPATION FACTOR 1 MHz* (ASTM D 150)
Alumina (99.9% Al_2O_3)	340	10.1	0.0002
Aluminum silicate	150	4.1	0.0027
Beryllia (99% BeO)	350	6.4	0.0001
Boron nitride	950	4.2	0.00034
Cordierite	200	4.8	0.0050
Magnesia	na	5.4	<0.0003
Porcelain	na	8.5	0.005
Quartz	na	3.8	0.0038
Sapphire	na	9.3–11.5	0.00003–0.000086
Silica (fused)	na	3.2	(0.0045 @ 10 GHz)
Steatite	230–390	5.5–7.2	0.0010
Zircon	na	5.0	0.0023

*At 25°C (77°F).

Note: Because of variance in composition and processing methods, the actual value for a specific material in the above table may vary significantly from the value shown.

na—not available.

Sources: Various.

SUMMARY OF PROPERTIES AND USES

Specific property values are shown in the preceding tables. The following are noteworthy features of the principal ceramics used for electrical insulation.

- *Alumina* has the highest mechanical properties throughout a wide useful temperature range. A dissipation factor of 0.0002 at 1 megahertz is among the lowest of all ceramics, although other dielectric properties are not outstanding. Thermal conductivity is relatively high and dimensional stability is excellent. Overall, alumina is one of the best ceramic insulations available. It is used to insulate spark plugs, for vacuum-tight seals to metal, and for a variety of electrical/electronic components.
- *Aluminum nitride* substrates and packages appeared in the late 1980s as an alternative to beryllium. This ceramic has high thermal conductivity, thermal expansion close to silicon, and excellent dielectric properties.
- *Aluminum silicate* is noted for its heat shock resistance, and also has one of the lowest dielectric constants (4.1 at 1 megahertz) of all ceramics. Mechanical properties are poor. It is used for specialized applications.

• *Beryllia* has the highest thermal conductivity and specific heat of any oxide ceramic. Machined parts can be held to a tolerance of ±0.0002 inch. Exceptionally high impact strength can be achieved by special processing. Dielectric strength is high and a dissipation factor of 0.0001 is even lower than alumina. Beryllia ceramics are used extensively for semiconductor packages, and for heat sinks, ceramic-to-metal seals, waveguide windows, radomes, and electrical/electronic components.

• *Boron nitride* is less brittle than most ceramics, has high thermal shock resistance, high thermal conductivity, and a very low rate of thermal expansion. Dielectric strength is outstanding and the dielectric constant is among the lowest for all ceramics. Mechanical strength and moisture resistance are low unless compounded with 40–60 percent silica. Uses include additives to other ceramics to increase thermal conductivity and reduce thermal expansion, transistor and rectifier mounting wafers, and nonabrading electronic parts.

• *Cordierite* has excellent heat shock resistance and fair dielectric properties. Mechanical strength is low. It is suitable for applications where heat shock is severe.

• *Diamond film* is a material of exceptionally good properties for electronics applications. It has a thermal conductivity five times higher than copper, making it a unique heat sink to reduce chip temperatures. Dielectric properties are among the best for most ceramics.

• *Magnesia* has the highest coefficient of thermal expansion of all ceramics. Dielectric properties are good, but mechanical properties are weak. Its main application is as insulation in sheathed heating units and thermocouples. A semiconductor grade is available.

• *Porcelain* is chemically inert and has satisfactory dielectric properties for applications at power frequencies, where it is widely used. Mechanical properties and thermal shock resistance are low. Glazed porcelain is used extensively for insulation on electrical transmission lines, circuit breakers, cutouts, and spark plugs. Low voltage uses include switches, bushings, fuse blocks, and light sockets.

• *Quartz* and fused silica possess the lowest dielectric loss properties of any inorganic material. Fused quartz is virtually immune to thermal shock. Thermal expansion is very low. The dissipation factor is among the lowest for ceramics. Physical properties are generally very low. Uses include radomes, nose cones, wave filters, and other electronic components.

• *Sapphire* has a single crystal surface desirable for integrated circuit and other electronic systems. A dielectric constant of 11.5 is the highest of all ceramics. High-temperature stability is excellent. Uses include electron and microwave tubes, and substrates for integrated circuits.

• *Steatite* has good dielectric properties, average mechanical properties, and poor thermal shock resistance. It can be fabricated to close tolerances. Die wear is low. It is suitable for making electronic components where mechanical properties are not demanding.

• *Zircon* ceramics offer improved mechanical and dielectric properties over other porcelains. Thermal shock resistance is also better. The material is abrasive and die wear is high. Uses include stand-off insulators, pole lightning arrestors, and applications requiring high arc resistance.

DEVELOPMENT PROGRAMS

Property values of ceramics are significantly affected by changes in the ratios of basic materials in the composition, sometimes with synergistic effects. Of promise is a blend of silicon carbide and beryllia which is being evaluated as an improved material for integrated circuits.

Development continues on polymer compounds as replacements for ceramics in general use as high-voltage transmission and distribution line insulators. In addition to being mechanically suitable, materials must have high resistance to forming carbonizing paths and to erosion under outdoor high-voltage service conditions. Surface degradation of polymer insulator is a combination of surface erosion and interaction with contaminants. Surface contamination is caused by industrial pollution, wind-blown agricultural chemicals, and salt fog along coastal regions. Contaminated surfaces tend to wet and erode readily. Eventual failure of the insulator is caused by flashover and/or tracking encouraged by wet, contaminated surfaces, as well as by imperfections incurred in the manufacture of the insulator.

Silicone rubber, one of the polymeric candidates for replacing ceramics, has inherently low arc resistance which, however, is improved to the acceptable level by addition of alumina trihydrate (ATH) fillers. Ethylene-propylene-diene copolymer (EPDM rubber) with ATH fillers is also being used to replace ceramic high-voltage power line insulators. ATH fillers may also be added to room-temperature-vulcanizing (RTV) silicone rubber dispersions as surface coatings for ceramic, fiberglass reinforced resin, ethylene-propylene rubber, and epoxy insulators to provide enduring water repellency. These coatings also have high resistance to corona and arcing, and are more permanent than greases which require reapplication.

Thus, the selection of a suitable polymer in preference to porcelain includes several criteria involving the environment to which the insulator will be exposed:

- Temperature range
- Prevailing humidity and rainfall
- Salt fog and mist
- Industrial pollutants and agricultural chemicals
- Corona attack
- Arcing

MARKET TRENDS

For electrical applications, ceramics will lose market share and volume as the acceptance and use of polymeric materials becomes widespread. Ceramics used in electronic devices and packages continue to keep pace with the dynamic growth of high-technology applications. Ceramics are especially important in meeting the military's needs for materials with long-term environmental stability. Japanese ceramics for electronic uses already dominate world markets, and will undoubtedly continue to provide formidable competition to United States manufactured products.

16

Dielectric Gases

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INTRODUCTION

The first gases used in the insulation of electrical equipment were air and its major constituent, nitrogen. These gases, however, possessed inherent limitations, and the need for gases with improved characteristics grew as the equipment requiring gaseous insulation became more complex and demanding. Answering this need, other gases were developed or adapted for use as dielectrics. Dielectric gases may be classified as follows:

- Simple gases—air, nitrogen, hydrogen, helium, oxygen
- Oxide gases—carbon dioxide, sulfur dioxide
- Hydrocarbon gases—methane, ethane, propane, butane, hexane
- Electronegative gases (all but SF_6 used mainly as refrigerants)
  - Sulfur hexafluoride (SF_6)
  - Dichlorodifluoromethane (CCl_2F_2, Freon 12, Genetron 12)
  - Chlorotrifluoromethane ($CClF_3$, Freon 13)
  - Carbon tetrafluoride (CF_4, Freon 14)
  - Chlorodifluoromethane ($CHClF_2$, Freon 22)
  - Chloropentafluoroethane (CF_3CF_2Cl, Freon 115)
  - Hexafluoroethane (CF_3CF_3, Freon 116)

Electronegative gases are gases with the ability to remove free electrons by negative ion formation, thereby increasing dielectric strength over gases which do not have this property, such as nitrogen and air. The principal electronegative dielectric gases are halides of sulfur and carbon. This chapter is primarily concerned with SF_6, the most widely used electronegative gaseous dielectric. Because of harmful effects on the ozone layer, chlorofluorocarbons (CFCs) will not be produced after 1995. Principal suppliers of electronegative gases include:

- AlliedSignal Corporation, SF_6 and halogenated hydrocarbons (Genetron™)
- Ashland Chemical, SF_6
- Du Pont, halogenated hydrocarbons (Freons™)

Conversion factors and formulas for frequently used units are shown in the Appendix.

TECHNOLOGY

Breakdown in Gases

In a dielectric gas subjected to low electric stress, there can be no current flowing between electrodes unless there are free electrons or ions present in significant numbers. However, a small quantity of charged particles caused by environmental radioactivity and cosmic radiation is always present, and as the electric field strength is increased, more collisions occur between electrons and gas molecules, creating additional charged particles. As this process proceeds, the gas becomes conductive at some point. It is characteristic of molecules of electronegative gases to attach free electrons before they cause conduction, which makes them the most effective dielectric gases.

An electron "avalanche" can occur if the field strength is high enough and if the free electrons are not captured by attachment. A single electron ionizes a gas molecule by collision, producing two free electrons and a positive ion. The two free electrons may then cause further ionization and more free electrons. This cumulative process eventually produces a swarm of electrons and ions, and the gas becomes conductive. Secondary avalanches may be produced at the cathode by the impact of positive ions or photons from an ongoing avalanche. These in turn initiate more avalanches, creating a self-sustaining discharge known as the Townsend theory of breakdown.

Another theory, the *streamer theory*, was developed to explain the breakdown of a gas where secondary processes are not a factor. According to this theory, there are two requirements for initiation and propagation of a streamer.

- The space charge produced in the avalanche causes sufficient distortion of the electric field that those free electrons move toward the avalanche head, generating further, cumulative avalanches.
- Photons from the avalanche head produce free electrons by photoionization.

This theory applies when the number of electrons in the average avalanche reaches a critical value, generally taken as 10^8.

The sudden occurrence of a voltage greater than the breakdown voltage of the system does not immediately result in dielectric failure. This time lag is caused by the interval between the application of voltage and the event of the first free electrons plus the time required for the avalanche to build from the initiating electrons to the point where dielectric breakdown occurs.

In essence, then, free electrons or negative ions from any source colliding with electronegative gas molecules can cause a dielectric breakdown when the rate at which electrons are produced exceeds the rate at which they are absorbed.

Paschen's Law

The dielectric strength of most electrical insulating gases follows Paschen's Law up to a pressure of about 150 psi, which includes pressures used in most applications. Factors that may cause significant deviations from the law are:

- Shape, surface condition, and material of electrodes
- Gap between electrodes
- Degree of purity of the gas
- Uniformity of the electrical field
- Extremes of temperatures and pressures

In brief, Paschen's Law states that over a certain pressure and temperature range in a uniform field, using parallel plate electrodes, the sparking potential of a gas depends on the product of gas pressure and electrode spacing:

$$V_s = f(pd)$$

where

V_s is the sparking potential,
p is the gas pressure at a given temperature,
d is the gap spacing, and
f is a function of pd only.

Paschen's Law is also sometimes stated as

$$V_s = f(Nd)$$

where N is the gas number density in molecules per cm^3.

The latter form of the law is useful in considering a scaled system such as a gas insulated cable or substation bus where pressure increases with temperature, but N remains constant, so the breakdown strength remains unchanged. Likewise, if the pressure is doubled (at constant temperature) and the gap spacing is halved, the breakdown voltage remains unchanged.

Above the pressure range where Paschen's Law applies, the breakdown voltage rises more slowly than the pressure. The law also does not apply at extremely low gas pressures approaching a perfect vacuum, where the reduced number of molecules severely limits ionization by collision, resulting in high dielectric strength. However, the engineering problems of maintaining a high vacuum preclude its use for most electrical equipment applications, except for electronic capacitors.

Because of the increased dielectric strength values obtainable, it is common practice to place a gas under pressure when it functions as a dielectric. However, a system should be designed so that liquefaction is not possible under foreseeable operating conditions plus a safety factor, since liquefaction acts to lower dielectric strength values and to promote instability and corrosion.

Electrode Condition and Configuration

The breakdown strength of most strongly electronegative gases is especially sensitive to conductor surface condition. Grooved, pitted, or roughened surfaces create nonuniform electrical fields and appreciably decrease dielectric breakdown strengths of gases below that for a uniform field gap. With practical electrode finishes, the dielectric strength of SF_6 is reduced by at least 50 percent of its theoretical value at 4 atmospheres pressure. Breakdown strength is also affected by dust, moisture, gas decomposition products, and other contaminants on the surfaces of electrodes.

The effect of electrode configuration is demonstrated for SF_6 by rapidly declining breakdown voltage with increasing pressure as the radius of the rod is decreased in a rod-plane electrode-type tester with gap and testing conditions remaining constant. In one study,[1] the breakdown voltage was over three times higher using a 5 mm radius with 20 mm gap versus using a 0.5 mm radius at 4 atmospheres pressure, although at 1 atmosphere pressure, breakdown values were not significantly different. Thus, different electrode configurations have different effects on space charge for-

[1]S. Sangkasaad, Doctor of Technical Sciences Dissertation, Swiss Federal Institute of Technology Diss. ETH No. 5738, Zurich, 1976.

mation and corona stabilization processes. While the physics of this phenomenon is not fully understood, it involves the ionic space charges produced when corona discharges occur from sharp points. This type of breakdown is usually referred to as *corona stabilized breakdown*.

Controlled insulating coatings on the electrodes can significantly increase breakdown strength by 25–50 percent, so that Paschen's Law will hold to higher pressures and field strengths than for bare electrodes.

The approved industry method for determining dielectric breakdown voltage is described in ASTM Standard D 2477, *Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Insulating Gases at Commercial Power Frequencies*. This method employs vertically mounted sphere and plane electrodes. The sphere shall be a precision steel ball bearing 0.75 inch (19.1 mm in diameter). The plane electrode shall be of brass 1.50 inches (38.1 mm) in diameter with rounded edges. The gap setting shall be 0.100 ± 0.001 inch (2.54 ± 0.025 mm). This procedure covers testing only under standard conditions of 760 torr and 25°C (77°F). There is no provision for testing under higher or lower pressures or temperatures. A formula is given for converting ambient to standard conditions:

$$\textit{Multiply ambient conditions by } F = (273 + T)/0.392P$$

where

T = ambient temperature, degrees C

P = gas pressure, torr.

Test results using this method are stated to be reproducible within acceptable limits for samples of the same gas tested in different laboratories under similar test conditions.

However, because of the considerable effect on dielectric breakdown of electrode test gaps, shapes, and surface irregularities, it is generally accepted practice to compare breakdown strengths of gases and gas mixtures with the breakdown strengths of nitrogen or SF_6 determined in the same test equipment under similar test conditions. Using this approach, mean breakdown strengths of selected dielectric gases and gas mixtures are shown in "Gas Mixtures" (p. 449) in this chapter. Three pure gases from this table have as high or higher dielectric strengths as SF_6, but their higher boiling points would prevent them from serving the full useful temperature range covered by SF_6.

	BREAKDOWN STRENGTH %	BOILING POINT °C	BOILING POINT °F
Chloropentafluoroethane, CF_3CF_2C1	114	–38.7	–37.7
Sulfur dioxide, SO_2	102	–10.0	+14.0
Dichlorodifluoromethane, $CC1_2F_2$	100	–29.8	–21.6
Sulfur hexafluoride, SF_6	100	–63.9	–83.0

Conducting Particles

The presence of free conducting particles in a gaseous insulating system may lead to reduction in dielectric strength and failure of the system. For example, the dielectric strength of SF_6 may be significantly reduced at higher gas pressures when conducting particles are present.[2] Conducting particles can be introduced during assembly or be produced by abrasion between components during assembly. These particles can be lifted by the electric field, and migrate to the conductor or insulators where they can initiate breakdown at voltages well below those of particle-free systems. It is reported that particle traps incorporating adhesive material in trap cavities offer effective protection against particle contamination, thus increasing reliability of the system.

Moisture

It is important to keep moisture in a system below a critical level determined by the minimal utilization temperature in order to avoid condensation on insulators.

CHEMISTRY

SF_6 is made by directly combining sulfur vapor with fluorine. Byproducts are removed by treatment with caustic, followed by heating to 400°C to break down large molecules of sulfur and fluorine to SF_4 and SF_6. A second scrubbing with caustic removes SF_4, but not SF_6, which does not react with caustic. SF_6 is then dried in a sulfuric acid tower to remove all traces of moisture, liquefied, and distilled to its high degree of purity.

Dichlorodifluoromethane is made by two methods:

- Reaction of carbon tetrachloride and anhydrous hydrogen fluoride in the presence of an antimony halide catalyst
- High-temperature chlorination of vinylidene fluoride (made by addition of hydrogen fluoride to acetylene).

GRADES

Only grades with the lowest moisture content are suitable for use as gaseous dielectrics. Commercially available SF_6 is supplied to these specifications:

Dew point	–60°C (–76°F)
Air as nitrogen, weight percent	0.04 maximum
Acidity as HF, weight percent	0.00003 maximum

[2]Steinar, J. Dale, and Melvin D. Hopkins, "Methods of particle control in SF_6 insulated CGIT systems," paper presented at the IEEE PES 1981 Transmission and Distribution Conference and Exposition, Minneapolis, MN, Sept. 20–25, 1981.

CF_4, weight percent	0.04 maximum
Oil, weight percent	0.0005 maximum
Toxicity	Nontoxic
Odor	None
Assay weight percent	99.9 minimum

ASTM STANDARDS FOR DIELECTRIC GASES

The American Society for Testing and Materials has developed the following standards for dielectric gases.

• D 1933, *Nitrogen Gas as an Electrical Insulating Material*. This specification covers three types of nitrogen used as an electrical insulating material in electrical equipment:

Type I, obtained from air by liquefaction processes and dried
Type II, obtained from air by liquefaction processes, deoxidized with hydrogen over a platinum catalyst and dried
Type III, obtained from air by liquefaction processes and, if necessary, deoxidized by suitable means.

The required characteristics for these types are shown in Table 16-1.

• D 2472, *Sulfur Hexafluoride*. Sulfur hexafluoride for use as an electrical insulation material shall conform to the requirements in Table 16-2.

In addition to the above requirements, the manufacturer shall be able to certify that the material is at least as nontoxic as Group VI of the Underwriters' Laboratories classification.

• D 3283, *Air as an Electrical Insulating Material*. Air used as an electrical insulation material shall conform to the requirements in Table 16-3.

TABLE 16-1 Composition and Properties for Nitrogen Dielectric Gas (ASTM D 1933)

	TYPE I	TYPE II	TYPE III
Nitrogen and rare gases, minimum volume %	99.8	98.998	99.993
Hydrogen, maximum volume %	0.0	1.0	0.005
Oxygen, maximum volume %	0.2	0.002	0.002
Dew point, maximum °F (°C)	−67 (−55)	−67 (−55)	−75 (−60)

*Corresponds to a water content of 8.9 ppm by weight or 71 ppm by volume.

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TABLE 16-2 Requirements for Sulfur Hexafluoride Dielectric Gas (ASTM D 2472)

	VALUE
Water content, maximum dew point, °F (°C)	–50* (–45)
Hydrolyzable fluorides, expressed as HF acidity maximum ppm by weight	0.3
Air, expressed as N_2, maximum weight %	0.05
Carbon tetrafluoride, maximum weight %	0.05
Molecular weight	146 ± 2%
Assay, minimum weight %	99.8

*Corresponds to a water content of 8.9 ppm by weight or 71 ppm by volume.

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TABLE 16-3 Composition and Properties for Air Dielectric Gas (ASTM D 3283)

	VALUE
Oxygen, volume %	19 to 23
Carbon monoxide, maximum volume %	0.0020
Carbon dioxide, maximum volume %	0.10
Nitrogen	balance
Dewpoint, maximum °F (°C)	–72 (–58)

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PROPERTIES

Important factors to be considered in evaluating gaseous dielectrics are:

- Degree to which the gas is electronegative as measured by electron affinity and electron capture
- Toxicity of a gas and its decomposition byproducts
- Formation of carbon deposits under arcing conditions
- Nonflammability
- Inertness
- Chemical stability
- Thermal stability
- Critical temperature
- Critical pressure

- Dielectric properties
- Heat transfer rate
- Compatibility with other materials used in electrical equipment
- Availability
- Price

Toxicity

Gases that are toxic to humans and that are hazardous to the environment are virtually ruled out from further consideration as dielectrics, however attractive their other properties. Table 16-4 lists the limits of worker exposure to selected gases as determined by NIOSH (see Chapter 19, *Government Activities*).

Thus, sulfur dioxide is high in toxicity, while SF_6 and dichlorodifluoromethane are much safer to use in work areas, although precautions must be taken even with these gases. The major problem of toxicity, however, occurs when gases are decom-

TABLE 16-4 Air Contaminants Limits of Worker Exposure (8 h Time-Weighted Averages)

GAS	PARTS/MILLION (volt) @ 25°C 760 mm MERCURY PRESSURE
Carbon dioxide	5,000
Sulfur hexafluoride	1,000
Freons 12, 13, 14, 22, 115, 116	1,000
Propane	1,000
n-Hexane	500
Sulfur dioxide	5

Source: NIOSH.

TABLE 16-5 Threshold-Limiting Values* of Potential Gaseous Decomposition Products of Sulfur Hexafluoride

GAS	PARTS/MILLION (vol) @ 25°C 760 mm MERCURY PRESSURE
Sulfuryl fluoride (SO_2F_2)	5
Hydrofluoric acid (HF)	3
Sulfur dioxide (SO_2)	2
Thionyl fluoride (SOF_2)	1.6
Silicon tetrafluoride (SiF_4)	0.6
Sulfur monofluoride (S_2F_2)	0.5
Thionyl tetrafluoride (SOF_4)	0.5
Sulfur tetrafluoride (SF_4)	0.1
Tungsten hexafluoride (WF_6)	0.1
Disulfur decafluoride (S_2F_{10})	0.01

*Concentration to which a worker can be safely exposed during a 40-hour week.

Source: American Conference of Governmental Industrial Hygienists.

posed by high temperatures or an electric arc. While simple gases, such as nitrogen, present no problem, more complex gases may form toxic byproducts when decomposed (as solid insulations may also do).

The most severe application for a dielectric gas is in circuit breakers. Scrubbers, incorporating soda lime (CaO and NaOH), or activated alumina (Al_2O_3), installed in breakers absorb small amounts of decomposition products, but when arcing or corona discharge cause equipment failure, large amounts of these products are formed. For example, SF_6 may decompose into a variety of toxic byproducts, usually through reaction with oxygen or water. The most common byproducts are sulfur dioxide, thionyl fluoride, and sulfuryl fluoride. The threshold limiting value (TLV) for each possible decomposition product is shown in Table 16-5.

Arcing

SF_6 is more stable in arcs than most other electronegative gases and, in fact, arcing does not lessen the dielectric strength of the gas. All halogenated hydrocarbons have carbon, a conductor, as a potential breakdown byproduct. Free carbon deposits from breakdown in fluorocarbon gases are decreased somewhat by the addition of SF_6 in concentrations of 20–30 percent, usually with improved dielectric strength.

Chemical and Thermal Stability

Along with low toxicity, dielectric gases should be inert, nonflammable, and be chemically and thermally stable over a wide useful temperature range. All the dielectric gases covered here, except the hydrocarbon gases, are considered unreactive, nonflammable, and chemically stable at room temperature and atmospheric pressure. Hydrocarbon gases are inherently flammable. For example, the closed cup flash points of propane and n-heptane are –104°C (–155°F) and –21°C (–5.8°F), respectively. Liquid propane, in fact, is widely used as a fuel.

All chemical compounds have temperature limits above which they are no longer chemically stable. The decomposition rates of dry SF_6 in contact with metals used in electrical equipment are shown in Table 16-6.

TABLE 16-6 Stability of Sulfur Hexafluoride in Selected Materials of Construction

	DECOMPOSITION %/year	
MATERIAL	@ 200°C	@ 250°C
Aluminum	—	0.006
Copper	0.18	1.4
Silicon steel	0.005	0.01
Mild steel	0.2	2

Source: Chemical Sector, AlliedSignal.

Decomposition rates increase significantly with higher concentrations of moisture and other contaminants.[3] A feature of nitrogen is its chemical stability at all operating temperatures to which electrical apparatus could be exposed. Tests by Du Pont indicate that under certain conditions, Freon 116 (C_2F_6) has somewhat higher thermal stability than SF_6. However, both gases exhibit significantly increased fluoride ion formation as moisture content rises, and this is the paramount factor in determining the thermal and electrical stability of both gases. There are difficulties in measuring moisture content, and different equipment can produce different results. Decomposition products can also affect the instrument probe sensitivity.

Thermal Properties

The cooling capacity of a dielectric gas in electrical apparatus depends on its specific heat, its specific thermal conductivity, and its convection characteristics. Specific heat at a given temperature and pressure is the amount of heat required to raise a unit weight of substance 1 degree of temperature at either constant pressure or constant volume. Since gases have extremely low densities compared with liquids and solids, specific heat values are usually not high enough to affect cooling capacity significantly.

Thermal conductivity is the quantity of heat passing in a unit time through a unit thickness of a substance across a unit area for a unit difference in temperature. The specific thermal conductivity of a gas rises with temperature and pressure, indicating improved ability to transfer heat as this occurs. Table 16-7 shows specific thermal conductivities for selected dielectric gases.

Convection characteristics, measured by viscosity, are the most important cooling mechanism for gases. The coefficient of viscosity of a material is defined as the tangential force per unit area of either of two horizontal planes at unit distance apart, one of which is fixed, while the other moves with a unit velocity, the space between being filled with the material to be tested. Thus, the higher the coefficient of viscosity, the poorer is the convection and dissipation of heat. Coefficients for gases increase with temperature (they decrease for liquids). Values for selected gases are shown in Table 16-8.

Critical Constants

Each gas has its own critical temperature above which it cannot be liquefied by pressure alone. The critical pressure of a gas is the minimum pressure under which a substance may exist in gas/liquid equilibrium at the critical temperature. Below the critical temperature, less pressure is required to maintain this equilibrium. Table 16-9 shows the critical constants for certain dielectric gases.

[3]R. J. Van Brunt, "Production rates for oxyfluorides, SOF_2, SO_2F_2, and SOF_4 in SF_6 corona discharges." *Journal of Research of the National Bureau of Standards*, vol. 90, no. 3, 1985.

TABLE 16-7 Specific Thermal Conductivities for Selected Dielectric Gases (At Normal Atmospheric Pressure)

	TEMPERATURE		Calories*/s/cm/°C for 1 cm^2
	°C	°F	
Helium (He)	26.7	80	360.4×10^{-6}
Oxygen (O_2)	26.7	80	63.6×10^{-6}
Nitrogen (N_2)	26.7	80	62.4×10^{-6}
Air	26.7	80	62.2×10^{-6}
Carbon dioxide (CO_2)	26.7	80	39.7×10^{-6}
Hexafluoroethane (CF_3CF_3)	25	77	36.5×10^{-6}
Sulfur hexafluoride (SF_6)	30	86	33.6×10^{-6}
Chloropentafluoroethane, Freon 115 (CF_3CF_2Cl)	25	77	33.1×10^{-6}
Chlorodifluoromethane, Freon 22 ($CHClF_2$)	26.7	80	28.1
Dichlorodifluoromethane, Freon 12, Genetron 12 (CCl_2F_2)	26.7	80	22.7
Sulfur dioxide (SO_2)	0	32	15.0

*One calorie is the amount of heat required at a pressure of 1 atm to raise the temperature of 1 g of water from 4°C to 5°C (where water has its greatest density).

Source: Handbook of Physics and Chemistry.

TABLE 16-8 Coefficients of Viscosity for Selected Dielectric Gases (At Normal Atmospheric Pressure)

	TEMPERATURE		
	°C	°F	POISES*
Sulfur dioxide (SO_2)	20	68	125×10^{-6}
Dichlorodifluoromethane, Freon 12 (Cl_2F_2)	25	77	130×10^{-6}
Chlorodifluoromethane, Freon 22 ($CHClF_2$)	25	77	130×10^{-6}
Chloropentafluoroethane, Freon 115 (CF_3CF_2Cl)	25	77	130×10^{-6}
Carbon dioxide (CO_2)	20	68	160×10^{-6}
Sulfur hexafluoride (SF_6)	25	77	161×10^{-6}
Air	20	68	181×10^{-6}
Nitrogen (N_2)	20	68	184×10^{-6}
Helium (He)	20	68	200×10^{-6}
Oxygen (O_2)	20	68	206×10^{-6}

*One poise is equal to 1 dyn · s/cm^2.

Source: Handbook of Physics and Chemistry, Lange's Handbook of Chemistry.

TABLE 16-9 Critical Constants for Selected Dielectric Gases

	CRITICAL TEMPERATURE °C (°F)	CRITICAL PRESSURE (atmospheres)
Helium (He)	−268.0 (−450.4)	2.26
Nitrogen (N2)	−147.1 (−232.3)	33.5
Air	−140.7 (−221.3)	32.2
Oxygen (O_2)	−118.4 (−202.5)	50.1
Carbon tetrafluoride (CF_4)	−45.7 (−50.3)	37.0
Hexafluoroethane (CF_3CF_3)	19.7 (67.5)	29.4
Chlorotrifluoromethane ($CClF_3$)	28.9 (84.0)	38.2
Carbon dioxide (CO_2)	31.1 (88.0)	73.0
Sulfur hexafluoride (SF_6)	45.6 (114.1)	37.2
Chloropentafluoroethane (CF_3CF_2Cl)	80.0 (176.0)	30.8
Chlorodifluoromethane ($CHClF_2$)	96.0 (204.8)	49.1
Dichlorodifluoromethane (CCl_2F_2)	112.0 (233.6)	40.6
Sulfur dioxide (SO_2)	157.5 (315.5)	77.9

Source: Handbook of Physics and Chemistry.

The estimated pressures required to liquefy SF_6 and hexafluoroethane at various temperatures are shown in Tables 16-10 and 16-11. The working pressure for many practical SF_6 systems is in the range of 3–5 atmospheres.

Boiling Temperatures

The boiling or sublimation temperature of a dielectric gas at normal atmospheric pressure should be well below the minimum temperature to which the equipment it insulates could be exposed. Otherwise, placing the gas under pressure would cause

TABLE 16-10 Pressures at Selected Temperatures Required to Liquefy SF_6

TEMPERATURE			
°F	°C	psi	atmospheres
−83	−63.9	14.7	1
−40	−40.0	33	2.2
−20	−28.9	57	3.9
0	−17.8	90	6.1
20	−6.7	130	8.8
40	4.4	180	12.2
60	15.6	260	17.7
80	26.7	330	22.4
100	37.8	430	29.3
114	45.6 (critical)	546	37.2

Source: Estimated from the Vapor Pressure Versus Temperature Chart, Chemical Sector, AlliedSignal, Technical Bulletin 524-003 AccuDri SF_6.

TABLE 16-11 Pressures at Selected Temperatures Required to Liquefy Hexafluoroethane

TEMPERATURE			
°F	°C	psi	atmospheres
–40	–40.0	80	5.4
–20	–28.9	125	8.5
0	–17.8	175	11.9
20	–6.7	240	16.3
40	4.4	300	20.4
60	15.6	400	27.2
67.4	19.7 (critical)	432	29.4

Source: Estimated from the Vapor Pressure Versus Temperature Chart, "Freon" Products Division, Du Pont, Product Information Bulletin EL-15, "Freon" 116 Dielectric Gas.

liquefaction. Table 16-12 lists the boiling or sublimation temperatures for selected gases with values of –10°C (14°F) or lower.

Most gas-insulated equipment is designed to allow a minimum temperature of –40°C (–40°F) without auxiliary heaters. Heaters may be required in circuit breakers for pressures above 5 atmospheres.

Dielectric Constant

The dielectric constant of all dielectric gases is generally accepted as 1.0, although values are actually slightly higher. The dielectric constant of SF_6 gas, for example, is reported as 1.002; for nitrogen and carbon tetrafluoride, the dielectric constant is 1.0006.

TABLE 16-12 Boiling or Sublimation Temperatures for Selected Dielectric Gases (At Normal Atmosphere Pressure)

	°C	°F
Helium (He)	–269.8	–453.8
Nitrogen (N_2)	–195.8	–320.4
Oxygen (O_2)	–183.0	–297.4
Carbon tetrafluoride (CF_4)	–128.0	–198.4
Chlorotrifluoromethane ($CClF_3$)	–81.4	–114.5
Carbon dioxide (sublimes) (CO_2)	–78.5	–109.3
Hexafluoroethane (CF_3CF_3)	–78.2	–108.8
Sulfur hexafluoride (sublimes) (SF_6)	–63.9	–83.0
Chlorodifluoromethane ($CHClF_2$)	–40.75	–41.35
Chloropentafluoroethane (CF_3CF_2Cl)	–38.7	–37.7
Dichlorodifluoromethane (CCl_2F_2)	–29.8	–21.6
Sulfur dioxide (SO_2)	–10.0	+14.0

Source: Handbook of Physics and Chemistry.

Since SF_6 is nonpolar, its dielectric constant does not vary with frequency. Pressure changes do, however, affect its dielectric constant. Over a pressure increase of 22 atmospheres, the increase in dielectric constant is about 7 percent.

Compatibility

Compatibility of components in electrical equipment is of paramount importance to its performance and longevity. Of at least equal consequences is the freedom of the system from moisture and impurities. Thus, performance characteristics of individual components do not always predict accurately the behavior of equipment in actual service. Therefore, it is prudent for a manufacturer to ensure a high degree of compatibility among components, and also the capability to assemble them into equipment free from moisture and other contaminants before settling on final specifications. This is usually not a problem for pure SF_6, since the gas is chemically inert at normal operating temperatures. Problems of compatibility arise only when the gas is decomposed by electrical discharge and forms reactive byproducts such as hydrogen fluoride and free fluorine.

Availability

SF_6, halogenated hydrocarbons, and nitrogen, the most commonly used dielectric gases, are readily available from two or more sources each. Although the price of SF_6 is relatively high compared with most other dielectric gases, its cost in equipment is usually 10 percent or less. Technologically it is still unsurpassed for most applications.

PROPERTIES OF SF_6

The basic properties of SF_6 which make it the preeminent dielectric gas may be summarized as follows:

- It suppresses carbonization.
- It is useful over the normal range of utility operating conditions.
- It has the best obtainable arc-interrupting properties.
- It has excellent dielectric properties.
- It is nontoxic and easy to handle.
- It is chemically inert.
- It has good heat transfer properties.
- It is highly electronegative.

Comparative properties of SF_6 with other gases are shown in the preceding tables. Table 16-13 shows specific properties of SF_6, the principal dielectric gas.

TABLE 16-13 Properties of Sulfur Hexafluoride (SF_6)

	VALUE
Physical	
Molecular weight	146.05
Sublimation temperatures at 1 atm °C	−63.9
°F	−83
Melting point at 32.5 psia °C	−50.8
°F	−59.4
Density at 21.1°C, 1 atm, g/L	6.139
at 70°F, 1 atm, lb/ft^3	0.382
Surface tension at −°20C, dyn/cm	8.02
Viscosity, centipoises	
liquid at 13.52°C (56.34°F)	0.305
gas at 31.16°C (88.08°F)	0.0157
Index of refraction at 0°C (32°F), 1 atm, n_D	1.000738
Critical temperature, °K	318.70
Critical pressure, bars	37.71
atmospheres	37.22
Critical volume, cm^3/g	1.356
Solubility at 1 atm	
in transformer oil at 27°C (80.6°F), mL SF_6/mL oil	0.408
in water at 24.85°C (76.73°F), cm^3 SF_6/cm^3 H_2O	0.0055
Solubility of water in SF_6, percent by weight	0.0097
Electrical	
Dielectric strength relative to nitrogen = 1 at 60 Hz–1.2 MHz	2.3–2.5
Dielectric constant at 25°C (77°F)	1.002
Loss tangent (tan δ) at 1 atm	$<2 \times 10^{-7}$
Thermodynamic	
Heat of sublimination, cal/gram · mol	5,640
Heat of fusion, cal/g · mol	1,200
Heat of vaporization at 70°F, Btu/lb	28.380
at 25°C, cal/g	15.767
Heat of formation at 25°C, kcal/g · mol	−291.77
Thermal conductivity at 30°C, cal/s · cm · °C	3.36×10^{-5}

Source: AlliedSignal Technical Bulletin *Sulfur Hexafluoride*.

GAS MIXTURES

Because of the relatively high cost of SF_6, its higher than desirable boiling point, and its sensitivity to surface imperfections on electrodes, there is a continuing search for dielectric gases that would provide satisfactory alternatives. Since no single gas appears to be an adequate replacement, the principal focus is on gas mixtures.[4]

Since SF_6 liquefies more readily than nitrogen, dispensing mixtures of these gases in correct proportions requires special precautions.

[4]EPRI Report EL.-2620, "Gases superior to SF_6 for insulation and interruption," 1982. 5 EPRI Report EL-2620 "Gases ect."

Table 16-14 shows breakdown strengths for selected gases in mixtures with SF_6.

TABLE 16-14 Mean Breakdown Strengths of Selected Dielectric Gases and Binary Gas Mixtures with SF_6 (SF_6 = 100)

GAS	FORMULA	UNMIXED	PERCENT OF GAS MIXED WITH SF_6		
			75	50	25
Chloropentafluoroethane	CF_3CF_2Cl	114	111	108	104
Sulfur dioxide	SO_2	102	111	116	108
Dichlorodifluoromethane	CCl_2F_2	100	108	107	106
Hexafluoroethane	CF_3CF_3	81	88	90	95
Chlorotrifluoromethane	$CClF_3$	58	78	88	95
Chlorodifluoromethane	$CHClF_2$	43	84	92	97
Carbon tetrafluoride	CF_4	42	63	78	89
Air	$N_2 + O_2$	37	78	85	94
Nitrogen	N_2	37	77	88	95
Carbon dioxide	CO_2	32	65	80	91

Source: Measurements are made in uniform fields using an aluminum sphere with radius 49 mm and a high-voltage plane electrode 26 mm in diameter. Gap is 5 mm and pressure is 0.15 MPa with ultraviolet radiation.

ELECTRICAL/ELECTRONIC USES

The principal application for SF_6 is in circuit breakers. These devices are used for current interruption in high-voltage equipment. Circuit breakers for 765 kV operation and with continuous ratings of up to 3,000 amperes are in service. As even higher voltages come into use, the advantages of SF_6 become more important. There is some replacement of oil or air circuit breakers with "puffer" breakers using SF_6. Typically, this type of breaker includes three cylindrical aluminum-interrupting modules containing SF_6 at a pressure of 75 psig. Within each module is mounted an epoxy filament-wound tube. A hydraulic or spring-driven mechanism opens and closes the breaker contacts and compresses the spring which provides the energy for opening the breaker. When the breaker is tripped, the arcing contacts part and the compressed gas flows along the arc until interruption occurs at ac current zero.

SF_6 is also the gaseous insulation for high-voltage coaxial power transmission lines with voltage ratings up to 765 kV for use above ground, underground, and underwater where their high cost is justified. These lines can be laid close together, requiring $^1/_{10}$–$^1/_{20}$ the space for conventional overhead air-insulated power lines.

Waveguides with SF_6 insulation can transport seven–ten times more microwave power than with air or nitrogen at the same pressure, or the same power as with air or nitrogen at lower pressure. Similarly, the ratings of both Van de Graaff and linear accelerators can be raised by using SF_6. The arc-extinguishing ability of SF_6 is also important in these applications.

SF_6 is used to insulate transmitter sections on large high-power radar installations such as AWACS.

Nitrogen is used primarily in liquid-filled transformers to prevent oxidation of the oils.

DEVELOPMENT PROGRAMS

There is growing interest in minisubstations, some of which are in operation in Europe and Japan. Because of its inherent properties, SF_6 insulated circuit breakers, transformers, cables, disconnect switches, and other equipment can be made more compact with these advantages:

- Much less land area would be needed for minisubstations
- Conventional substations are dangerous, unsightly, and in the open, whereas minisubstations can be installed inside structures, protected from the weather, pollutants, and vandalism.

Compact capacitor designs using SF_6 are under investigation.

A new application for SF_6 could be in high-voltage dc transmission systems.

Evaluation of gas mixtures continues with the aim of determining a mixture that would be technologically satisfactory and lower cost than pure SF_6. An 80% SF_6/20% N_2 mixture has nearly the same breakdown strength as pure SF_6 due to synergistic effects. There is interest in ternary mixtures composed of 40–60 percent nitrogen, 20–30 percent SF_6, and as much halocarbon gas as permissible without condensation under operating pressures and low temperatures and without formation of carbon under arcing conditions. Such a mixture, if technologically acceptable to industry, would significantly decrease gas cost versus 100 percent SF_6. For example, 50% N_2 + 40% SF_6 + 10% CCl_2F_2 has 85 percent the dielectric strength of SF_6 alone at approximately 40 percent of the cost of SF_6 alone. However, as noted earlier, the cost of gas is usually a small fraction of the cost of the equipment it insulates, and the use of chlorofluorocarbons is likely to be strictly regulated because of the effect they have on depleting ozone in the upper atmosphere.

MARKET TRENDS

It is likely that SF_6 will continue to be the predominant gaseous dielectric for the foreseeable future.

REFERENCES FOR FURTHER READING

- EPRI EL-2620, "Gases Superior to SF_6 for Insulation and Interruption," obtainable from Research Reports Center, Box 50490, Palo Alto, CA 94303 (contains numerous references on all aspects of subject), 1982.

- EPRI EL-1007, *Investigation of High-Voltage Particle-Initiated Breakdown in Gas-Insulated Systems* (obtainable as above), 1979.
- L. G. Christophorou et al., *Recent Advances in Gaseous Dielectrics*, from Conference Record of the 1984 IEEE International Symposium on Electrical Insulations, June 11–13, Montreal (obtainable from author, Oak Ridge National Laboratory, Oak Ridge, TN 37831).
- J. M. Meek and J. D. Craggs, *Electrical Breakdown of Gases*, John Wiley & Sons, ISBN 0-471-995533, 1979.
- E. Nasser, *Fundamentals of Gaseous Ionization & Plasma Electronics*, Wiley Interscience, ISBN 0-471-63056-X, 1971.
- R. J. Van Brunt and J. T. Herron, *Fundamental Process of SF_6 Decomposition in Glow and Corona Discharges*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, pp. 75–94, 1990.

17

Dielectric Liquids

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INTRODUCTION

Dielectric liquids have long served as electrical insulation for transformers, capacitors, cables, and switchgear. Some of the formerly widely used fluids, polychlorinated biphenyls (PCBs, askarels), are no longer available because of their toxicity and detrimental environmental effects (see "Toxic Substances Control Act," p. 516, in Chapter 19, *Government Activities*). Tetrachloroethylene (perchloroethylene) has also been banned by the Naval Facilities Engineering Command for use in transformers because of its toxicity. Consequently, fluids have been developed that do not have these problem properties, but which provide functionality for their specific uses. Thus, there is no single fluid type suitable for all applications, but rather, there is an assortment of fluids, each of which is tailored to a certain end use. Liquids now available include mineral (petroleum) oils, high-molecular-weight paraffinic oils, silicones, fluoropolymers, and other synthetic oils. Major producers include:

COMPANY	PRODUCT
Allco Chemicals	Dixylylethane (DXE)
Dow Corning	Silicones
Exxon	Mineral Oil (Univolt™)
General Electric	Silicones
Mobil Oil	Mineral Oil (Mobilect™)
RTE Corporation	High-Molecular-Weight Oils (RTEmp™), (Envirotemp™)
Texaco	Mineral Oil
Union Carbide	Silicones

TECHNOLOGY

The fundamental processes leading to breakdown in dielectric liquids are generally stated to be similar to breakdown in dielectric gases (see discussion in Chapter 16, *Dielectric Gases*). Briefly, breakdown is the cumulative process in which charged particles accelerated by an electric field produce additional charged particles through collision with neutral liquid molecules or atoms, resulting in a cascade multiplication of ions sufficient to conduct a current.

Because dielectric liquids come into contact with a variety of other insulating and metallic materials, as well as moisture and foreign particles introduced in the course of storage and equipment manufacture, the breakdown strength of a liquid in an installation is almost always significantly lower than that of a laboratory-tested pure sample. Particles may jump between electrodes. The charge that a particle acquires near one electrode causes it to be repelled toward the opposing electrode where it gives up its charge and is repelled back to the other electrode. In liquids contaminated with moisture or gases, operating temperatures can cause formation of bubbles around submicron sized particles, thus lowering dielectric properties.

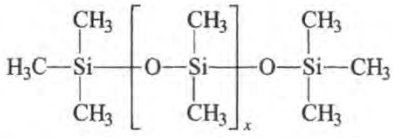
It is, therefore, of utmost importance that liquids and the equipment in which they are to be used be as free as possible from moisture and particle contamination for optimum performance.

For further reading on breakdown in liquids, see *Electrical Insulation*, A. Bradwell, Ed., Peter Peregrinus Ltd., London, UK, 1983.

CHEMISTRY

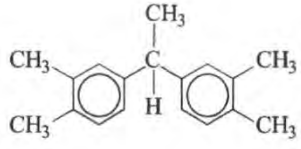
Historically, mineral insulating oils have been naphthenic-base products derived from petroleum. More recently, paraffinic-base oils of high molecular weight have become widely used, a development encouraged by the unavailability of PCBs. The exact composition of these oils is, however, highly complex and proprietary, depending on the petroleum source, degree and method of refining, additives, and many other factors. Oils containing principally saturated hydrocarbons are oxidized readily, but this may be controlled by addition of oxidation inhibitors. To reduce the volatile content and increase the fire point of mineral oils, special hydrogenation and stripping processes are employed, with a resultant increase in viscosity. The oxidation rate of conventional mineral oils may be slowed significantly by refining methods that leave in the oil some naturally occurring aromatic compounds while removing other aromatic compounds which promote oxidation and the formation of sludge.

Silicone dielectric liquids are polydimethylsiloxanes. These linear polymers have the general structure:



These liquids are characterized by narrower molecular weight distribution than mineral oils or askarels. They have volatile content of less than 0.5 percent, which permits operation at higher temperatures with a corresponding lower vapor pressure.

DXE (1,1-di(ortho-xylyl)ethane, dixylylethane) is a thermally stable aromatic alkane derived from petroleum with the structural formula:



GRADES

Mineral oils and silicone liquids with a wide range of viscosities are available. The most widely used new mineral oil products have viscosities at 40°C (104°F) of approximately 10 centistokes, and for silicone liquids, viscosities are approximately 40 centistokes (nominal 50 centistokes). The viscosity of high-molecular-weight mineral oil is much higher, about 130 centistokes. Conventional new mineral oils are available with

normal and greater oxidation resistance. DXE is available with a viscosity of 12.5 centistokes at 38°C (100°F).

PROCESSING

Too much emphasis cannot be placed on the importance of removing from dielectric liquids particulate contamination, water, and dissolved air. Cartridge filters with ratings of 5 microns (the largest size particle that can be passed) or less are generally sufficient for removing solids. Water, including free water, is more difficult to remove by filtration, as filter elements become saturated and the water is then dispersed in the liquid. This is evidenced by the liquid becoming milky. It is then necessary to allow the water to settle in a cool, dry environment. This water may then be removed by syphoning or draining. Remaining dissolved water is removed by filtration or vacuum degasification until dielectric measurements indicate the appropriate degree of purity has been reached. Dissolved gases are also removed by this process, which requires specialized equipment. The best procedures are based on exposure to vacuum of a thin layer of liquid over a large area. Of course, it is necessary to take equal precautions to decontaminate other components of the equipment in which it is installed, since upon final assembly, equilibrium of moisture and gas will occur in all materials.

SIGNIFICANCE OF FUNCTIONAL PROPERTIES OF MINERAL INSULATING OIL

The following properties specifically refer to mineral insulating oils, but apply in general to all dielectric oils.

Physical Properties

- Aniline Point—The lowest temperature at which equal volumes of aniline and the test liquid are miscible.
- Color—An increase in the color number during service is an indicator of deterioration of the oil.
- Flash Point—The safe operation of the apparatus requires an adequately high flash point.
- Interfacial Tension—A high value indicates the absence of undesirable polar contaminants.
- Pour Point—The lowest temperature at which the oil will just flow.
- Specific Gravity—Influences the heat transfer rate.
- Viscosity—Influences the heat transfer rate and, consequently, the temperature rise of apparatus. High viscosity affects the speed of moving parts, a major concern in cold climates.

• Visual Examination—Indicates the absence or presence of undesirable contaminants.

Dielectric Properties

• Dielectric Breakdown Voltage, 60Hz—Indicates the ability of the oil to resist breakdown at power frequencies in electrical apparatus.

• Dielectric Breakdown, Disk Electrodes—Used for assessing the quality of oil as received in tank cars, tank trucks, or drums.

• Dielectric Breakdown, VDE Electrodes—Verband Deutscher Elektrotechniker (VDE) Specification 0370 electrodes are spherically capped electrodes used to determine if a processed oil meets the minimum acceptable breakdown strength of new oils.

• Dielectric Breakdown Voltage, Impulse—Indicates the ability of an oil to resist electrical breakdown under transient voltage stresses (lightning and switching surges).

• Power Factor (Dissipation Factor)—Measures the dielectric losses in an oil. A low value indicates a low level of soluble contaminants.

Chemical Properties

• Oxidation Inhibitor Content—Oxidation inhibitor added to mineral oil retards the formation of oil sludge and acidity under oxidative conditions.

• Corrosive Sulfur—The absence of elemental sulfur and thermally unstable sulfur-bearing compounds is necessary to prevent the corrosion of metals such as copper and silver in contact with the oil.

• Water Content—A low water content of the oil is necessary to achieve adequate dielectric strength and low dielectric loss characteristics, to maximize the insulation system life, and to minimize metal corrosion.

• Neutralization Number—A low total acid content of oil is necessary to minimize electrical conduction and metal corrosion and to maximize the useful life of the insulation system.

• Oxidation Stability—The development of oil sludge and acidity resulting from oxidation during storage, processing, and long service life should be held to a minimum in order to minimize electrical conduction and metal corrosion, to maximize insulation system life and electrical breakdown strength, and to ensure satisfactory heat transfer.

• Gassing—The gassing tendency of oil is a measure of the rate of absorption or desorption of hydrogen into or out of the oil under prescribed conditions.

ASTM STANDARDS FOR DIELECTRIC LIQUIDS

The American Society for Testing and Materials has developed the following standards for dielectric liquids:

Specifications

- Silicone fluids—D 2225
- Polybutene oil for capacitors—D 2296
- Mineral oils for electrical apparatus—D 3487
- Chlorinated aromatic hydrocarbons (Askarels) for capacitors—D 2233
- Chlorinated aromatic hydrocarbons (Askarels) for transformers—D 2283

Test Methods

- Petroleum-based oils—D 117
- Synthetic fluids for capacitors—D 3809

- D 117, *Electrical Insulating Oils of Petroleum Origin*. This standard describes methods of testing and specifications for oils of petroleum origin intended for use as dielectrics or heat transformer media in electrical cables, transformers, oil circuit breakers, capacitors, and other electrical apparatus. Table 17-1 lists the test methods.

TABLE 17-1 Property Tests and Test Methods for Dielectric Oils of Petroleum Origin (ASTM D 117)

PROPERTY MEASURED	ASTM METHOD
PHYSICAL	
Aniline point	D 611
Coefficient of thermal expansion	D 1903
Color	D 1500
Examination	D 1500
	D 1524
Flash and fire point	D 92
Interfacial tension	D 971
	D 2285
Molecular weight	D 2224
Pour point	D 97
Refractive index	D 1218
	D 1807
Sampling	D 923
	D 2759
	D 3613
Specific gravity	D 287
	D 1298
	D 1481
Steam emulsion	D 1935
Viscosity	D 88
	D 445
	D 2161
ELECTRICAL	
Dielectric breakdown voltage	D 877
	D 1816
	D 3300

(continued)

TABLE 17-1 (*Continued*)

PROPERTY MEASURED	ASTM METHOD
Gas evolution	D 2298
	D 2300
Power factor	D 294
Resistivity	D 1169
CHEMICAL	
Acidity, approximate	D 1534
	D 1902
Carbon-type composition	D 2140
Characteristic groups	D 2007
Compatibility with construction materials	D 3455
Copper content	D 2608
	D 2675
Gas analysis	D 3612
Gas content	D 831
	D 1827
	D 2945
Inorganic chlorides and sulfates	D 878
Neutralization number	D 664
	D 974
Oxidation inhibitor content, phenolic	D 2668
Oxidation stability	D 1313
	D 1934
	D 2112
	D 2440
Peroxide number	D 1563
Saponification number	D 94
Sediment and soluble sludge	D 1698
Sulfur, corrosive	D 1275
Water content	D 1533
SPECIFICATIONS	
Transformer and circuit breaker oils	D 3487

• D 2225, *Silicone Fluids Used for Electrical Insulation*. This standard covers the testing of silicone fluids for use in transformers, capacitors, and electronic assemblies as an insulating or cooling medium. Table 17-2 lists the test methods.

• D 2296, *Continuity of Quality of Electrical Insulating Polybutene Oil for Capacitors*. This specification provides the limits within which the properties of Type D27-3000-1 electrical insulating polybutene oil for capacitors shall conform in order to ensure an unvarying continuity in the quality and grade of oil supplied. Requirements for this type oil are shown in Table 17-3. ASTM test methods are listed in D 117.

• D 3487, *Mineral Insulating Oil Used in Electrical Apparatus*. This specification applies only to new insulating oil as received prior to any processing. It covers mineral oil of petroleum origin for use as an insulating and cooling medium in new and existing power and distribution electrical apparatus, such as transformers, regulators, reactors, circuit breakers, switch-gear, and attendant equipment. This oil should be functionally interchangeable and miscible with existing oils. Two types of this oil are designated:

TABLE 17-2 Property Tests and Test Methods for Silicone Dielectric Fluids (ASTM D 2225)

PROPERTY MEASURED	ASTM METHOD
PHYSICAL	
Color	D 2129
Flash point	D 92
Fire point	D 92
Pour point	D 97
Refractive index	D 1807
Specific gravity	D 1298
Volatility	
Viscosity	D 445
CHEMICAL	
Neutralization number	D 974
Water content	
ELECTRICAL	
Dielectric constant	D 924
Dielectric breakdown voltage	D 877
Power factor	D 924
Specific resistance	D 1169
Compatibility	D 3455

TABLE 17-3 Requirements for Type D-27-3000-1 Polybutene Oil (ASTM D 2296)

PROPERTY	REQUIREMENTS
PHYSICAL	
Specific gravity, maximum, 15.6/15.6°C (60/60°F)	0.890
Pour point, maximum	10°C (50°F)
Flash point, minimum	218°C (425°F)
Viscosity: kinematic, centistokes at 100°C (212°F)	600–771
Color, maximum	1
Water content as shipped, ppm	40
CHEMICAL	
Chlorine, maximum, ppm	40
Inorganic chlorides and sulfates	none distinguishable
Neutralization number, maximum, mg KOH/g	0.04
Sulfur, corrosive	noncorrosive
ELECTRICAL	
Dielectric breakdown, min. kV at 25°C (77°F), 0.10 in gap	35 (ASTM D 877)
Power factor, 60 Hz, maximum at 100°C (212°F)	0.0003
Resistivity, minimum, $10^{12}\ \Omega \cdot$ cm at 100°C (212°F)	50
AGING TESTS (AFTER HEATING 96 h at 115°C (239°F)	
Color, maximum	1.5
Neutralization number, maximum, mg KOH/g	0.04
Power factor, 60 Hz, maximum at 100°C (212°F)	0.0005
Resistivity, minimum, $10^{12}\ \Omega \cdot$ cm at 100°C (212°F)	10

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Type I Mineral Oil—an oil for apparatus where normal oxidation resistance is required.

Type II Mineral Oil—an oil for apparatus where greater oxidation resistance is required.

Requirements for these oils are shown in Table 17-4.

Table 17-4 Requirements for Type I and Type II Mineral Oils (ASTM D 3487)

PROPERTY	LIMIT		ASTM METHOD
	TYPE I	TYPE II	
PHYSICAL			
Aniline point °C	63–84	63–84	D 611
Color, maximum	0.5	0.5	D 1500
Flash point, minimum °C	145	145	D 92
Interfacial tension at 25°C, minimum, dyn/cm	40	40	D 971
Pour point, maximum, °C	–40	–40	D 97
Specific gravity, 15/15°C maximum	0.91	0.91	D 1298
Viscosity, maximum, centistokes			D 445 or
at 100°C	3.0	3.0	D 88
at 40°C	12.0	12.0	
at 0°C	76.0	76.0	
Visual examination	clear, bright	clear, bright	D 1524
ELECTRICAL			
Dielectric breakdown voltage at 60 Hz, 25°C			
disk electrodes, minimum kV, 0.10 in gap	30	30	D 877
VDE electrodes, minimum kV			D 1816
0.040 in (1.02 mm) gap	28	28	
0.080 in (2.03 mm) gap	56	56	
Dielectric breakdown, impulse conditions			D 3300
25°C, minimum, kV, needle negative to sphere grounded, 1 in (25.4 mm gap)	145	145	
Power factor, 60 Hz, maximum percent			D 924
at 25°C	0.05	0.05	
at 100°C	0.30	0.30	
CHEMICAL			
Oxidation stability (acid-sludge test) 72 h			D 2440
percent sludge, maximum, by mass	0.3	0.2	
total acid number, maximum, mg KOH/g	0.6	0.4	
Oxidation stability (rotating bomb test) minimum, minutes	—	195	D 2112
Oxidation inhibitor content, maximum, percent by mass	0.08	0.3	D 1473
Sulfur, corrosive	noncorrosive	noncorrosive	D 1275
Water, maximum, ppm	35	35	D 1533
Neutralization number, total acid number, maximum, mg KOH/g	0.03	0.03	D 974

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• D 3809, *Synthetic Dielectric Fluids for Capacitors*. This standard covers testing synthetic dielectric fluids in use for capacitors. Table 17-5 lists the test methods.

• D 2233, *Chlorinated Aromatic Hydrocarbons (Askarels) for Capacitors*. This specification covers synthetic nonflammable liquids of the chlorinated aromatic type used as a dielectric and cooling medium in capacitors. Included are liquids that were previously available and are still in use. Four types are identified:

Type A—biphenyl with chlorine content of 42 percent by weight
Type B—biphenyl with chlorine content of 54 percent by weight
Type C—a mixture of approximately 70 percent Type B and 25 percent trichlorobenzene
Type D—The same as Type A, except with higher boiling homologs removed to a maximum of 0.4 percent.

Detailed requirements for these askarels are listed in this standard.

• D 2283, *Chlorinated Aromatic Hydrocarbons (Askarels) for Transformers*. This specification covers synthetic nonflammable liquids of the chlorinated aromatic type used as a dielectric and cooling medium in liquid-filled transformers. Eight types are identified:

Type A—50 percent hexachlorobiphenyl chlorinated to a chlorine content of 60 percent by weight, 40 percent trichlorobenzene isomers, plus 0.18–0.22 percent phenoxypropene oxide
Type B—45 percent hexachlorobiphenyl chlorinated to a chlorine content of 60 percent by weight, 55 percent blend of trichlorobenzene and tetrachlorobenzene, plus 0.115–0.135 percent diepoxide-type compound
Type C—80 percent trichlorobiphenyl chlorinated to a chlorine content of 42 percent by weight, 20 percent blend of trichlorobenzene and tetrachlorobenzene, plus 0.115–0.135 percent diepoxide-type compound

TABLE 17-5 Property Tests and Test Methods for Synthetic Dielectric Fluids for Capacitors (ASTM D 3809)

PROPERTY MEASURED	ASTM METHOD
PHYSICAL	
Coefficient of thermal expansion	D 1903
Flash point	D 92
Pour point	D 97
Refractive index	D 1218
Specific gravity	D 1298
Viscosity	D 445
CHEMICAL	
Acid number	D 664
Water content	D 1533
ELECTRICAL	
Dielectric constant	D 924
Dielectric strength	D 877
Power factor	D 924

Type D—70 percent pentachlorobiphenyl chlorinated to a chlorine content of 45 percent by weight, 30 percent trichlorobenzene isomers, plus 0.18–0.22 percent oxide

Type E—100 percent trichlorobiphenyl plus 0.18–0.22 percent phenoxypropene oxide by weight

Type F—45 percent pentachlorobiphenyl chlorinated to a chlorine content of 45 percent by weight, 55 percent blend of isomers of trichlorobenzene and tetrachlorobenzene, plus 0.115–0.135 diepoxide-type compound

Type G—60 percent pentachlorobiphenyl chlorinated to a chlorine content of 45 percent by weight, 40 percent trichlorobenzene isomers, plus 0.115–0.135 percent diepoxide-type compound

Type H—100 percent blend of isomers of trichlorobenzene and tetrachlorobenzene, plus 0.10–0.135 percent diepoxide compound. This type does not contain biphenyls.

The diepoxide-type compound in the above formulations is 3,4-epoxycyclohexylmethyl-3,4-epoxycyclohexane carboxylate.

Detailed requirements for these askarels are listed in this standard.

Current governmental regulations prohibit the manufacture and sale of askarels except Type H. The information in D 2233 and D 2283 is being maintained as a reference for those units still in service. (The EPA document regulating PCBs in effect in 1994 is *40 CFR Part 761* (July 1, 1991 Edition).)

PROPERTIES

There are several factors to be considered which vary in importance with each application:

- Toxicity
- Nonflammability (or high flash and fire points)
- Purity
- Inertness
- Chemical stability
- Thermal stability
- Dielectric characteristics
- Heat transfer rate
- Compatibility with other materials in electrical equipment
- Availability
- Price

Toxicity

With the exception of PCBs and tetrachloroethylene, widely used dielectric liquids are essentially nontoxic. Decomposition products, however, may have varying amounts of toxicity, but this is generally not a deterrent to their use. Some proposed chlorinated

substitutes for PCBs, such as tetrachloroethylene, are, however, considered toxic by the National Institute of Occupational Safety and Health and the Clean Water Act, and this has slowed their adoption. Trichlorotrifluoroethane is thought to be potentially detrimental to the atmospheric ozone layer.

Flammability

Flammable liquids are defined by the National Fire Protection Association and the Department of Transportation (DOT) as those having a flash point below 100°F (37.7°C) (closed cup) and a vapor pressure of not over 40 psia at 100°F. The term "noncombustible" (often confused with "nonflammable") refers to any substance that will not burn, such as highly halogenated liquids. Even these liquids, however, when decomposed by arcing, may form highly flammable products. The applicable standard approved by Underwriters Laboratories is UL 340, *Tests for Comparative Flammability of Liquids*.

Except in low-risk, isolated areas, flammability is a major concern in selecting a dielectric liquid. Silicone oils and highly refined high-molecular-weight paraffinic oils, with fire points of 600°F (315°C) or over, have low flammability. The1981 National Electric Code, Article 450-23 states: "Transformers insulated with less-flammable liquids shall be permitted to be installed without a vault in noncombustible occupancy areas of noncombustible buildings, provided there is a liquid confinement area and the liquid is listed as having a fire point of not less than 300°C (572°F)."

Purity, Inertness, and Chemical and Thermal Stability

A high degree of purity, inertness, and chemical and thermal stability is necessary if a dielectric liquid is to withstand long service without deterioration. Commercially available products of all types have a high degree of purity when shipped as mandated by ASTM standards. Of the most widely used liquids, silicones are the most stable. They begin to break down thermally at temperatures over 450°F (230°C), with formation of more volatile cyclic silicone compounds. Silicone transformer liquid will begin to oxidize slowly with oxygen present at temperatures over 175°C (347°F). As it oxidizes, it gradually polymerizes, increasing in viscosity until gelation occurs. No harmful acids or sludges are formed, and dielectric properties remain stable. In service, no degradation takes place over the useful service life of a 65°C (149°F) rise or a 110°C (230°F) rise transformer.

Mineral oils without inhibitor oxidize readily in the presence of oxygen with the formation of sludge and acidity. This tendency may be slowed by addition of an oxidation inhibitor, such as 2,6-ditertiary-butyl paracresol. High-molecular-weight paraffinic fluids oxidize at a much slower rate than conventional mineral oils. Equipment may also be designed to minimize the effects of oil oxidation. Transformers can be designed to limit the supply of air in contact with the oil. Another effective measure is to blanket the liquid with an inert gas, such as nitrogen.

The oxidation rate of all mineral oils is increased with increasing temperature. An often used rule of thumb is that the rate of oxidation is doubled for each increase of

10°C (18°F). In equipment containing mineral oil, commonly used metals, such as copper, iron, and lead, act as catalysts to further increase the oxidation rate of the oil. The effect is different for each metal and its concentration, and depends on the amount of available oxygen, being insignificant where the supply of oxygen is severely limited.

Arcing

Both silicones and mineral oils evolve flammable gases under high current arcing, and can produce a flash or fireball under catastrophic failure conditions. Arcing gases from both liquids include hydrogen (the major gas), nitrogen, methane, oxygen–argon, carbon monoxide, with traces of ethylene, acetylene, and carbon dioxide. When decomposed by arcing, halogenated compounds form toxic and corrosive products which attack cellulosics. The energies involved in arcing determine how the evolution of gases develops.

Water Content

Liquids may be exposed to water during shipment and storage, as well as during the manufacture of electrical equipment when liquids may come into contact with materials containing relatively high moisture content. However, it is essential that the moisture content of dielectric liquids be kept to a minimum. Otherwise, moisture will react with other contaminants, accelerating chemical and dielectric degradation of the liquid. When excess moisture is present, water may separate from the liquid at low temperatures with formation of emulsions and significant reduction in dielectric values. Table 17-6 lists water content specification maximum limits for widely used dielectric liquids. The delivered liquids are usually much lower in water content.

Dielectric Properties

The dielectric breakdown voltage of a liquid at commercial power frequencies is influenced by the following factors:

- Shape, area, surface condition, and material of the electrodes
- Spacing between electrodes

TABLE 17-6 Water Content Maximum Limits in Specifications for Typical Dielectric Liquids (Determined by ASTM D 1533)

	ppm WATER
New mineral oil	25
High molecular weight mineral oil	15
Silicone fluid	50
DXE	300 max

Sources: Manufacturers' data sheets.

- Length of time for which the liquid is under electrical stress
- Temperature of the liquid
- Degree of purity
- Concentration of dissolved gases and gassing tendency.

In designing apparatus containing liquid dielectrics, ample allowance should be made for the cumulative and, in some cases, interacting effects of the above factors. The insulation systems of transformers, cables, and capacitors often include paper and other cellulosic and absorbant materials with greater affinity for water than have dielectric liquids. Thus, dielectric systems must establish moisture equilibrium before dielectric measurements can be meaningful.

Because dielectric measurements among manufacturers are often made under different test conditions in key matters such as test methods employed, electrode types and spacings, frequencies used, moisture content, degree of purity, etc., it is difficult to compare dielectric values among insulating liquids. The most meaningful comparisons are those made on complete systems, although as a practical matter, end use conditions often dictate the liquid to be used. For widely used products, dielectric values for dry, filtered, and degassed transformer liquids fall within the ranges shown in Table 17-7.

A noteworthy feature of all liquid dielectrics is their self-healing properties after dielectric breakdown, as the device containing the liquid is immediately reinsulated by liquid flow.

Heat Transfer Rate

The suitability of a dielectric liquid as a cooling medium is determined by its heat transfer properties, namely:

- Viscosity (resistance to flow)
- Density (weight per unit volume)
- Thermal conductivity (the quantity of heat passing in a unit time through a unit thickness of a substance across a unit area for a unit difference in temperature)
- Specific heat (the ratio of the quantity of heat required to raise the temperature of a body 1 degree to that required to raise the temperature of an equal mass of water 1 degree)

TABLE 17-7 Dielectric Properties of Typical Dielectric Liquids for Transformers

	ASTM METHOD	TEMPERATURE	RANGE
Dielectric strength, 0.080 gap, kV	D 1816	25°C (77°F)	56–60
Dielectric constant, power frequencies	D 924	25°C (77°F)	2.2–2.7
Volume resistivity, Ω · cm	D 1169	25°C (77°F)	1×10^{13} 1×10^{15}

• Coefficient of thermal expansion (the ratio of the increase in volume of a liquid for a unit rise in temperature to the original volume).

For optimum heat transfer, the viscosity of a liquid should be as low as possible, and other property values should be as high as possible. The thermal properties of widely used dielectric liquids are shown in Tables 17-8 to 17-13.

TABLE 17-8 Viscosities and Pour Points of Typical Transformer Dielectric Liquids (ASTM D 445)

	CENTISTOKES			
	0°C (32°F)	40°C (104°F)	100°C (212°F)	POUR POINT
New mineral oil	55	9	2.3	–45°C (–49°F)
High-molecular-weight mineral oil	—	130	13	–24°C (–11°F)
Silicone	95	38	16	–55°C (–67°F)
DXE	—	13	—	–34°C (–30°F)

Sources: Manufacturers' data sheets.

TABLE 17-9 Densities of Typical Transformer Dielectric Liquids (ASTM D 1298)

	TEMPERATURE	g/cm^3
New mineral oil	15°C (59°F)	0.91
High-molecular-weight mineral oil	25°C (77°F)	0.87
Silicone fluid	25°C (77°F)	0.96
Trichlorotrifluoroethane	25°C (77°F)	1.42
Tetrachloroethylene	25°C (77°F)	1.63
DXE	16°C (60°F)	0.98

Sources: Manufacturers' data sheets.

TABLE 17-10 Thermal Conductivities of Typical Transformer Dielectric Liquids

	TEMPERATURE	cal/s cm2 °C/cm
New mineral oil	25°C (77°F)	3.5×10^{-4}
High-molecular-weight mineral oil	25°C (77°F)	3.1×10^{-4}
Silicone fluid	25°C (77°F)	3.6×10^{-4}
DXE	—	1.2×10^{-4}

Sources: Manufacturers' data sheets.

TABLE 17-11 Specific Heats of Typical Transformer Dielectric Liquids

	TEMPERATURE	cal/g/°C
New mineral oil	25°C (77°F)	0.53
High-molecular-weight mineral oil	25°C (77°F)	0.46
Silicone fluid	25°C (77°F)	0.36
DXE	260°C (500°F)	0.63

Sources: Manufacturers' data sheets.

TABLE 17-12 Coefficients of Thermal Expansion of Typical Transformer Dielectric Liquids (ASTM D 1903)

	TEMPERATURE	$cm^3/cm^3/°C$
New mineral oil	na	na
High-molecular-weight mineral oil	25°C (77°F)	0.0007
Silicone fluid	25°C (77°F)	0.0010
DXE	25°C (77°F)	0.00063

Sources: Manufacturers' data sheets.

TABLE 17-13 Flash and Fire Points of Typical Transformer Dielectric Liquids (ASTM D 92)

	FLASH POINT °C (°F)	FIRE POINT °C (°F)
New mineral oil	145 (293)	na
High-molecular-weight mineral oil	284 (543)	312 (594)
Silicone fluid	300 (572)	315 (600)
DXE	163 (325)	193 (380)

Sources: Manufacturers' data sheets.

Compatibility

Liquids that have achieved wide usage as dielectrics are, of necessity, compatible with most other materials used in the construction of electrical equipment, for example, cellulose and polyamide papers, films, wire enamels, varnishes, mica products, wood, and metals. However, care is needed in selecting seal and gasket materials, and testing is required to ensure compatibility. Contact of silicone liquids with silicone rubber gaskets, silicone rubber wire coverings, and other silicone materials should be avoided. Silicone rubber and silicone transformer liquid are chemically similar, and the liquid is readily absorbed into the rubber, causing it to swell and lose physical properties. Silicone liquids also tend to leach plasticizers from natural and synthetic rubber compounds, causing an increase in hardness and loss of effectiveness as gasket materials. Where replacement of

PCB liquids is required, only liquids designated as suitable should be considered, for example, high-molecular-weight paraffinic oils or certain silicone oils.

Availability and Price

Dielectric liquids of the types discussed in this chapter are available from several sources as noted. Where specifications and circumstances permit consideration of alternative liquids, price is the predominant factor. Conventional mineral oil is by far the lowest in price, and silicone liquids are the most expensive. High-molecular-weight paraffinic oils, although not as expensive as silicone liquids, are much higher in price than conventional mineral oils. It is important, however, to consider the total cost of an installation. In some cases, when there are alternatives, the lower cost of conventional mineral oil may be more than offset by requirements for vaults and fire protection equipment not necessary when less-flammable, higher-price liquids are used.

ELECTRICAL/ELECTRONIC USES

Mineral oil is used extensively in electrical equipment that is often nitrogen blanketed, such as distribution and substation transformers. It is also used in low- and high-pressure cable systems, and in capacitors, regulators, circuit breakers, and switchgear in isolated areas or where its flammability does not present a hazard. It is interchangeable and miscible with other dielectric oils.

High-molecular-weight paraffinic oils are used primarily in transformers and load break switchgear. They are also suitable as make-up fluids replacing askarels. They are less flammable than conventional mineral oils, and can be used with fewer precautions than are required of conventional oils.

Silicone liquids are used in small and medium transformers, capacitors, and other apparatus primarily because of their high-temperature properties, low volatility, and their resistance to oxidation and sludge formation.

Polybutene liquids are of generally high purity and have excellent dielectric characteristics, making them suitable for use in capacitors. They are also used as paper impregnants and as pipe oils.

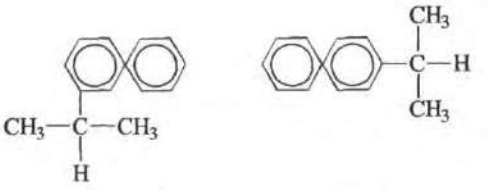
Fluoropolymers are used as convective or evaporative dielectric coolants, where they are up to 100 times as effective as mineral oil in free convection. They are also used in applications where nonflammability is required.

DXE is used as a heat transfer and dielectric liquid in transformers.

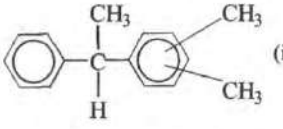
NEW CAPACITOR DIELECTRIC LIQUIDS

There have been intensive efforts to evaluate alternatives to traditional capacitor dielectric fluids (askarels, mineral oils, silicones). It has been found[1] that highly aromatic fluids give the best high-voltage results. Two of the most promising products are:

[1]R. L. Miller, L. Mandelcorn, and G. E. Mercier, *Evaluation of Capacitor Impregnants*, paper presented at the Conference on the Properties and Applications of Dielectric Materials, Xian, China, June 24–28, 1985. Reprint, Westinghouse R&D Center, Pittsburgh, PA 15235.



isopropylbiphenyl (Westinghouse's "Wemcol™")



(isomer mixture)

phenylxylyl ethane (Nippon Oil's "PXE™")

The aliphatic groups in these products contribute low-temperature fluidity and low-vapor pressure. However, since aliphatic groups tend to be susceptible to high-voltage effects, the optimum percentage of aliphatic carbons appears to be in the 15–25 percent range. Key properties of Wemcol and PXE are shown in Tables 17-14 and 17-15.[2]

[2]Ibid.

TABLE 17-14 Physical Properties of Two Newer Capacitor Fluids

		CENTISTOKES			
	DENSITY	−50°C (−55°F)	25°C (77°F)	100°C (212°F)	POUR POINT
Wemcol	0.99	11,000	7.0	1.4	−50°C (−58°F)
PXE	0.98	23,000	6.5	1.6	−45°C (−49F)

TABLE 17-15 Dielectric Properties of Two Newer Capacitor Fluids

	DIELECTRIC CONSTANT		DISSIPATION FACTOR		BREAKDOWN VOLTAGE, kV (ASTM D 877)
	25°C (77°F)	100°C (212°F)	25°C (77°F)	100°C (212°F)	
Wemcol	2.6	2.5	0.02	0.02	60
PXE	2.6	2.5	0.02	0.03	60

DEVELOPMENT PROGRAMS

Better dielectric mineral oils are under development through improvements in refining method, degree of refining, and antioxidants, as well as in evaluation of crudes for the best feedstock.

Although improvements can undoubtedly be made in silicone dielectric liquids, industry seems to have settled on polydimethylsiloxanes as satisfying most of the needs silicones are expected to fulfill.

MARKET TRENDS

While much effort has been made to develop alternatives to askarels, it should be noted that the applications served by these materials in reality represent less than 10 percent of the total market for dielectric liquids. This market is directly linked to the growth of the electrical industry.

18

Industry Activities

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INTRODUCTION

The electrical/electronic industries are fortunate to be served by a number of long-established, progressive organizations described in this chapter. Of these, ANSI serves solely as a clearinghouse for consensus voluntary standards. UL and ASTM primarily are dedicated to testing and standardization of materials, products, processes, and devices for all the nation's industries, among which the electrical/electronic industries are prominent. The SAE is broad in scope within the automotive and aerospace industries, but directs part of its efforts to electrical/electronic interests. All other organizations are concerned only with the electrical/electronic industries.

Important industry developments are presented at conferences/symposia, listed in this chapter, sponsored by industry and government groups.

Also included in this chapter are titles of encyclopedias and periodicals containing information on electrical/electronic insulating materials and their applications.

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

11 West 42nd Street, New York, NY 10036

ANSI was founded in 1918 as American Engineering Standards Committee. Its 1250 members are served by a staff of 107. The principal purpose is to serve as a clearinghouse for nationally coordinated voluntary safety, engineering, and industrial standards. ANSI gives status to standards developed by all groups concerned in such areas as definitions, terminology, symbols, and abbreviations; materials performance and characteristics; procedures and methods of rating; methods of testing and analysis; size, weight, volume; safety and health; and building construction. ANSI gathers and provides information on foreign standards, and represents the United States' interests in international standardization work.

Standards developed by any organization can be submitted to ANSI in one of the following ways:

1. A committee may be set up by the organization within ANSI; this committee is a balanced group of representatives from all areas interested in the standard.
2. The organization may submit a list of qualified parties throughout the industry whom the organization has designated to review the standard.
3. An organization can have their standards procedures approved by ANSI. ASTM, IEEE, and SAE are ANSI accredited. In each case, ANSI reviews and evaluates the proposed standard.

The end result of the work of ANSI is the publication of consensus standards developed by representatives from all groups that will be affected by the use of the standard, including manufacturers, consumers, government, and industry.

Publications include:

- *Standards Action*, biweekly
- *Catalogue of American National Standards*, annual, listing about 8,000 standards

ANSI holds an annual convention.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

1916 Race Street, Philadelphia, PA 19103

Formed in 1898 by 70 members of the American section of the International Association for Testing Methods, headquartered in Europe, ASTM grew to over 33,000 members by 1993, comprising engineers, scientists, managers, professionals, academicians, consumers, and technicians holding membership as individuals or representatives of manufacturers, educational institutions, laboratories, and government agencies. In 1993, ASTM employed a staff of 200.

The mission of the society is the development of consensus standards on characteristics and performance of products, materials, systems, and services, and for the promotion of related knowledge. Standards include definitions, classifications, specifications, test methods, and recommended practices. Work is carried out by 134 technical committees. Anyone technically qualified may be invited to participate in the work of a committee. Committees of interest to electrical/electronic industries include *Electrical Conductors*, *Electrical Insulating Materials*, *Materials for Electronics*, and *Plastics*.

Publications include:

- *Annual Book of ASTM Standards*, containing all current standards
- *Standardization News*, monthly, includes new standards
- *Journal of Testing and Evaluation*, bimonthly
- *Composites Technology Review*, quarterly
- *Geotechnical Testing Journal*, quarterly
- Numerous technical papers and reports

ASSOCIATION OF EDISON ILLUMINATING COMPANIES (AEIC)

600 North 18th Street, P.O. Box 2641, Birmingham, AL 35291

One of the oldest associations in the electrical industry, AEIC was formed in 1885 by investor-owned public utilities. In 1993, membership was 72 companies. Activities center around these committees: Electric Power Apparatus, Meter and Services, Power Distribution, Power Generation, Research.

Publications include reports, for example, on crosslinked polyethylene insulated cable and oil-impregnated paper-insulated cables.

AEIC convention/meetings are held each fall.

EDISON ELECTRIC INSTITUTE (EEI)

701 Pennsylvania Avenue NW, Washington, DC 20004

EEI was formed in 1933 by U.S. investor-owned electrical utility companies. The mission of the Institute is to advance the art of producing and transmitting electricity, and to provide a source of statistics related to the electrical industry. EEI has 7 divisions and 60 committees which cover every area of interest or concern to the industry, and which conduct and sponsor studies, surveys, and reports.

The Institute serves as a forum in which member companies exchange ideas, experiences, and information. EEI participates with other industries in joint activities of mutual interest.

Publications include a *Publications Catalogue* with a comprehensive listing of publications covering every aspect of the electric utility industry:

- Engineering
- Alternative fuels
- The environment
- Economics, finance, statistics

EEI holds an annual convention/meeting in June.

ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

3412 Hillview Avenue, Palo Alto, CA 94303

EPRI was formed in 1972 by electric power utilities to do research on long-term improvements in conventional electric energy production and on development of alternative energy sources. Activities are supported by U.S. electric utilities representing 70 percent of generating capacity, and the focus has shifted to shorter-term projects such as causes of and remedies for network failures, improved materials, and lower cost, higher efficiency transmission methods.

EPRI is organized to work in these areas:

- Electrical Systems
- Environment
- Exploratory and Applied Research
- Generation and Storage
- Nuclear Power
- Technical Operations

Projects are typically performed by commercial firms with EPRI in the role of project planning and contract management. EPRI publishes a monthly journal and *Technology Applications*, a series of one-page case histories prepared by the first utility to use an EPRI product or research result.

ELECTRICAL APPARATUS SERVICE ASSOCIATION (EASA)

1331 Baur Boulevard, St. Louis, MO 63132

EASA represents a service network of over 2,700 member companies throughout the world engaged in the repair, sale, and maintenance of electrical equipment, including motors, generators, transformers, controls, and power tools. A full-time engineering staff at headquarters is available to members for consultation. There are also management and training programs, and a convention and exhibition held each summer. EASA also maintains a library of training films and technical instructions as a service to members.

Publications include:

- *Currents*, monthly

ELECTRICAL MANUFACTURING AND COIL WINDING ASSOCIATION (EMCWA)

P.O. Box 278, Imperial Beach, CA 91933

EMCWA was organized in 1977 as the International Coil Winding Association to serve as the authoritative source of coil winding technology. In 1993, the name was changed to the Electrical Manufacturing and Coil Winding Association, with the mission to provide an array of educational opportunities which will enhance the general knowledge and use of electrical manufacturing technologies, including a scholarship program and an annual industry conference. In 1994, membership consisted of 120 company and 430 individual members. Publications include a *Proceedings* of the annual conference.

ELECTRONIC INDUSTRIES ASSOCIATION (EIA)

2001 Pacific Avenue NW, Washington, DC 20006

Started in 1924, EIA has since absorbed several electronic industry associations, and in 1993, membership totaled over 350 manufacturers of electronic parts; solid-state components; radio, TV, and video systems; governmental electronic systems; and industrial and communications electronic products. Divisions include Communications, Consumer Electronics Group, Distributor Products, Government, Industrial Electronics, Parts, Solid State Products, and Tubes.

EIA services all facets of the electronics industry with such activities as compiling statistics, monitoring legislative actions affecting the industry, representing the industry in government agencies by presenting consensus views and recommendations, and testifying at Congressional public hearings involving the industry. EIA develops industry standards and promotes their use. Most standards are submitted to ANSI.

Publications include:

- *Electronic Market Trends*, monthly
- *Electronic Market Data Book*, annual, provides information on industry sales and production
- *Publications Index*, listing publications covering all aspects of the Association's activities
- *Government Market Planning Information Service*, includes information on budget submissions and policy statements of Federal Departments
- *Consumer Electronics Annual Review*
- *Trade Directory*, annual
- *Electronics Foreign Trade*, features data on imports and exports
- *EIA Standards and Engineering Publications*, annual

EIA sponsors several events, including winter and summer consumer electronics shows, international telecommunications seminars and exhibits, and annual Design Engineers Electronic Components Conference.

INSTITUT DE RESERCHE D'HYDRO-QUÉBEC (IREQ)

1800, Montée Sainte-Julie, Varennes, Québec, Canada J3X 1S1

IREQ was created in 1967 to solve the technical problems that arise in the operation of Hydro-Québec's extensive power generation, transmission, and distribution system, and to study future needs, including alternative energy sources. It is widely recognized as one of the world's foremost research and development centers devoted to the technology, equipment, and materials of the electrical and electronics industries. Solid, liquid, and gaseous insulations are under continuous investigation.

IREQ works under contract for clients around the world wanting to carry out research or to develop new products. It also offers training courses and welcomes visits by technicians and scientists from other organizations.

Available from the Institute are conference papers, technical reports, addresses, and other publications on investigations undertaken by IREQ.

IREQ employs a staff of about 600 in permanent positions.

THE INSTITUTE FOR INTERCONNECTING AND PACKAGING ELECTRONIC CIRCUITS (IPC)

7380 North Lincoln Avenue, Lincolnwood, IL 60646

Formerly the Institute of Printed Circuits (organized in 1957), IPC is international in scope, serving manufacturers and users of electronic interconnecting devices, suppliers to the industry, and representatives from over 60 government agencies. The present name was adopted in 1977. Membership passed 1800 in 1993, with over 100 committees and working groups developing programs regarding interconnection technology, including printed wiring boards, flexible circuits, flat cable, hybrid circuits, connectors, and discrete wiring devices. IPC interfaces with government agencies, other industry organizations, and related professional groups. IPC employs a staff of 42.

IPC has developed a comprehensive set of *Standards and Specifications* covering all aspects of industry technology. Other publications include:

- *IPC Guidelines and Technical Reports*
- *The IPC Design Guide*
- *IPC Assembly/Joining Handbook*
- *IPC Test Manual*
- *IPC Gold Handbook*
- *Technical Reports*
- *The Technical Review*, monthly bulletin

IPC sponsors two major meetings annually plus numerous workshops and technical courses.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

345 East 47th Street, New York, NY 10017

IEEE was formed in 1963 by the merger of the American Institute of Electrical Engineers (founded in 1884) and the Institute of Radio Engineers (founded in 1912). By 1993, membership grew to approximately 320,000 in 145 countries, making it the largest professional engineering organization in the world. IEEE comprises 31 societies, including the *Dielectrics & Electrical Insulation Society*, each of which publishes its own periodicals and sponsors its own conferences. There are 530 local groups which meet periodically to hear lectures on and discuss topics of current engineering and scientific interest. IEEE has a staff of 500.

IEEE fosters the advancement of the theory and practice of electrical and electronic engineering and related arts and sciences through awards, conferences, publications, and the development of standards. The Institute supports the *Engineering Societies Library* in New York City, perhaps the largest electrical engineering library in the world.

Publications, with broad scope available to all IEEE members are:

- *IEEE Transactions on Dielectrics and Electrical Insulation*, monthly, publishes original papers edited to encourage deeper understanding and greater effectiveness in observing, classifying, interpreting, and reporting facts and theories germane to dielectric behavior and properties of electrical insulating materials and systems. It also lists scheduled national and international meetings and conferences in fields related to dielectric phenomena and measurements.
- *IEEE Electrical Insulation Magazine*, bimonthly, publishes articles dealing with materials, systems, and applications. Also included are columns dealing with tutorial and educational subjects, as well as columns expressing opinions and viewpoints. Other features are announcements of new products, calendar of events, and reports of matters of interest.
- *IEEE Spectrum*, monthly, contains articles on advanced technology, new product applications, industry news, information on IEEE activities, and employment opportunities.
- IEEE Standards covering the electrical/electronic industries
- *Proceedings of the IEEE*, monthly, contains fundamental papers of broad significance and long range interest.
- *IEEE Standard Dictionary of Electrical and Electronics Terms*
- Periodicals from each of its 31 societies
- *IEEE Potentials*, a magazine for students covering career issues, technical topics, and subjects of general interest to engineering students

IEEE is one of the sponsors of the *Electrical Insulation Conference*, held biennially in odd-numbered years, at which papers and exhibits are presented on all aspects of electrical insulations.

INSULATED CABLE ENGINEERS ASSOCIATION (ICEA)

P.O. Box 440, South Yarmouth, MA 02664

The predecessor to ICEA, the Insulated Power Cable Engineers Association, was formed in 1925. In 1993, there were 100 members, including the top engineers from most wire and cable manufacturers. The purpose of ICEA is to promote the safety, reliability, and economy of insulated conductors for the transmission and distribution of electrical energy. The principal activity of ICEA is to develop jointly with the Wire and Cable section of NEMA standards which are submitted to ANSI. ICEA also coordinates its activities on standards, where appropriate, with IEEE, UL, and ASTM, which organizations publish the standards.

There are five sections in ICEA:

- Extruded Dielectric Power Cable Section, including all cables with extruded insulations used from the transmission and distribution of electrical energy to equipment fixed in place.

- Laminar Dielectric Power Cable Section, including all cables with laminar insulations used for the transmission and distribution of electrical energy to equipment fixed in place.
- Communications Cable Section, including all insulated cables used to transmit voice, video, and data signals.
- Control and Instrumentation Cable Section, including all insulated cables used to convey electrical signals used for controlling or monitoring processes or electrical systems.
- Portable Cable Section, including all insulated electrical cables for equipment portable or movable in nature or used in mines or other similar applications.

Publications include standards, guides, and books on cable subjects. There is an annual conference.

INTERNATIONAL CONFERENCE ON LARGE HIGH VOLTAGE ELECTRICAL SYSTEMS (CIGRÉ)

112 Boulevard Hausmann, F–75008, Paris, France

CIGRÉ (Conference Internationale des Grands Reseaux Electricques à Haute Tension) was established in 1921 by the International Electrotechnical Commission to facilitate the interchange of technical knowledge and data between all countries in the general field of electricity generation and transmission at high voltages. All together, there are over 700 Collective Members and 3,000 Individual Members.

CIGRÉ Headquarters are in Paris, France. Conferences are held there and elsewhere biennially for the presentation of technical papers and for the free discussion thereof. Continuity of work between conferences is carried on by 15 special groups known as International Study Committees. Reports of their discussions and progress are published in the journal *ELECTRA*.

Publications include:

- *ELECTRA* (in English and French), bimonthly
- *Proceedings of the Session*, biennial

THE INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC)

United States National Committee of IEC
A Committee of the American National Standards Institute
11 West 42nd Street, New York, NY 10036

The IEC was founded in 1906, following a resolution passed in 1904 by the Chamber of Government Delegates, consisting of eminent engineers and scientists, at the International Electrical Congress in St. Louis, MO, U.S.A. It is the body responsible for

preparing and publishing international standards for the electrical and electronics fields. The IEC is a nongovernmental organization composed of National Committees in 43 countries that together represent over 80 percent of the world's population, and produce over 95 percent of the world's electric energy.

The principal organ of the IEC is the Council, consisting of representatives from all National Committees, with annual meetings. The management of the technical work of the IEC is delegated to the Committee of Action, comprising members from 12 National Committees elected by the Council. Technical committees develop standards, kept under constant review, covering the entire electrical and electronic fields. These standards are used as the basis of national rules and international trade. Committees include Insulating Materials and Systems, and Insulation Coordination in a total of 77 technical committees.

A general meeting of IEC takes place annually, comprising sessions of the Council, the Committee of Action, and of some 30–40 technical committees and subcommittees. Other meetings are held as required.

A complete list of publications can be obtained from the National Committee or from the IEC Central Office in Geneva, Switzerland. Participants in the IEC Registered Subscribers Scheme receive all or selected groups of IEC publications and draft standards.

Selected publications include the following:

- 371: *Specification for insulating materials based on mica*
- 394: *Varnished fabrics for electrical purposes*
- 454: *Specification for pressure-sensitive adhesive tapes for electrical purposes*
- 455: *Specification for solventless polymerizable resinous compounds used for electrical insulation*
- 464: *Specification for insulating varnishes containing solvent*
- 554: *Specification for cellulosic papers for electrical purposes*
- 626: *Specification for combined flexible materials for electrical insulation*
- 641: *Specification for pressboard and presspaper for electrical purposes*
- 667: *Specification for vulcanized fibre for electrical purposes*
- 672: *Specification for ceramic and glass insulating materials*
- 674: *Specification for plastic films for electrical purposes*
- 763: *Specification for laminated pressboard*

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION (NEMA)

2101 L Street NW, Washington, DC 20037

NEMA was formed in 1926 by the merger of the Associated Manufacturers of Electrical Supplies and the Electric Power Club. Membership in 1993 included more than 600 companies engaged in the manufacture of equipment for the generation, transmission, distribution, and utilization of electric power. The association, with a staff of 100, is the largest trade organization of electrical product companies in the United States.

Principal objectives of NEMA are to develop and promote the use of standards for the industries it serves, to provide an exchange of information on industry and product statistics and engineering safety, and to keep members informed on governmental activities affecting electrical/electronic industries. Many NEMA standards are submitted to ANSI.

NEMA publications include newsletters, standards, and manuals. Standards of special relevance are listed in the Appendix.

NEMA is one of the sponsors of the *Electrical Insulation Conference*, held biennially in odd-numbered years in the fall, at which papers and exhibits are presented on all aspects of insulating materials.

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)

400 Commonwealth Drive, Warrendale, PA 15096

The origins of SAE date back to 1905. Although primarily comprised of automotive engineers, SAE enrolls in a special affiliation engineers and scientists in fields of self-propelled sea, air, and space vehicles, and engineering students. The mission of SAE is to advance the arts, sciences, standards, and engineering practices related to self-propelled mechanisms. Research on utilization of fuels and lubricants is carried out with the American Petroleum Institute through the Coordinating Research Council.

A principal activity of SAE is the development of standards and specifications with emphasis on motor vehicle and aerospace industries. General interest standards are submitted to ANSI. The society conducts research on a contract basis for both industry and government agencies.

Publications include:

- *SAE Handbook*, an annual compilation of standards, recommended practices, and information reports
- *Automotive Engineering*, monthly, covers current topics in the automotive industry
- *Advances in Engineering Series*
- *Aerospace Standards*
- *Aerospace Material Specifications*

An annual convention is held in Detroit, MI, with attendance over 30,000. In excess of 400 papers are presented at its technical sessions.

SOCIETY OF PLASTICS ENGINEERS (SPE)

14 Fairfield Drive, Brookfield, CT 06804

Founded in 1942, SPE, with 1993 membership of 37,000, is a professional society of plastics scientists, engineers, educators, students, and others interested in the design, development, production, and utilization of plastics materials, products, and equipment. The society maintains an awards program in recognition of fundamental contributions

to the technology of polymer science and engineering, and for achievements in engineering and technology, education, business management, research, and unique plastic products in both industrial and consumer fields. Divisions include *Advanced Polymer Composites*, *Blow Molding*, *Color and Appearance*, *Electrical and Electronics*, *Engineering Properties and Structure*, *Extrusion*, *Injection Molding*, *Molding*, *Moldmaking and Mold Design*, *Plastics Analysis*, *Plastics in Automotive*, *Thermoplastics Materials and Foams*, *Thermosetting Molding*, and *Vinyl Plastics*.

Publications include:

- *Polymer Engineering and Science*, 24 semi-monthly issues per year
- *Plastics Engineering*, monthly
- *Journal of Vinyl Technology*, quarterly
- *Polymer Composites*, bimonthly
- *Preprint Volumes*, as required
- *Plastics Engineering Series*, books

SPE holds an annual convention in May.

SOCIETY OF THE PLASTICS INDUSTRY (SPI)

1275 K Street NW, Washington, DC 20005

Founded in 1937, SPI membership in 1983 comprised over 2,000 manufacturers and processors of molded, extruded, fabricated, laminated, calendered, and reinforced plastics; manufacturers of raw materials, machinery, tools, dies, and molds; and research, development, and testing laboratories. The society supports the preparation of voluntary product standards and commercial standards in cooperation with other agencies. SPI maintains the Plastics Hall of Fame and staffs a speakers bureau.

Publications include:

- *Facts and Figures*, annual, contains statistics on plastics markets and production
- *Proceedings of Conferences*, annual
- *Membership Directory and Buyers Guide*, annual

SPI holds an annual meeting in Washington, DC, an annual APC/I conference, and a triennial National Plastics Exposition.

UNDERWRITERS LABORATORIES (UL)

333 Pfingsten Road, Northbrook, IL 60062

Organized in 1894, primarily to test products for electrical and fire hazards for insurance companies, by 1993 the scope of UL had expanded to include the investigation and testing of materials, devices, products, equipment, constructions, methods, and systems with respect to hazards to life and property with a staff of 3,900

in laboratories in Northbrook, IL; Melville, NY; Santa Clara, CA; and Research Triangle Park, NC.

There are seven departments in UL: *Burglary Protection*; *Casualty and Chemical Hazards*; *Electrical*; *Fire Protection*; *Heating, Air-Conditioning and Refrigeration*; and *Marine*. The Electrical Department evaluates appliances, rebuilt motors and generators, and electrical construction materials and wiring used to distribute power inside buildings. Approved products are given a UL label or mark.

In conjunction with testing work, UL has developed and published hundreds of standards. Most of these are submitted to ANSI, where they are generally accepted.

UL publishes annual lists of approved materials, devices, products, equipment, constructions, methods, and systems. Other publications include pamphlets on safety and fire protection, research bulletins with test procedures, and the quarterly *Lab Data* covering product testing and safety.

Specifically related to insulating materials are the following publications:

- UL *746A Polymeric Materials—Short-Term Property Evaluations*
- UL *746B Polymeric Materials—Long-Term Property Evaluations*
- UL *746C Polymeric Materials—Use in Electrical Equipment*
- UL *1446 Systems of Insulating Materials—General*
- UL 94—*Tests for Flammability of Plastic Materials for Parts in Devices and Appliances.*

CONFERENCES/SYMPOSIUMS

Dielectric materials are discussed and displayed at many meetings, conferences, and symposiums, including the following:

- *BEMA International Electrical Insulation Conference*, held periodically. *Proceedings* are available from:

  BEMA Limited
  Leicester House, 8 Leicester Street
  London WC2H 7BN, England

- *Conference on Electrical Insulation and Dielectric Phenomena*, held annually in the fall. Sponsor is the Dielectrics and Electrical Insulation Society of the Institute of Electrical and Electronics Engineers. *Proceedings* are available from:

  Institute of Electrical and Electronics Engineers
  Service Center
  445 Hoes Lane
  Piscataway, NJ 08855

- *Electrical/Electronics Insulation Conference*, held biennially in odd-numbered years in the fall. Sponsors are the Dielectrics and Electrical Insulation Society of the Institute of Electrical and Electronics Engineers, the Electrical Manufacturing and Coil Winding Association, and the National Electrical Manufacturers Association. *Proceedings* are available from:

Institute of Electrical and Electronics Engineers
Service Center
445 Hoes Lane
Piscataway, NJ 08855

• *IEEE International Symposium on Electrical Insulation*, held periodically since 1976. *Proceedings* are available from:

Institute of Electrical and Electronics Engineers
Service Center
445 Hoes Lane
Piscataway, NJ 08855

• *International Conference on Dielectric Materials, Measurements and Applications*. Principal organizer is the Science, Education and Technology Division of the Institution of Electrical Engineers. *Proceedings* are available from:

The Institution of Electrical Engineers—LS(C)
P.O. Box 26, Hitchin
Herfordshire SG5 1SA, England

• *International Wire and Cable Symposium*, held annually in the fall. Sponsor is the International Wire and Cable Symposium, Inc. and the U.S. Army Electronics Command. *Proceedings* are available from:

International Wire and Cable Symposium Inc.
174 Main Street
Eatontown, NJ 07724

• *Printed Circuit World Expo*, held periodically. Sponsors are *ELECTRI*ONICS* magazine, *Microelectronic Manufacturing and Testing* magazine, and Worldwide Convention Management Company, a Division of Lake Publishing Corporation. *Proceedings* are available from:

Worldwide Convention Management Company
Division of Lake Publishing Corporation
17730 West Peterson Road
Box 159
Libertyville, IL 60048

PUBLICATIONS

There are several encyclopedias, handbooks, and periodicals covering electrical/electronic insulating materials:

ENCYCLOPEDIAS AND HANDBOOKS

Encyclopedia of Chemical Technology, Kirk—Othner
John Wiley & Sons, Inc.
605 3rd Avenue
New York, NY 10158

Concise Encyclopedia of Polymer Science and Technology
John Wiley & Sons, Inc.

Encyclopedia of Science and Technology
McGraw-Hill, Inc.
P.O. Box 602
Hightstown, NJ 08520

Modern Plastics Encyclopedia
McGraw-Hill, Inc.

Plastics 1980
The International Plastics Selector, Inc.
2251 San Diego Avenue, Suite A216
San Diego, CA 92110

Plastics Technology Manufacturing Handbook and Buyers Guide
633 Third Avenue
New York, NY 10017

PERIODICALS

Circuit News
125 Jericho Turnpike
Jericho, NY 11753

Circuits Assembly
13760 Noel Road, Ste. 500
Dallas, TX 75240
circulation 32,543

EPRI Journal
P.O. Box 10412, 12X
Palo Alto, CA 94303

Electrical Engineering in Japan
605 3rd Avenue
New York, NY 10158
circulation 400

Electrical Review—England
Perrymount Road/Haywards Heath
West Sussex RH16 3BR
England

Electrical World
11 West 19th Street
New York, NY 10011

Electronic Engineering Times
111 East Shore Road
Manhasset, NY 11030

Electronic News
7 East 12th Street
New York, NY 10003
circulation 72,000

Electronic Packaging and Production
1350 East Touhy Avenue
Des Plaines, IL 60018

Electronics
611 Route 46 West
Hasbrouck Heights, NJ 07604

Electronics Today International
Ryrie House
15 Boundary Street
Rushcutter's Bay, NSW 2011
Australia
circulation 33,500

IEEE Electrical Insulation
IEEE Publishing Services Department
445 Hoes Lane
Piscataway, NJ 08855

IEEE Spectrum
IEEE Publishing Services Department
445 Hoes Lane
Piscataway, NJ 08855
circulation 320,000

Journal of Elastomers & Plastics
851 New Holland Avenue
P.O. Box 3535
Lancaster, PA 17604
circulation 350

Journal of Vinyl Technology
Society of Plastics Engineers
14 Fairfield Drive
Brookfield, CT 06804

Modern Plastics
1221 Avenue of the Americas
New York, NY 10020
circulation 50,000

Plastics Engineering
Society of Plastics Engineers
14 Fairfield Drive
Brookfield, CT 06804
circulation 36,113

Plastics World
Society of Plastics Engineers
14 Fairfield Drive
Brookfield, CT 06804
circulation 1,380

Polymer Composites
Society of Plastics Engineers
14 Fairfield Drive
Brookfield, CT 06804

Polymer Engineering & Science
Society of Plastics Engineers
14 Fairfield Drive
Brookfield, CT 06804

Polymer Plastics Technology & Engineering
270 Madison Avenue
New York, NY 10016
circulation 800

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INTRODUCTION

In recent years, the federal government has become increasingly active in developing and administering regulations and standards which affect the manufacture and use of dielectrics and their raw materials. As a result, these groups are faced with problems of compliance with a multitude of federal, state, regional, and local statutes enacted to protect the health and safety of workers, and to ensure a clean, safe environment.

This chapter discusses the principal governmental agencies involved in these activities and lists targeted materials. Also included is information on agencies developing and distributing standards and specifications, and an example of a recent military specification on polyamide-imide materials.

WORKER SAFETY AND HEALTH

In launching the program to improve worker safety and health, Congress passed the Williams–Steiger Occupational Safety and Health Act on December 29, 1970, to become effective April 28, 1971. The stated purpose of the act is

> To assure safe and healthful working conditions for working men and women: by authorizing enforcement of the standards developed under the act; by assisting and encouraging the States in their efforts to assure safe and healthful working conditions; by providing for research, information, education, and training in the field of occupational safety and health and for other purposes.

Two government organizations were established to administer the act:

- *The Occupational Safety and Health Administration (OSHA)* functions within the Department of Labor, setting and enforcing standards, encouraging states to develop their own safety and health programs, and establishing certain record-keeping requirements
- *The National Institute for Occupational Safety and Health (NIOSH)*, a research activity of the Department of Health and Human Services, which conducts research and recommends criteria to OSHA on health standards, undertakes education and training programs, and performs work in the area of safety engineering.

Current occupational safety and health standards are published in *Code of Federal Regulations, Title 29, Part 1910*, effective June 30, 1993, obtainable from the Department of Labor or OSHA regional or field offices. This document lists approximately 600 materials as air contaminants with limits of permissible concentrations in air to which workers are exposed.

An employee's exposure to any material in Table 19-1 in any 8-hour work shift of a 40-hour work week shall not exceed the values for that material in the table.

TABLE 19-1 Air Contaminants Limits of Worker Exposure (8 hour Time-Weighted Averages)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m^3 of Air
Acetaldehyde	200	360
Acetic acid	10	25
Acetic anhydride	5	20
Acetone	1,000	2,400
Acetonitrile	40	70
Acetylene dichloride, see 1,2-Dichloroethylene		
Acetylene tetrabromide	1	14
Acrolein	0.1	0.25
Acrylamide—Skin		0.3
Aldrin—Skin		0.25
Allyl alcohol—Skin	2	5
Allyl chloride	1	3
Allyl propyl disulfide	2	12
2-Aminoethanol, see Ethanolamine		
2-Aminopyridine	0.5	2
Ammonia	50	35
Ammonium sulfamate (Ammate)		15
n-Amyl acetate	100	525
sec-Amyl acetate	125	650
Aniline—Skin	5	19
Anisidine (o, p-isomers)—Skin		0.5
Antimony and compounds (as Sb)		0.5
ANTU (alpha naphthyl thiourea)		0.3
Arsenic organic compounds (as As)		0.5
Arsine	0.05	0.2
Azinphos-methyl—Skin		0.2
Barium (soluble compounds)		0.5
p-Benzoquinone, see Quinone		
Benzoyl peroxide		5
Benzyl chloride	1	5
Biphenyl, see Diphenyl		
Boron oxide		15
Bromine	0.1	0.7
Bromoform—Skin	0.5	5
Butadiene (1,3-butadiene)	1,000	2,200
Butanethiol, see Butyl mercaptan		
2-Butanone	200	590
2-Butoxy ethanol (Butyl Cellosolve)—Skin	50	240
Butyl acetate (n-butyl acetate)	150	710
sec-Butyl acetate	200	950
tert-Butyl acetate	200	950
Butyl alcohol	100	300
sec-Butyl alcohol	150	450
tert-Butyl alcohol	100	300
n-Butyl glycidyl ether (BGE)	50	270
Butyl mercaptan	10	35
p-tert-Butyltoluene	10	60
Calcium oxide		5
Camphor		2

(*continued*)

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m^3 of Air
Carbaryl (Sevin®)		5
Carbon black		3.5
Carbon dioxide	5,000	9,000
Carbon monoxide	50	55
Chlordane—Skin		0.5
Chlorinated camphene—Skin		0.5
Chlorinated diphenyl oxide		0.5
Chlorine dioxide	0.1	0.3
a-Chloroacetophenone (phenacychloride)	0.05	0.3
Chlorobenzene (monochlorobenzene)	75	350
o-Chlorobenzylidene malononitrile (OCBM)	0.05	0.4
Chlorobromomethane	200	1,050
2-Chloro-1,3-butadiene, see Chloroprene		
Chlorodiphenyl (42 percent Chlorine)—Skin		1
Chlorodiphenyl (54 percent Chlorine)—Skin		0.5
1-Chloro, 2,3-epoxypropane, see Epichlorhydrin		
2-Chloroethanol, see Ethylene chlorohydrin		
Chloroethylene, see Vinyl chloride		
1-Chloro-1-nitropropane	20	100
Chloropicrin	0.1	0.7
Chloroprene (2-chloro-1,3-butadiene)—Skin	25	90
Chromium, sol. chromic, chromous salts as Cr		0.5
Metal and insol. salts		1
Coal tar pitch volatiles (benzene soluble fraction) anthracene, BaP, phenanthrene, acridine, chrysene, pyrene		0.2
Cobalt, metal fume and dust		0.1
Copper fume		0.1
Dusts and mists		1
Cotton dust (raw)		11
Crag® herbicide		15
Cresol (all isomers)—Skin	5	22
Crotonaldehyde	2	6
Cumene—Skin	50	245
Cyanide (as CN)—Skin		5
Cyclohexane	300	1,050
Cyclohexanol	50	200
Cyclohexanone	50	200
Cyclohexene	300	1,015
Cyclopentadiene	75	200
2,4-D		10
DDT—Skin		1
DDVP—Skin		1
Decaborane—Skin	0.05	0.3
Demeton®—Skin		0.1
Diacetone alcohol (4-hydroxyl-4-methyl-2-pentanone)	50	240
1,2-Diaminoethane, see Ethylene-diamine		
Diazomethane	0.2	0.4
Diborane	0.1	0.1

(*continued*)

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m^3 of Air
Dibutyl phosphate	1	5
Dibutylphthalate		5
p-Dichlorobenzene	75	450
Dichlorodifluoromethane	1,000	4,950
1,3-Dichloro-5,5-dimethyl hydantoin		0.2
1,1-Dichloroethane	100	400
1,2-Dichloroethylene	200	790
Dichloromethane, see Methylenechloride		
Dichloromonofluoromethane	1,000	4,200
1,2-Dichloropropane, see Propylenedichloride		
Dichlorotetrafluoroethane	1,000	7,000
Dieldrin—Skin		0.25
Diethylamine	25	75
Diethylamino ethanol—Skin	10	50
Diethylether, see Ethyl ether		
Difluorodibromomethane	100	860
Dihydroxybenzene, see Hydroquinone		
Diisobutyl ketone	50	290
Diisopropylamine—Skin	5	20
Dimethoxymethane, see Methylal		
Dimethyl acetamide—Skin	10	35
Dimethylamine	10	18
Dimethylaminobenzene, see Xylidene		
Dimethylaniline (N-dimethyl-aniline)—Skin	5	25
Dimethylbenzene, see Xylene		
Dimethyl 1,2-dibromo-2,2-dichloroethyl phosphate, (Dibrom)		3
Dimethylformamide—Skin	10	30
2,6-Dimethylheptanone, see Diisobutyl ketone		
1,1-Dimethylhydrazine—Skin	0.5	1
Dimethylphthalate		5
Dimethylsulfate—Skin	1	5
Dinitrobenzene (all isomers)—Skin		1
Dinitro-o-cresol—Skin		0.2
Dinitrotoluene—Skin		1.5
Dioxane (Diethylene dioxide)—Skin	100	360
Diphenyl	0.2	1
Diphenylmethane diisocyanate, see Methylene bisphenyl isocyanate (MDI)		
Dipropylene glycol methyl ether—Skin	100	600
Di-sec, octyl phthalate (Di-2-ethylhexylphthalate)		5
Endrin—Skin		0.1
Epichlorohydrin—Skin	5	19
EPN—Skin		0.5
1,2-Epoxypropane, see Propyleneoxide		
2,3-Epoxy-1-propanol, see Glycidol		
Ethanethiol, see Ethylmercaptan		
Ethanolamine	3	6
2-Ethoxyethanol—Skin	200	740
2-Ethoxyethylacetate (Cello-solve acetate)—Skin	100	540
Ethyl acetate	400	1,400

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m^3 of Air
Ethyl acrylate—Skin	25	100
Ethyl alcohol (ethanol)	1,000	1,900
Ethylamine	10	18
Ethyl sec-amyl ketone (5-methyl-3-heptanone)	25	130
Ethyl benzene	100	435
Ethyl bromide	200	890
Ethyl butyl ketone (3-Heptanone)	50	230
Ethyl chloride	1,000	2,600
Ethyl ether	400	1,200
Ethyl formate	100	300
C Ethyl mercaptan	10	25
Ethyl silicate	100	850
Ethylene chlorohydrin—Skin	5	16
Ethylenediamine	10	25
Ethylene glycol monomethyl ether acetate, see Methyl cellosolve acetate		
Ethylene imine—Skin	0.5	1
Ethylene oxide	50	90
Ethylidine chloride, see 1,1-Dichloroethane		
N-Ethylmorpholine—Skin	20	94
Ferbam		15
Ferrovanadium dust		1
Fluoride (as F)		2.5
Fluorine	0.1	0.2
Fluorotrichloromethane	1,000	5,600
Formic acid	5	9
Furfural—Skin	5	20
Furfuryl alcohol	50	200
Glycidol (2,3-Epoxy-1-propanol)	50	150
Glycol monoethyl ether, see 2-Ethoxyethanol		
Guthion®, see Azinphosmethyl		
Hafnium		0.5
Heptachlor—Skin		0.5
Heptane (n-heptane)	500	2,000
Hexachloroethane—Skin	1	10
Hexachloronaphthalene—Skin		0.2
Hexane (n-hexane)	500	1,800
2-Hexanone	100	410
Hexone (Methyl isobutyl ketone)	100	410
sec-Hexyl acetate	50	300
Hydrazine—Skin	1	1.3
Hydrogen bromide	3	10
Hydrogen cyanide—Skin	10	11
Hydrogen peroxide (90%)	1	1.4
Hydrogen selenide	0.05	0.2
Hydroquinone		2
Iron oxide fume		10
Isoamyl acetate	100	525
Isoamyl alcohol	100	360
Isobutyl acetate	150	700

(*continued*)

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m³ of Air
Isobutyl alcohol	100	300
Isophorone	25	140
Isopropyl acetate	250	950
Isopropyl alcohol	400	980
Isopropylamine	5	12
Isopropylether	500	2,100
Isopropyl glycidyl ether (IGE)	50	240
Ketene	0.5	0.9
Lindane—Skin		0.5
Lithium hydride		0.025
L.P.G. (liquefied petroleum gas)	1,000	1,800
Magnesium oxide fume		15
Malathion—Skin		15
Maleic anhydride	0.25	1
Mesityl oxide	25	100
Methanethiol, see Methyl mercaptan		
Methoxychlor		15
2-Methoxyethanol, see Methyl cellosolve		
Methyl acetate	200	610
Methyl acetylene (propyne)	1,000	1,650
Methyl acetylene-propadiene mixture (MAPP)	1,000	1,800
Methyl acrylate—Skin	10	35
Methylal (dimethoxymethane)	1,000	3,100
Methyl alcohol (methanol)	200	260
Methylamine	10	12
Methyl amyl alcohol, see Methyl isobutyl carbinol		
Methyl (n-amyl) ketone (2-Heptanone)	100	465
Methyl butyl ketone, see 2-Hexanone		
Methyl cellosolve—Skin	25	80
Methyl cellosolve acetate—Skin	25	120
Methyl chloroform	350	1,900
Methylcyclohexane	500	2,000
Methylcyclohexanol	100	470
O-Methylcyclohexanone—Skin	100	460
Methyl ethyl ketone (MEK), see 2-Butanone		
Methyl formate	100	250
Methyl iodide—Skin	5	28
Methyl isobutyl carbinol—Skin	25	100
Methyl isobutyl ketone, see Hexone		
Methyl isocyanate—Skin	0.02	0.05
Methyl methacrylate	100	410
Methyl propyl ketone, see 2-Pentanone		
Molybdenum:		
Soluble compounds		5
Insoluble compounds		15
Monomethyl aniline—Skin	2	9
Morpholine—Skin	20	70
Naphtha (coaltar)	100	400
Naphthalene	10	50
Nickel carbonyl	0.001	0.007
Nickel, metal and soluble cmpds, as Ni		1

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m^3 of Air
Nicotine—Skin		0.5
Nitric acid	2	5
Nitric oxide	25	30
p-Nitroaniline–Skin	1	6
Nitrobenzene—Skin	1	5
p-Nitrochlorobenzene—Skin		1
Nitroethane	100	310
Nitrogen trifluoride	10	29
Nitromethane	100	250
1-Nitropropane	25	90
2-Nitropropane	25	90
Nitrotoluene—Skin	5	30
Nitrotrichloromethane, see Chloropicrin		
Octachloronaphthalene—Skin		0.1
Octane	500	2,350
Oil mist, mineral		5
Oxmium tetroxide		0.002
Oxalic acid		1
Oxygen difluoride	0.05	0.1
Ozone	0.1	0.2
Paraquat—Skin		0.5
Parathion—Skin		0.1
Pentaborane	0.005	0.01
Pentachloronaphthalene—Skin		0.5
Pentachlorophenol—Skin		0.5
Pentane	1,000	2,950
2-Pentanone	200	700
Perchloromethyl mercaptan	0.1	0.8
Perchloryl fluoride	3	13.5
Petroleum distillates (naphtha)	500	2,000
Phenol—Skin	5	19
p-Phenylene diamine—Skin		0.1
Phenyl ether (vapor)	1	7
Phenyl ether-biphenyl mixture (vapor)	1	7
Phenylethylene, see Styrene		
Phenyl glycidyl ether (PGE)	10	60
Phenylhydrazine—Skin	5	22
Phosdrin (Mevinphos®)—Skin		0.1
Phosgene (carbonyl chloride)	0.1	0.4
Phosphine	0.3	0.4
Phosphoric acid		1
Phosphorus (yellow)		0.1
Phosphorus pentachloride		1
Phosphorus pentasulfide		1
Phosphorus trichloride	0.5	3
Phthalic anhydride	2	12
Picric acid—Skin		0.1
Pival® (2-Pivalyl-1,3-indandione)		0.1
Platinum (Soluble salts) as Pt		0.002
Propane	1,000	1,800

(*continued*)

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m³ of Air
n-Propyl acetate	200	840
Propyl alcohol	200	500
n-Propyl nitrate	25	110
Propylene dichloride	75	350
Propylene imine—Skin	2	5
Propylene oxide	100	240
Propyne, see Methylacetylene		
Pyrethrum		5
Pyridine	5	15
Quinone	0.1	0.4
Rhodium, Metal fume and dusts, as Rh		0.1
Soluble salts		0.001
Ronnel		15
Rotenone (commercial)		5
Selenium compounds (as Se)		0.2
Selenium hexafluoride	0.05	0.4
Silver, metal and soluble compounds		0.01
Sodium fluoroacetate (1080)—Skin		0.05
Sodium hydroxide		2
Stibine	0.1	0.5
Stoddard solvent	500	2,900
Strychnine		0.15
Sulfur dioxide	5	13
Sulfur hexafluoride	1,000	6,000
Sulfuric acid		1
Sulfur monochloride	1	6
Sulfur pentafluoride	0.025	0.25
Sulfuryl fluoride	5	20
Systox, see Demeton®		
2,4,5T		10
Tantalum		5
TEDP—Skin		0.2
Tellurium		0.1
Tellurium hexafluoride	0.02	0.2
TEPP—Skin		0.05
1,1,1,2-Tetrachloro-2,2-difluorethane	500	4,170
1,1,2,2-Tetrachloro-1,2-difluorethane	500	4,170
1,1,2,2-Tetrachloroethane—Skin	5	35
Tetrachloromethane, see Carbon tetrachloride		
Tetrachloronaphthalene—Skin		2
Tetraethyl lead (as Pb)—Skin		0.075
Tetrahydrofuran	200	590
Tetramethyl lead (as Pb)—Skin		0.075
Tetramethyl succinonitrile—Skin	0.5	3
Tetranitromethane	1	8
Tetryl (2,4,6-trinitrophenyl methyl-nitramine)—Skin		1.5
Thallium (soluble compounds)—Skin as Tl		0.1
Thiram		5
Tin (inorganic cmpds, except oxides)		2
Tin (organic cmpds)		0.1
Titaniumdioxide		15

TABLE 19-1 (*Continued*)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m^3 of Air
o-Toluidine—Skin	5	22
Toxaphene, see Chlorinated camphene		
Tributyl phosphate		5
1,1,1-Trichloroethane, see Methyl chloroform		
1,1,2-Trichloroethane—Skin	10	45
Trichloromethane, see Chloroform		
Trichloronaphthalene—Skin		5
1,2,3-Trichloropropane	50	300
1,1,2-Trichloro 1,2,2-trifluoroethane	1,000	7,600
Triethylamine	25	100
Trifluoromonobromomethane	1,000	6,100
2,4,6-Trinitrophenol, see Picric acid		
2,4,6-Trinitrophenylmethyl-nitramine, see Tetryl		
Trinitrotoluene—Skin		1.5
Triorthocresyl phosphate		0.1
Triphenyl phosphate		3
Turpentine	100	560
Uranium (soluble compounds)		0.05
Uranium (insoluble compounds)		0.25
Vinyl benzene, see Styrene		
Vinylcyanide, see Acrylonitrile		
Vinyl toluene	100	480
Warfarin		0.1
Xylene (xylol)	100	435
Xylidine—Skin	5	25
Yttrium		1
Zinc chloride fume		1
Zinc oxide fume		5
Zirconium compounds (as Zr)		5

Source: Occupational Safety and Health Administration, *Toxic and Hazardous Substances 29 CFR Part 1910.*

The cumulative exposure for an 8-hour work shift is computed as follows:

$$E = (C_a T_a + C_b T_b + \cdots C^n T^n) \div 8$$

where

E is the equivalent exposure for the working shift

C is the concentration during any period of time T where the concentration remains constant.

For compliance, the value of E should not exceed the 8-hour time-weighted average limit in the table.

An employee's exposure to any material in Table 19-2 shall not exceed the ceiling value given for that material in the table.

TABLE 19-2 Air Contaminants Limits of Worker Exposure (Ceiling Limits)

SUBSTANCE	Parts/Million (vol) @ 25°C, 760 mm Mercury Pressure	mg/m³ of Air
Allylglycidyl ether (AGE)	10	45
Boron trifluoride	1	3
Butylamine—Skin	5	15
Tert-Butyl chromate (CrO_3) Skin	—	0.1
Chlorine	1	3
Chlorine trifluoride	0.1	0.4
Chloroacetaldehyde	1	3
Chloroform (trichloromethane)	50	240
o-Dichlorobenzene	50	300
Dichloroethyl ether—Skin	15	90
1,1-Dichloro-1-nitroethane	10	60
Diglycidyl ether (DGE)	0.5	2.8
Ethyl mercaptan	10	25
Ethylene glycol dinitrate—Skin	0.2	1
Hydrogen chloride	5	7
Iodine	0.1	1
Manganese	—	5
Methyl bromide—Skin	20	80
Methyl mercaptan	10	20
Methyl styrene	100	480
Methylene bisphenyl isocyanate (MDI)	0.02	0.2
Monomethyl hydrazine—Skin	0.2	0.35
Nitrogen dioxide	5	9
Nitroglycerin—Skin	0.2	2
Terphenyls	1	9
Soluene-2,4-diisocyanate (TDI)	0.02	0.14
Vanadium		
V_2O_5 dust	—	0.5
V_2O_5 fume	—	0.1

TABLE 19-3 Air Contaminants Limits of Worker Exposure
(8 h Time-Weighted Averages, Ceiling Limit, and Acceptable Maximum Peak Above Ceiling Limit)

MATERIAL	8 h TIME-WEIGHTED AVERAGE	ACCEPTABLE CEILING CONCENTRATION	ACCEPTABLE MAXIMUM PEAK ABOVE THE ACCEPTANCE CEILING CONCENTRATION FOR AN 8 h SHIFT	
			CONCENTRATION	MAXIMUM DURATION
Benzene	10 p.p.m.	25 p.p.m.	50 p.p.m.	10 min
Beryllium and beryllium compounds	2 $\mu g/M^3$	5 $\mu g/M^3$	25 $\mu g/M^3$	30 min
Cadmium fume	0.1 mg/M^3	0.3 mg/M^3		
Cadmium dust	0.2 mg/M^3	0.6 mg/M^3		
Carbon disulfide	20 p.p.m.	30 p.p.m.	100 p.p.m.	30 min
Carbon tetrachloride	10 p.p.m.	25 p.p.m.	200 p.p.m.	5 min in any 4 h
Chromic acid and chromates		1 $mg/10M^3$		
Ethylene dibromide	20 p.p.m.	30 p.p.m.	50 p.p.m.	5 min
Ethylene dichloride	50 p.p.m.	100 p.p.m.	200 p.p.m.	5 min in any 3 h
Formaldehyde	3 p.p.m.	5 p.p.m.	10 p.p.m.	30 min
Hydrogen fluoride	3 p.p.m.			
Hydrogen sulfide		20 p.p.m.	50 p.p.m.	10 min once only if no other measurable exposure occurs
Fluoride as dust	2.5 mg/M^3			
Mercury		1 $mg/10M^3$		
Methyl chloride	100 p.p.m.	200 p.p.m.	300 p.p.m.	5 min in any 3 h
Methylene chloride	500 p.p.m.	1,000 p.p.m.	2,000 p.p.m.	5 min in any 2 h
Organo (alkyl) mercury	0.01 mg/M^3	0.04 mg/M^3		
Styrene	100 p.p.m.	200 p.p.m.	600 p.p.m.	5 min in any 3 h
Tetrachloroethylene	do	do	300 p.p.m.	5 min in any 3 h
Toluene	200 p.p.m.	300 p.p.m.	500 p.p.m.	10 min
Trichloroethylene	100 p.p.m.	200 p.p.m.	300 p.p.m.	5 min in any 2 h

An employee's exposure to any material listed in Table 19-3, in any 8-hour work shift of a 40-hour work week, shall not exceed the 8-hour time-weighted average limit given for that material in the table, or its ceiling concentration or maximum peak above ceiling limits, except as indicated in the table.

Vinyl chloride permissible exposure limits are as follows:

- No employee may be exposed to vinyl chloride at concentrations greater than one part per million of atmosphere averaged over any 8-hour period.
- No employee may be exposed to vinyl chloride at concentrations greater than five parts per million of atmosphere averaged over any period not exceeding 15 minutes.
- No employee may be exposed to vinyl chloride by direct contact with liquid vinyl chloride.

Acrylonitrile permissible exposure limits are as follows:

- No employee may be exposed to acrylonitrile at concentrations greater than two parts per million of atmosphere averaged over any 8-hour period.
- No employee may be exposed to acrylonitrile at concentrations greater than ten parts per million of atmosphere as averaged over any 15-minute period during the work day.
- No employee may be exposed to skin or eye contact with acrylonitrile.

HAZARD COMMUNICATION STANDARD

On November 25, 1983, OSHA issued a regulation referred to as the *Hazard Communication Standard*, requiring manufacturers, importers, and distributors to establish an information and training program for employees exposed to hazardous chemicals listed in Table 19-1 earlier in this chapter.

This requires employers to establish a comprehensive hazard communication program which includes the mandated container labeling and material safety data sheets (MDS), elements of which are shown in Exhibit 19-1. Also required is a training program containing information on how the employer plans to meet the criteria of the standards governing each hazardous chemical present in each work area. A list of these materials must be posted for workers to see.

Labels are required on all containers of hazardous chemicals leaving work areas, with the appropriate identity hazard warnings, and the name and address of the manufacturer. A sign may be posted if there are a number of stationary containers within a workplace instead of individually labeling each piece of equipment. The standard also requires that employers ensure that labels on incoming containers are not removed or defaced unless they are immediately replaced. Any container leaving a facility must be appropriately labeled.

Chemical manufacturers and importers are required to develop material safety data sheets for each hazardous chemical they produce or import. Employers are

ANATOMY OF A MATERIAL SAFETY DATA SHEET (OSHA FORM 174)

SECTION I, CHEMICAL IDENTITY

Who makes the product
Their emergency phone number(s)
Date the MSDS was prepared

The chemical should be listed by its chemical and common name.

SECTION II, HAZARDOUS INGREDIENTS

If it is a tested mixture, the information will include the substance's hazardous components, which includes all the chemicals in the mixture which are hazardous.

If it is not a tested mixture, when all components of the chemical have been mixed, then the chemical and common name of all chemicals included in the mixture that are hazardous in concentrations of 1% or more must be listed.

The chemical and common name of each hazardous chemical that are carcinogens and are in concentrations of 0.1% or more must also be listed.

SECTION III, PHYSICAL AND CHEMICAL CHARACTERISTICS

Boiling Point
Vapor Pressure
Vapor Density
Specific Gravity
Evaporation Rate
Melting Point
Water Solubility
Appearance and Odor (Under Normal Conditions)

SECTION IV, PHYSICAL HAZARD DATA

Flash Point
Flammability Limits
Fire Extinguishing Media(s)
Special Firefighting Instructions
Fire/Explosion Hazards

(*continued*)

Exhibit 19-1.

SECTION V, HEALTH HAZARD DATA

Any known allowable/permissible exposure limits
Signs and symptoms of exposure and overexposure
Primary routes of entry
Cancer data
Applicable precautions for safe use and handling

SECTION VI, REACTIVITY DATA

Stability of material
Conditions to avoid
Hazardous decomposition products
Occurrence of hazardous polymerization
Incompatibilities

SECTION VII, SPILL AND DISPOSAL DATA

Steps to take if the material is released
How to dispose of the material

SECTION VIII, SPECIAL PROTECTION INFORMATION

Proper respiratory protection
Proper type of ventilation
Other types of protective equipment: gloves, glasses, etc.

SECTION IX, SPECIAL HANDLING AND STORAGE

Any special precautions for handling and storage

SECTION X, MISCELLANEOUS INFORMATION

Dept. of Transportation shipping classes
Shipping information/methods
Any other useful information

Exhibit 19-1 (*cont.*)

required to obtain or develop an MSDS for each hazardous chemical used in their workplace. These sheets must be accessible to all employees in the work area where the chemicals exist. MSDS must include the identity of the chemical, ingredients physically present within the chemical, and precautionary measures, emergency and first aid procedures, and identification of the person responsible for the sheet. New information on a chemical must be added to the MSDS within three months. Information is permitted to be withheld from MSDS if certain conditions are met:

- If claimed that the information withheld is a trade secret;
- If information concerning properties and effects of the hazardous chemical is disclosed as required on the appropriate MSDS;
- If the MSDS indicate that a specific chemical identity is being withheld as a trade secret;
- If the specific chemical identity is made available to health professionals under certain specified situations.

In the case of a medical emergency, the specific chemical identity of a hazardous chemical must be made available to a treating physician or nurse when the information is needed for proper emergency or first aid treatment.

Training is to be provided to the employee at the time of initial assignment and when a new hazardous chemical is introduced in the work area. Training programs must inform employees where in their work area hazardous chemicals are present; where written communication regarding chemicals are kept; how to detect them (i.e., odor of chemicals); methods to be taken by employees to protect themselves from the hazards; and specific procedures implemented by the employer to provide protection.

A sample of the OSHA Hazard Communication Program is shown in Exhibit 19-2.

COMPANY NAME
SAMPLE
HAZARD COMMUNICATION PROGRAM

I. GENERAL

To comply with the Federal Hazard Communication Standards (29 CFR 1910.1200 and 1926.59) as required by the Occupational Safety and Health Administration, the following Hazard Communication Program has been established. The following pages document the actions we have taken regarding our chemical information list, material safety data sheets, labels, and employee information and training. This program will be available in each department supervisor's office for review by all employees at any time and on all shifts.

(*continued*)

Exhibit 19-2.

II. EMPLOYEE TRAINING AND INFORMATION

Before starting work, each new employee will attend a safety class which will educate and train them as to:

a. The Company's Hazard Communication Program.

b. Processes used within their department and how they can be a hazard.

c. Product inventory lists for their department and how to use them.

d. Material Safety Data Sheets (MSDSs).

e. Product labeling requirements.

f. How exposure to hazardous products/chemicals can be controlled by such means as work practices, and personal protective equipment both during normal use and foreseeable emergencies.

g. What the Company has done to lessen or prevent workers' exposure to products/chemicals.

h. Procedures to follow if exposed to products/chemicals.

After attending the class, each employee will sign a form (sample attached) stating that they have received the training outlined above.

Before any new hazardous product is introduced into any department, each employee will be given information in the same manner as when newly hired. The department supervisor will be responsible for seeing that MSDSs on the new product(s) are available.

Monthly safety meetings will be held within each department, and hazardous products/chemicals used in the department will be discussed. Attendance is mandatory for all employees.

Notices will be posted on the employee bulletin boards that provide an explanation of our container labeling system and the location of the written hazard communication program.

III. CONTAINER LABELING

The supervisor will verify that all product/chemical containers received for use by the department are clearly labeled with:

a. the trade name of the product;

b. the name and address of the manufacturer; and

c. the appropriate hazard warnings (target organs and type of protective equipment required).

No containers will be released for use until the above data are verified. Material in unlabeled piping will be addressed in the same manner.

If hazardous products/chemicals are transferred from the original shipping containers to other containers, the department supervisor is responsible for the labeling with the appropriate from a. & c. above.

Exhibit 19-2 (*cont.*)

IV. MATERIAL SAFETY DATA SHEETS (MSDSs)

It is our company policy not to use a hazardous chemical for which no MSDS has been received. We therefore require all suppliers of hazardous chemicals to provide an appropriate MSDS. Our company will not accept any new hazardous materials without an accompanying MSDS for the product.

Copies of MSDSs for all of the hazardous products to which department employees may be exposed will be kept in the department supervisor's office (with this program) and in the plant office.

MSDSs will be available to all employees during each workshift. Copies of MSDSs will be made available to any employee upon request to the department supervisor.

It is important to know what a MSDS is and what it is designed to do; they help you identify health and physical hazards of the chemicals you work with.

Please note that the information on an MSDS may not be in the exact same order about to be addressed, but will be very similar. While MSDSs may take different shapes, they must all contain the information identified.

V. ADDITIONAL PROVISIONS

A. Informing Contractors

It is the responsibility of the facility manager to coordinate with the department supervisor(s) to ensure that contractors and their employees are provided with the following information prior to entering the worksite:

1. Hazardous products to which they may be exposed while on the job site;
2. Measures the employees may take to lessen the possibility of exposure;
3. Steps the company has taken to lessen the risks;
4. MSDSs for all hazardous products are on file in the plant office, and the department supervisor has a copy of each one; and
5. Procedures to follow if they are exposed.

By the same token, contractors must notify the facility manager of the hazardous materials which they will be using. The facility manager must then notify the plant employees of this information.

B. Hazardous Nonroutine Tasks

It is the Company's policy that no employee will begin any "nonroutine" task without first receiving a safety briefing. Each "nonroutine" task must be described in detail and the following information discussed:

1. Specific chemical hazards;
2. Protective equipment and safety measures the employee(s) are to use; and

(*continued*)

Exhibit 19-2 (*cont.*)

3. Measures the company has taken to lessen the hazards (engineering controls, protective equipment, additional employees, and emergency procedures).

VI. INVENTORY OF HAZARDOUS MATERIALS

Attached is an inventory of hazardous products used in each department. The list is arranged in alphabetical order by common name, and either the chemical name or common name is the identity shown on the MSDS and container labels. Further information on each hazardous product listed can be obtained by reviewing the product's MSDS in the supervisor's office. (Use the corresponding MSDS # for quick cross-reference.)

PRODUCT TRADE NAME	MANUFACTURER/ ADDRESS	PHONE #	MSDS NO

_____

Company President

EMPLOYEE ACKNOWLEDGMENT OF HAZARD COMMUNICATION TRAINING

I, _____, have been trained in the company's hazard communication program. The materials/processes in my work area have been explained, and I am aware of the material safety data sheets (MSDSs) which apply, as well as their location.

_____ _____

Employee's Signature Date

_____ _____

Supervisor's Signature Date

Exhibit 19-2 (*cont.*)

OSHA REGIONAL OFFICES

OSHA regional offices are shown in Table 19-4.

TABLE 19-4 OSHA Regional and Area Offices

REGION 1
(CT, MA, ME, NH, RI, VT)
133 PORTLAND STREET
BOSTON, MA 02114

Bridgeport, CT 06604
One Lafayette Square

Hartford, CT 06103
Federal Office Bldg.
450 Main Street

Augusta, ME 04330
U.S. Federal Bldg.
40 Western Avenue

Concord, NH 03301
279 Pleasant Street

Springfield, MA 01103-1493
1145 Main Street

Braintree, MA 02184
639 Granite Street

Methuen, MA 01844
Valley Office Park
13 Branch Street

Providence, RI 02903
380 Westminster Hall

REGION 2
(NJ, NY, PR, VI)
201 VARICK STREET
NEW YORK, NY 10014

Avenel, NJ 07001
Plaza 35
1030 Saint Georges Avenue

Hasbrouck Heights, NJ 07604
Teterboro Airport
Professional Bldg.
500 Route 17 South

Marlton, NJ 08053
Marlton Executive Park
701 Route 73 South

Parsippany, NJ 07054
299 Cherry Hill Road

Hato Rey, PR 00918
U.S. Courthouse & FOB
Carlos Chardon Street

Albany, NY 12205-3826
401 New Karner Road

Bowmansville, NY 14026
5360 Genesee Street

Bayside, NY 11361
42-40 Bell Blvd.

New York, NY 10007
90 Church Street

Syracuse, NY 13260
100 South Clinton Street

Tarrytown, NY 10591
660 White Plains Road

Westbury, NY 11590
990 Westbury Road

(*continued*)

TABLE 19-4 (*Continued*)

REGION 3
(DC, DE, MD, PA, VA, WV)
GATEWAY BLDG.
3535 MARKET STREET
PHILADELPHIA, PA 19104

Baltimore, MD 21201
Federal Bldg.
40 Western Avenue

Allentown, PA 18102
850 North 5th Street

Erie, PA 18506
3939 West Ridge Road

Harrisburg, PA 17109
Progress Plaza
49 North Progress Street

Philadelphia, PA 19106
U.S. Custom House
Second and Chestnut Streets

Pittsburgh, PA 15222
Federal Bldg.
1000 Liberty Avenue

Wilkes-Barre, PA 18701
Penn Place
20 North Pennsylvania Ave.

Norfolk, VA 23510
Federal Office Bldg.
200 Granby Mall

Charlestown, WV 25301
550 Egan Street

REGION 4
(AL, FL, GA, KY, MS, NC, SC, TN)
1375 PEACHTREE STREET, N.E.
ATLANTA, GA 30367

Birmingham, AL 35216
2047 Canyon Road—Todd Mall

Mobile, AL 36693
3737 Government Blvd.

Savannah, GA 31401
1600 Dryton Street

Smyrna, GA 30080
Herodian Way

Tucker, GA 30084
Bldg. 7
La Vista Perimeter Office Park

Jackson, MS 39269
Federal Bldg.
100 West Capitol Street

Columbia, SC 29201
1835 Assembly Street

Nashville, TN 37215
2002 Richard Jones Road

Fort Lauderdale, FL 33324
Jacaranda Executive Court
8040 Peters Road

Jacksonville, FL 32216
3100 University Blvd. South

Tampa, FL 33602
700 Twiggs Street

Frankfort, KY 40601
John C. Watts Federal Bldg.
330 West Broadway

Raleigh, NC 27601
Century Station
300 Fayetteville Street Mall

TABLE 19-4 (*Continued*)

REGION 5
(IL, IN, MI, MN, OH, WI)
230 SOUTH DEARBORN STREET
CHICAGO, IL 60604

Calumet City, IL 60409
1600 167th Street

Des Plaines, IL 60018
2360 East Devon Avenue

North Aurora, IL 60524
344 Smoke Tree Business Park

Peoria, IL 61614-1223
2001 West Willow Knolls Road

Appleton, WI 54915
2618 North Ballard Road

Madison, WI 53713
2934 Fish Hatchery Road

Milwaukee, WI 53203
310 West Wisconsin Avenue

Indianapolis, IN 46204
46 East Ohio Street

Minneapolis, MN 55401
110 South 4th Street

Lansing, MI 48917
801 South Waverly Road

Cincinnati, OH 45246
36 Triangle Park Drive

Cleveland, OH 44199
Federal Office Bldg.
1240 East 9th Street

Columbus, OH 43215
Federal Office Bldg.
200 North High Street

Toledo, OH 43604
Federal Office Bldg.
234 North Summit Street

REGION 6
(AR, LA, NM, OK, TX)

Little Rock, AR 72201
Savers Bldg.
320 West Capitol Avenue

Baton Rouge, LA 70806
2156 Wooddale Blvd.
Hoover Annex

Albuquerque, NM 87102
320 Central Avenue, S.W.

Oklahoma City, OK 73102
420 West Main Place

Austin, TX 78701
611 East 6th Street

Corpus Christi, TX 78401
Government Plaza
400 Mann Street

Dallas, TX 75228
8344 East R.L. Freeway

Fort Worth, TX 76180-7604
North Star 2 Bldg.

Houston, TX 77004
2320 La Branch Street

Houston, TX 77060
350 N. Sam Houston Pkwy.

Lubbock, TX 79401
Federal Bldg.
1205 Texas Avenue

(*continued*)

TABLE 19-4 (*Continued*)

REGION 7
(IA, KS, MO, NE)
911 WALNUT STREET
KANSAS CITY, MO 64106

Des Moines, IA 50309
210 Walnut Street

Kansas City, MO 64106
6200 Connecticut Avenue

St. Louis, MO 63120
4300 Goodfellow Blvd.

Wichita, KS 67202
216 North Waco

Omaha, NE 68106
Overland-Wolf Bldg.
6910 Pacific Street

REGION 8
(CO, MT, ND, SD, UT, WY)
FEDERAL BLDG.
1961 STOUT STREET
DENVER, CO 80294

Denver, CO 80204
1244 Speer Blvd.
Colonade Center

Englewood, CO 80111
7935 E. Prentice Avenue

Bismarck, ND 58501
Federal Bldg.

Billings, MT 59101
19 North 25th Street

Salt Lake City, UT 84165-0200
1781 South 300 West

REGION 9
(AMERICAN SAMOA, AZ, CA, GUAM, HI, NV,
TRUST TERRITORIES OF THE PACIFIC)
71 STEVENSON STREET
SAN FRANCISCO, CA 94105

Phoenix, AZ 85016
3221 North 16th Street

Honolulu, HI 96850
300 Ala Moana Blvd.

San Francisco, CA 94105
71 Stevenson Street

Carson City, NV 68106
1050 East Williams Street

TABLE 19-4 (*Continued*)

REGION 10 (AK, ID, OR, WA) 1111 THIRD AVENUE SEATTLE, WA 98101-3212	
Anchorage, AK 99513-7571 Federal Bldg. 222 West 7th Avenue	Boise, ID 83702 3050 North Lake Harbor Lane
Portland, OR 97204 1220 S.W. Third Avenue	Bellevue, WA 98004 121 107th Avenue, N.E.

ENVIRONMENTAL PROTECTION AGENCY (EPA)

The EPA is an independent federal agency, created in 1970 to protect the country's environment. The EPA administers the Toxic Substances Control Act (TSCA), the Federal Air Pollution Program, the Federal Water Pollution Program, and the Resource Conservation and Recovery Act (RCRA). All federal agencies are required to file with the EPA a written analysis of the environmental impact of a proposed action, including alternatives and any expected adverse effects. The EPA must comment on these impact statements before final action by the Council on Environmental Quality (CEQ), which coordinates Federal environmental activities.

The Office of Research and Development of EPA has established the Technology Information Transfer and Support Program to disseminate information on successful technology to control air, water, and solid waste pollution. Seminars, held on a regional basis, are used as the method of communication backed by special publications, films, photos, and exhibits. The publications include *Technical Capsule Reports*, a series on proven pollution control techniques. The information presented at seminars is published in the *Seminar Publication Series*. Basic to the seminars are process design manuals which present information on all of the usable and practical technology needs of the areas in which they are held.

The EPA also publishes semi-annually a *Regulatory Agenda* which summarizes the status of regulations under development, revision, and review. The purpose is to keep interested parties informed of the progress of these regulations. Persons wishing to be on the mailing list for Regulatory Agenda may contact:

Regulatory Development Branch (PM-223Y)
Environmental Protection Agency
401 M Street SW
Washington, DC 20460

TOXIC SUBSTANCES CONTROL ACT (TSCA)

The mission of TSCA is to prevent risk of injury from harmful chemicals. The EPA is authorized to regulate against such risk at any stage in the life cycle of a chemical, including manufacture, processing, distribution, use, and disposal. The EPA may require manufacturers and processors of a designated chemical to test for certain adverse health or environmental effects and to keep appropriate records of results. EPA has the authority to require testing after finding that:

1. a chemical substance may present an unreasonable risk of injury to human health or the environment, or the chemical is produced in substantial quantities which could result in significant or substantial human or environmental exposure,
2. available data to evaluate the chemical are inadequate,
3. testing is needed to develop the necessary data.

The EPA's Office of Pollution Prevention and Toxics administers the Existing Chemical Program which screens, establishes testing requirements for, assesses, and develops strategies for managing risks posed by approximately 14,000 chemicals (other than polymers) that are produced in quantities of more than 10,000 pounds per year. Excluded are eight product categories: pesticides, tobacco, nuclear material, firearms and ammunitions, food, food additives, drugs, and cosmetics. An important component of this program is the Master Testing List of 320 specific chemicals (1992 List). This list may be obtained from:

Office of Pollution Prevention and Toxics
U.S. Environmental Protection Agency
Washington, DC 20460

Actions taken on asbestos, dioxin, and polychlorinated biphenyls (PCBs) have been widely publicized. Asbestos is being phased out of industrial uses, including electrical and thermal insulation.

Dioxin, 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) is a highly toxic contaminant in the manufacture of a herbicide. The disposal of dioxin in wastes is now closely monitored and controlled by EPA.

The rule governing use of PCBs as liquid dielectric in electrical equipment became effective August 18, 1982. This rule allows the use of certain electrical equipment containing PCBs to continue under specified conditions. The rule prohibits use of PCBs in transformers and electromagnets (with concentration of 500 parts per million or greater), posing an exposure to food or feed, after October 1, 1985. A weekly inspection of this equipment is required until that date. Other provisions include:

- A requirement for a quarterly inspection of other PCB transformers for their remaining useful life
- A requirement to maintain records of inspection/maintenance for at least three years after disposing of PCB transformers
- An authorization for the use of large PCB capacitors located in contained and restricted access electrical substations for the remainder of their useful lives

• A prohibition on the use of all other large PCB capacitors after October 1, 1988.

Formaldehyde has been investigated in a TSCA study conducted by the National Cancer Institute involving 26,561 workers at ten facilities that produce either formaldehyde or formaldehyde-containing products. The study showed mortality rates no different among these workers than in the general population. The study concluded that formaldehyde can be used safely in the workplace and in consumer products.

FEDERAL AIR POLLUTION PROGRAM

The major law, administered by the EPA, governing air pollution is the *Clean Air Act*, as amended. This act is designed to enhance the quality of air resources, and thereby concerns manufacturers and users of organic coatings.

The EPA prepares a Guideline Series to assist regional, state, and local jurisdictions in the development of air pollution regulations for volatile organic compounds (VOC) which contribute to the formation of photochemical oxidants.

The official definition of a volatile organic compound is stated in the *Federal Register*, Vol. 57, No. 22/Monday, February 3, 1992, /Rules and Regulations, p. 3945. As generally understood, a volatile organic compound is any organic compound that, when released into the atmosphere, can remain long enough to participate in a photochemical reaction. Known exceptions, which have been determined to have negligible photochemical activity, include methane, ethane, methyl chloride, 1,1,1,-trichloroethane (methyl chloroform), and certain fluorocarbons.

Table 19-5 lists hazardous air pollutants from Section 112 of the Clean Air Act, as amended and effective in 1993.

TABLE 19-5 EPA Title III—Hazardous Air Pollutants

Acetaldehyde	Biphenyl
Acetamide	Bis(2-ethylhexyl)phthalate (DEHP)
Acetonitrile	Bis(chloromethyl)ether
Acetophenone	Bromoform
2-Acetylaminofluorene	1,3-Butadiene
Acrolein	Calcium cyanamide
Acrylamide	Caprolactam
Acrylic acid	Captan
Acrylonitrile	Carbaryl
Allyl chloride	Carbon disulfide
4-Aminobiphenyl	Carbon tetrachloride
Aniline	Carbonyl sulfide
o-Anisidine	Catechol
Asbestos	Chloramben
Benzene (including benzene from gasoline)	Chlordane
Benzidine	Chlorine
Benzotrichloride	Chloroacetic acid
Benzyl chloride	2-Chloroacetophenone

(*continued*)

TABLE 19-5 (*Continued*)

Chlorobenzene
Chlorobenzilate
Chloroform
Chloromethyl methyl ether
Chloroprene
Cresols/Cresylic acid (isomers and mixture)
o-Cresol
m-Cresol
p-Cresol
Cumene
2,4-D, salts and esters
DDE
Diazomethane
Dibenzofurans
1,2-Dibromo-3-chloropropane
Dibutylphthalate
1,4-Dichlobenzene(p)
3,3,-Dichlorobenzidene
Dichloroethyl ether (Bis(2-chloroethyl)ether)
1,3-Dichloropropene
Dichlorvos
Diethanolamine
N,N-Diethyl aniline (N,N-Dimethylaniline)
Diethyl sulfate
3,3-Dimethoxybenzidine
Dimethyl aminoazobenzene
3,3-Dimethyl benzidine
Dimethyl carbamoyl chloride
Dimethyl formamide
1,1-Dimethyl hydrazine
Dimethyl phthalate
Dimethyl sulfate
4,6-Dinitro-o-cresol, and salts
2,4-Dinitrophenol
2,4-Dinitrotoluene
1,4-Dioxane (1,4-Diethyleneoxide)
1,2-Diphenylhydrazine
Epichlorohydrin (1-Chloro-2,3-epoxypropane)
1,2-Epoxybutane
Ethyl acrylate
Ethyl benzene
Ethyl carbamate (Urethane)
Ethyl chloride (Chloroethane)
Ethylene dibromide (Dibromoethane)
Ethylene glycol
Ethylene imine (Aziridine)
Ethylene oxide
Ethylene thiourea
Ethylidene dichloride (1,1-Dichloroethane)
Formaldehyde
Heptachlor
Hexachlorobenzene
Hexachlorobutadiene
Hexachlorocyclopentadiene
Hexachloroethane
Hexamethylene-1,6-diisocyanate
Hexamethylphosphoramide
Hexane
Hydrazine
Hydrochloric acid
Hydrogen fluoride (Hydrofluoric acid)
Hydrogen sulfide
Hydroquinone
Isophorone
Lindane (all isomers)
Maleic anhydride
Methanol
Methoxychlor
Methyl bromide (Bromomethane)
Methyl chloride (Chloromethane)
Methyl chloroform (1,1,1-Trichloroethane)
Methyl ethyl ketone (2-Butanone)
Methyl hydrazine
Methyl iodide (Iodomethane)
Methyl isobutyl ketone (Hexone)
Methyl isocyanate
Methyl methacrylate
Methyl tert butyl ether
4,4-Methylene bis(2-chloroaniline)
Methylene chloride (Dichloromethane)
Methylene diphenyl diisocyanate (MDI)
4,4-Methylenedianiline
Naphthalene
Nitrobenzene
4-Nitrobiphenyl
4-Nitrophenol
2-Nitropropane
N-Nitroso-N-methylurea
N-Nitrosodimethylamine
N-Nitrosomorpholine
Parathion
Pentachloronitrobenzene (Quintobenzene)
Pentachlorophenol
Phenol
p-Phenylenediamine
Phosgene
Phosphine
Phosphorus
Phthalic anhydride
Polychlorinated biphenyls (Aroclors)
1,3-Propane sultone
beta-Propiolactone
Propionaldehyde
Propoxur (Baygon)

TABLE 19-5 (*Continued*)

Propylene dichloride (1,2-Dichloropropane)	Vinyl bromide
Propylene oxide	Vinyl chloride
1,2-Propylenimine (2-Methyl aziridine)	Vinylidene chloride (1,1-Dichloroethylene)
Quinoline	Xylenes (isomers and mixture)
Quinone	o-Xylenes
Styrene	m-Xylenes
Styrene oxide	p-Xylenes
2,3,7,8-Tetrachlorodibenzo-p-dioxin	INORGANIC MATERIALS
1,1,2,2,-Tetrachloroethane	Antimony Compounds
Tetrachloroethylene (Perchloroethylene)	Arsenic Compounds (inorganic including arsine)
Titanium tetrachloride	Beryllium Compounds
Toluene	Cadmium Compounds
2,4-Toluene diamine	Chromium Compounds
2,4-Toluene diisocyanate	Cobalt Compounds
o-Toluidine	Coke Oven Emissions
Toxaphene (chlorinated camphene)	Cyanide Compounds *1
1,2,4-Trichlorobenzene	Glycol ethers *2
1,1,2-Trichloroethane	Lead Compounds
Trichloroethylene	Manganese Compounds
2,4,5-Trichlorophenol	Mercury Compounds
2,4,6-Trichlorophenol	Fine mineral fibers *3
Triethylamine	Nickel Compounds
Trifluralin	Polycyclic Organic Matter *4
2,2,4-Trimethylpentane	Radionuclides (including radon) *5
Vinyl acetate	Selenium Compounds

ASTM D 2369, *Standard Method of Test for Volatile Content of Coatings*, is recommended by EPA for determining compliance with standards. It is recognized that this method may not be suitable for determining the total VOC content of all coatings cured at elevated temperatures where photochemically reactive compounds may be formed and released to the atmosphere. Additional test methods may be required as more scientific information on this subject becomes available.

The document which is most directly related to insulation coatings is EPA-450/2-77-033 OAQPS No. 1.2-087, *Control of Volatile Emissions from Existing Stationary Sources, Volume IV: Coating for Insulation of Magnet Wire*. A wire enameling plant with only a few uncontrolled ovens could easily exceed 91 megagrams per year (100 tons per year) of VOC emissions. The most common control technique used for wire coating ovens is incineration. Essentially, all solvent emissions from the ovens can be directed to an incinerator with a combustion efficiency of at least 90 percent. This efficiency is reasonable to attain. Thermal incinerators have an efficiency range from 90 to 99 percent. Catalytic oxidizers have an efficiency range of 90–95 percent, if not fouled.

Low-polluting coatings are beginning to be used in the wire coating industry. It is reasonable to exempt an oven from the incineration requirement if the coatings used contain less than the recommended limitation for low-solvent coatings of 0.20 kilograms of solvent per liter of coating, (1.7 pounds of solvent per gallon of coating), minus any water. This emission limit can be met with high-solids coatings having

greater than 77 percent solids by volume. Powder coatings and hot melt coatings will both achieve this. This emission limit can also be met with a waterborne coating which contains 29 volume percent solids, 8 volume percent organic solvent, and 63 volume percent water. A waterborne emulsion with no organic solvent would, of course, meet the recommended limit.

Approximately the same amount of solvent will be emitted from a low-solvent coating meeting the above limitation as from an equal volume of solids applied as a conventional coating with 90 percent incineration of solvent emissions from the conventional coating.

The solvent content of solvent-type wire enamels typically ranges from 67 to 85 percent. Cresylic acid and various cresols, xylene, and mixtures of C_8 to C_{12} aromatics are widely used. Other solvents include:

- alcohols
- high-flash naphtha (known as hi-flash naphtha)
- methyl ethyl ketone
- phenol
- N-methyl pyrrolidine

The relevant document for control technologies is EPA/625/6-91/014, June 1991: *Handbook—Control Technologies for Hazardous Air Pollutants*.

FEDERAL WATER POLLUTION PROGRAM

The principal law governing pollution of the Nation's waterways is the Federal Water Pollution Control Act, or Clean Water Act. Originally enacted in 1948, it was totally revised by amendments in 1972 that gave the Act its current (1993) shape. The 1972 legislation spelled out ambitious programs for water quality improvement that are still being implemented by industries and municipalities. Congress made certain fine-tuning amendments in 1977, revised portions of the law in 1981, and enacted further amendments in 1987.

The Clean Water Act has as its objective the restoration and maintenance of the "chemical, physical, and biological integrity of the Nation's waters." Two goals also were established in the 1972 legislation: zero discharge of pollutants by 1985 and, where possible, water quality that is both fishable and swimmable by mid-1983. While those dates have passed without full implementation, the goals remain, and efforts to attain them continue.

The EPA issues regulations containing the best practicable technology (BPT) and best available technology (BAT) effluent standards applicable to various categories of industrial sources, including organic chemical manufacturing and related industries. This Act embodies a philosophy of Federal–State partnership in which the Federal government sets the agenda and standards for pollution abatement, while states carry out day-to-day activities of implementation and enforcement.

The EPA has prepared these publications relevant to companies in and serving the electrical and electronics industries. To inquire about their availability, write to:

U.S. Environmental Protection Agency
Office of Water Resource Center
RC-4100
401 M Street, SW
Washington, DC 20460

- *Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Organic Chemicals, Plastics, and Synthetic Fibers Point Source Category*
  Volume I EPA# 440/1-87-009a
  Volume II EPA# 440/1-87-009b
- *Supplement to the Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Organic Chemicals, Plastics, and Synthetic Fibers Point Source Category—Final*
  EPA# 821-R-93-007
- *Re-Evaluation of the Economic Impact Analysis of Effluent Limitations Guidelines and Standards for the Organic Chemicals, Plastics, and Synthetic Fibers Industry*
  EPA# 821/R-93-008
- *Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Plastics Molding and Forming Point Source Category—Final*
  EPA# 440/1-84-069
- *Economic Impact Analysis of Effluent Limitations Guidelines and Standards for the Plastics Molding and Forming Industry*
  EPA# 440/2-84-025

A list of 65 toxic pollutants, shown in Table 19-6, has been developed by a multidisciplinary task force of scientists, forming a basis for the development of effluent limitations from point sources. The EPA may, when appropriate, revise the list to add or remove pollutants, taking into account their toxicity, persistence, degradability, and the extent of their effect on the usual or potential organisms found in any waters.

TABLE 19-6 EPA Toxic Pollutant List for Effluents to Waterways

1. Acenaphthene
2. Aerolein
3. Acrylonitrile
4. Aldrin/Dieldrin[1]
5. Antimony and compounds[2]
6. Arsenic and compounds
7. Asbestos
8. Benzene
9. Benzidine[1]
10. Beryllium and compounds
11. Cadmium and compounds

(*continued*)

TABLE 19-6 (*Continued*)

12. Carbon tetrachloride
13. Chlordane (technical mixture and metabolites)
14. Chlorinated benzenes (other than dichlorobenzenes)
15. Chlorinated ethanes (including 1,2-dichloroethane, 1,1,1-trichloroethane, and hexachloroethane)
16. Chloroalkyl ethers (chloromethyl, chloroethyl, and mixed ethers)
17. Chlorinated naphthalene
18. Chlorinated phenols (other than those listed elsewhere; includes trichlorophenols and chlorinated cresols)
19. Chloroform
20. 2-chlorophenol
21. Chromium and compounds
22. Copper and compounds
23. Cyanides
24. DDT and metabolites[1]
25. Dichlorobenzenes (1,2-, 1,3-, and 1,4-dichlorobenzenes)
26. Dichlorobenzidine
27. Dichloroethylenes (1,1-, and 1,2-dichloroethylene)
28. 2,4-dichlorophenol
29. Dichloropropane and dichloropropene
30. 2,4-dimethylphenol
31. Dinitrotoluene
32. Diphenylhydrazine
33. Endosulfan and metabolites
34. Endrin and metabolites[1]
35. Ethylbenzene
36. Fluoranthene
37. Haloethers (other than those listed elsewhere; includes chlorophenylphenyl ethers, bromophenylphenyl ether, bis(dichloroisopropyl) ether, bis-((chloroethoxy) methane and polychlorinated diphenyl ethers)
38. Halomethanes (other than those listed elsewhere; includes methylene chloride, methylchloride, methylbromide, bromoform, dichlorobromomethane, trichlorofluoromethane, dichlorodifluoromethane)
39. Heptachlor and metabolites
40. Hexachlorobutadiene
41. Hexachlorocyclohexane (all isomers)
42. Hexachlorocyclopentadiene
43. Isophorone
44. Lead and compounds
45. Mercury and compounds
46. Naphthalene
47. Nickel and compounds
48. Nitrobenzene
49. Nitrophenols (including 2,4-dinitrophenol, dinitrocresol)
50. Nitrosamines
51. Pentachlorophenol
52. Phenol
53. Phthalate esters
54. Polychlorinated biphenyls (PCBs)[1]
55. Polynuclear aromatic hydrocarbons (including benzanthracenes, benzopyrenes, benzofluoranthene, chrysenes, dibenzanthracenes, and indenopyrenes)

TABLE 19-6 (*Continued*)

56. Selenium and compounds
57. Silver and compounds
58. 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)
59. Tetrachloroethylene
60. Thallium and compounds
61. Toluene
62. Toxaphene[1]
63. Trichloroethylene
64. Vinyl chloride
65. Zinc and compounds

[1]Effluent standard promulgated (40 CFR Part 129).

[2]The term "compounds" shall include organic and inorganic compounds.

EPA REGIONAL OFFICES

EPA regional offices are shown in Table 19-7.

TABLE 19-7 EPA Regional Offices

REGION	STATES COVERED
JFK Federal Building Boston, MA 02203	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont
26 Federal Plaza New York, NY 10278	New Jersey, New York, Virgin Islands, Puerto Rico
Curtis Building 6th and Walnut Streets Philadelphia, PA 19106	Delaware, Maryland, Pennsylvania, Virginia, West Virginia, District of Columbia
345 Courtland Street, NE Atlanta, GA 30365	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee
230 South Dearborn Street Chicago, IL 60604	Indiana, Illinois, Michigan, Minnesota, Ohio, Wisconsin
1201 Elm Street Dallas, TX 75270	Arkansas, Louisiana, New Mexico, Oklahoma, Texas
324 East 11th Street Kansas City, MO 64106	Iowa, Kansas, Missouri, Nebraska
1860 Lincoln Street Denver, CO 80295	Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming
215 Fremont Street San Francisco, CA 94105	Arizona, California, Hawaii, Nevada, American Samoa, Guam, Trust Territories of the Pacific, Wake Island
1200 Sixth Avenue Seattle, WA 98101	Alaska, Idaho, Oregon, Washington

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)

U.S. Department of Commerce
Gaithersburg, MD 20899-001

NIST's primary mission is to promote U.S. economic growth by working with industry to develop and apply technology, measurements, and standards. It administers a portfolio of four major programs:

- A rigorously competitive *Advanced Technology Program* providing cost-sharing grants to industry for development of high-risk technologies with significant commercial potential;
- A grassroots *Manufacturing Extension Partnership* helping small and medium-sized companies adopt new technologies;
- A strong laboratory effort planned and implemented in cooperation with industry and focused on measurements, standards, evaluated data, and test methods;
- A highly visible quality outreach program associated with the Malcolm Baldridge National Quality Award.

In 1993, the staff comprised 3,200 scientists, engineers, technicians, and support personnel, plus some 1,200 visiting researchers. The Institute operates more than 40 different research facilities that are accessible to outside researchers for collaborative or independent research. Some are one-of-a-kind facilities not available elsewhere in the United States.

Among the more than 350 publications of NIST are the following:

- *Journal of Research of the National Institute of Standards and Technology*, bimonthly reports on research and development results in physics, chemistry, engineering, mathematics, and computer science.
- *Technology at a Glance*, a free newsletter providing updates on NIST research, grants, and other program activities. Issued quarterly.
- *Guide to NIST*, provides an overview of the activities of NIST with brief descriptions of more than 250 research projects, grants, and industry outreach programs, services and facilities, followed by contact names and phone numbers.

Noteworthy programs include the following:

- *Electrical and Optical Properties of Polymers*
- *Gaseous Electronics*
- *Polymer Blends*
- *Polymer Combustion Research*
- *Polymer Mechanics and Structure*
- *Processing Science for Polymer Composites*
- *Semiconductor Electronics*
- *Testing Electronic Systems*

NATIONAL CENTER FOR STANDARDS AND CERTIFICATION INFORMATION (NCSCI)

Established in 1965 as part of NIST, The National Center for Standards and Certification Information provides information on U.S., foreign, and international voluntary standards, government regulations, and rules of certification for nonagricultural products. The Center serves as a referral service and focal point for information about standards and standards-related information. The NCSCI reference collection of standards-related documents includes:

- Microfilm files of military and federal specifications, U.S. industry and national standards, and international and selected foreign national standards;
- Reference books, including directories, technical and scientific dictionaries, encyclopedias, and handbooks;
- Articles, pamphlets, reports, and handbooks on standardization and certification;
- Standards-related periodicals and newsletters.

These documents are available in the Center for review only. NCSCI does not provide copies of its documents. This facility is open to visitors Monday–Friday, 8:30 AM–5:00 PM at Technology Building, Room B157, NIST, Gaithersburg, MD (about 25 miles northwest of Washington, DC).

RURAL ELECTRIFICATION ADMINISTRATION (REA)

U.S. Department of Agriculture, Washington, DC 20250

REA, an agency of the U.S. Department of Agriculture, was created by Executive Order in 1935 to finance electric and telephone facilities in rural areas. Loans for these activities reached a peak of over $7 billion in 1980, dropping to $1.2 billion in 1992, when agency staff headquartered in Washington was 417.

Electric Loan Program

REA makes loans to nonprofit and cooperative associations, public bodies, and other electric utilities. The loans finance the construction and operation of generating plants, transmission and distribution lines, or systems to provide initial and continued adequate electric service to persons in rural areas. The agency also provides engineering and management assistance to its borrowers. Loans are repaid from the operating revenues of the systems REA finances. Publications are available covering all aspects of this program.

Telephone Loan Program

Telephone loans may be made to telephone companies, to public bodies, and to cooperative nonprofit, limited-dividend or mutual associations. The agency also provides

engineering and management assistance to its borrowers. Loans are repaid from the operating revenues of the systems REA finances. Publications are available covering all aspects of this program.

U.S. GOVERNMENT SPECIFICATIONS

There are several thousand U.S. Government specifications relating to electrical/electronic insulating materials. Information about both government and industry specifications and standards is available from many government sources. Major sources are listed below. (The end of this chapter contains Exhibit 19-4, Military Specification MIL-P-46179 (MR), *Plastic Molding and Extrusion Material, Polyamide-imide*, which is typical for a plastic material.) Note references to ASTM standards and UL tests.

U.S. GOVERNMENT PRINTING OFFICE

Washington, DC 20402

Several key publications may be obtained from the Superintendent of Documents, U.S. Government Printing Office:

- *Department of Defense Index of Specifications and Standards (DODISS)*, D7.14:981. Subscription service consists of two parts. Part I, Alphabetical Index; Part II, Numerical Index. This is a consolidated edition of the indexes of Military Specifications and Standards used by the Department of the Air Force, Department of the Army, and the Department of the Navy, which were formerly issued separately.
- *Index of Federal Specifications, Standards and Commercial Item Descriptions*, GS2.8/2:981. Subscription service provides alphabetical, numerical, and Federal Supply Classification listings of Federal and Interim Federal Standards, Federal Handbooks, and Qualified Products Lists in general use throughout the Federal Government.
- *Plastics for Aerospace Vehicles, Part I—Reinforced Plastics (Handbook)*, MIL-HDBK-17A
- *Plastics (Handbook)*, MIL-HDBK-700
- *Adhesives—A Guide to Their Properties and Uses as Described by Federal and Military Specifications (Handbook)*, MIL-HDBK-725

GENERAL SERVICES ADMINISTRATION (GSA)

Federal specifications are available from the GSA Business Service Centers at the addresses shown in Table 19-8.

TABLE 19-8 GSA Business Service Centers

ADDRESS AND TELEPHONE NUMBER	SERVICE AREA
10 Causeway Street Boston, MA 02222 (617) 565-8100	*Region 1*—Connecticut, Massachusetts, New Hampshire, Maine, Rhode Island, and Vermont
26 Federal Plaza New York, NY 10278 (212) 264-1234	*Region 2*—New Jersey, New York, Puerto Rico, and Virgin Islands
Seventh and D Streets, SW Washington, DC 20407 (202) 708-5804	*Region 3 (National Capital Region)*—District of Columbia, nearby Maryland and Virginia
100 Penn Square East Philadelphia, PA 19107 (215) 656-5525	*Region 3*—Delaware, Pennsylvania, Maryland and Virginia (other than above), and West Virginia
401 West Peachtree Street Atlanta, GA 30365 (404) 331-5103	*Region 4*—Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee
230 South Dearborn Street Chicago, IL 60604 (312) 353-5383	*Region 5*—Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin
1500 East Bannister Road Kansas City, MO (816) 926-7203	*Region 6*—Iowa, Kansas, Missouri, and Nebraska
819 Taylor Street Fort Worth, TX 76102 (817) 334-3284	*Region 7*—Arkansas, Louisiana, New Mexico, Oklahoma, and Texas
Denver Federal Center, Building 41 Denver, CO 80225 (303) 236-7408	*Region 8*—Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming
525 Market Street San Francisco, CA 94105 (415) 744-5050	*Region 9*—Northern California, Hawaii, and all Nevada except Clark County
300 North Los Angeles Street Los Angeles, CA 90012 (213) 894-3210	*Region 9*—Los Angeles, Southern California, Arizona, and Clark County, Nevada
400 15th Street, SW Auburn, WA 98001 (206) 931-7956	*Region 10*—Alaska, Idaho, Oregon, and Washington

THE NAVAL PUBLICATIONS AND FORMS CENTER

5801 Tabor Avenue, Philadelphia, PA 19120

This facility has responsibility for the operation of Defense Single Stock Point for Standardization Documents included in the DoD Index of Military Specifications and Standards.

Publications available include:

• *Department of Defense Single Stock Point (DoD-SSP) for Specifications and Standards, A Guide for Private Industry*

• *Army, Navy, and Air Force Specifications, including MIL and JAN Specifications*

• *Plastics (Handbook)*, MIL-HDBK-700A

• *Adhesives—A Guide to Their Properties and Uses as Described by Federal and Military Specifications* (Handbook), MIL-HDBK-725

Exhibit 19-3 shows the order form for Military Specifications and Standards.

DEPARTMENT OF THE NAVY
NAVAL PUBLICATIONS AND FORMS CENTER
5801 Tabor Ave.
Philadelphia, Pa. 19120
OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

POSTAGE AND FEES PAID
DEPARTMENT OF THE NAVY
DOD - 316

Please self address the above label

SPECIFICATIONS AND STANDARDS REQUISITION

Send the number of copies of documents listed below which are in the DoD Index of Specifications and Standards. Limit 5 line items per request. Requests submitted on this form will speed service. Reorder forms will be enclosed with each shipment. *FORWARD REQUEST TO*: Naval Publications and Forms Center, Code 3015, 5801 Tabor Avenue, Philadelphia, PA 19120.

1. QUANTITY	2. STANDARDIZATION DOCUMENT SYMBOL	3. TITLE *(From DoD Index of Specifications and Standards)*	4. NONAVAILABILITY CODE * *(NPFC use only)*

*NONAVAILABILITY CODE EXPLANATION

B – Item temporarily not in stock. Resubmit request in 30 days.
E – Item not identifiable as an active document listed in the DODISS. Direct questions concerning this action to NPFC, Attn: Code 1052 or call (215) 697-3321.
I – For Official Use Only. Submit request via cognizant DoD Inspection Office or Contract Administrator for certification of "need to know."
L – Industry standardization documents will not be furnished by NPFC to commercial concerns. Copies may be purchased from the appropriate Industry Association.

5. SIGNATURE OF REQUESTOR	6. DATE PREPARED *(YY, MM, DD)*	7. CLOSING DATE *(YY, MM, DD) (IFB, RFQ, or RFP)*

DD FORM 1425
82 MAY

Previous editions of this form are obsolete.

S/N 0102-LF-001-4252

Exhibit 19-3 (a) Order Form DD 1425 for Military Specifications and Standards.

INSTRUCTIONS FOR COMPLETING DD FORM 1425

Item 1. **Quantity**: Enter the number of publications requested.

*2. **Standardization Document Symbol**: Indicate the appropriate Standardization Document Symbol for each document requested.

3. **Title**: Enter the title of the document requested.

*4. **Nonavailability Code**: (For NPFC use only): The Naval Publications and Forms Center will enter the appropriate code to indicate the reason the requested document is unavailable.

5. **Signature of Requestor**: Self-explanatory

*6. **Date Prepared**: Enter the date prepared in the sequence of year, month, day (e.g., July 1, 1980 would be entered 80/07/01).

*7. **Closing Date**: Enter the closing date in the following format: year, month, day.

"General Note for Personnel Processing This Report:

Items marked with an asterisk (*) have been registered in the DoD Data Element Program."

Exhibit 19-3 (b) DD FORM 1425 (*Back*).

POLYAMIDE-IMIDE MILITARY SPECIFICATION MIL-P-46179

The following (Exhibit 19-4) is an example of a military specification for a plastic insulating material.

MIL-P-46179(MR)
3 December 1979

MILITARY SPECIFICATION

PLASTIC MOLDING AND EXTRUSION MATERIAL, POLYAMIDE-IMIDE

This specification is approved for use by the Army Materials and Mechanics Research Center, Department of the Army, and is available for use by all Departments and Agencies of the Department of Defense.

1. SCOPE AND CLASSIFICATION

1.1 *Scope*. This specification covers two grades of polyamide-imide resins.

1.2 *Classification*.

1.2.1 *Grades*. The polyamide-imide resins shall be of the following grades, as specified (see 6.2).

Grade GP—General purpose
Grade E—Electrical

2. APPLICABLE DOCUMENTS

2.1 *Issues of documents*. The following documents, of the issues in effect on date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein.

SPECIFICATIONS
FEDERAL
PPP-D-723—Drums, Fiber
PPP-D-729—Drums, Metal, 55-Gallon (for Shipment of Noncorrosive Material)
STANDARDS
MILITARY
MIL-STD-105—Sampling Procedures and Tables for Inspection by Attributes

Exhibit 19-4.

MIL-STD-129—Marking for Shipment and Storage
MIL-STD-1188—Commercial Packaging of Supplies and Equipment

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 *Other publications.* The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARDS
D 150—AC Loss Characteristics and Dielectric Constant (Permittivity) of Solid Electrical Insulating Materials
D 257—D-C Resistance or Conductance of Insulating Materials
D 618—Conditioning Plastics and Electrical Insulating Materials
D 648—Deflection Temperature of Plastics Under Load
D 785—Rockwell Hardness of Plastics and Electrical Insulating Materials
D 792—Specific Gravity and Density of Plastics by Displacement
D 1708—Tensile Properties of Plastics by Use of Microtensile Specimens
(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103).

UNDERWRITERS' LABORATORIES (UL), INC.
UL 94—Tests for Flammability of Plastic Materials for Parts in Devices and Appliances, dated December 1973.
(Application for copies should be made to the Underwriters' Laboratories, Inc., 207 E. Ohio Street, Chicago, IL 60611).

3. REQUIREMENTS

3.1 *Material.* The material shall consist of polyamide-imide resins with a basic polymer structure consisting of aromatic diamines linked to trimellitic anhydrides. The resins may contain up to 10 percent pigments, 5 percent lubricants and no fibrous reinforcement. Addition of reground material shall be permitted to the extent that the resultant material meets all property requirements specified herein.

3.2 *General property values (applicable to grades GP and E).* The material shall conform to the property values specified in table I, when tested as specified in the applicable procedure of 4.3.

Table I. General property values

Property	Value
Specific gravity	1.36 to 1.44
Tensile strength MPa (psi), min.	172 (25,000)
Tensile elongation at break, percent, min.	10
Deflection temperature °C (°F), min.	268 (515)
Hardness, Rockwell scale E, min.	E 77
Flammability	94 V-0[1]

[1] 94 V-0 by Underwriters' Laboratories test specified in 4.3.7 correlation with flammability under actual use conditions is not necessarily implied.

Exhibit 19-4 (*cont.*)

3.3 *Electrical property values (applicable to grade E only).*

Table II. Electrical property values

Property	Value
Dielectric constant at 10^3 Hz, min.	3.65
Dissipation factor at 10^3 Hz, max.	0.022
Volume resistivity, ohms-cm (ohm-in), min.	0.8×10^{16} (2×10^{16})
Surface resistivity, ohms, min.	5×10^{16}

3.4 *Color*. Unless otherwise specified, the color shall be opaque greenish brown (see 6.2).

3.5 *Form*. The form shall be pellets. When specified by the procuring activity, the form shall be in the size and shape specified (see 6.2).

3.6 *Workmanship*. The material shall be free of contamination and color and form shall be uniform from container to container within each lot (see 4.2.2.1.1).

4. QUALITY ASSURANCE PROVISIONS

4.1 *Responsibility for inspection*. Unless otherwise specified in the contract, the contractor is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract, the contractor may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.2 *Sampling for inspection and acceptance*. Sampling for inspection shall be performed in accordance with the provisions set forth in MIL-STD-105 except where otherwise indicated. For purposes of sampling, an inspection lot for examination and tests shall consist of all material submitted for delivery at one time.

4.2.1 *Inspection of materials and components*. In accordance with 4.1, the supplier is responsible for insuring that materials and components used were manufactured, tested and inspected in accordance with the requirements of referenced subsidiary specifications and standards to the extent specified. In event of conflict, this specification shall govern. A supplier's certificate of compliance with 3.1 shall be furnished.

4.2.2 *Inspection of material*.

4.2.2.1 *Examination of the material*. Examination of the material shall be made in accordance with the classification of defects, inspection levels and acceptable quality levels (AQLs) set forth below. The lot size, for purpose of determining the sample size in accordance with MIL-STD-105, shall be expressed in units of 100 pounds for examination in 4.2.2.1.1, and in units of shipping containers for examination in 4.2.2.1.2.

4.2.2.1.1 *Examination of the material for defects in appearance and workmanship*. The sample unit for this examination specified in table III shall be approximately one pound.

Exhibit 19-4 (*cont.*)

Table III. Examination of the material for defects in appearance and workmanship

Examine	Defect
Appearance and workmanship	When required, form size not as specified Not uniform in form from container to container Not uniform in color from container to container Not clean, presence of foreign material

4.2.2.1.2 *Examination of the preparation for delivery.* An examination shall be made in accordance with table IV to determine that packing and marking comply with section 5 requirements. The sample unit for this examination shall be one shipping container fully packed, selected just prior to the closing operation. Shipping containers fully prepared for delivery shall be examined for closure defects.

Table IV. Examination of preparation for delivery

Examine	Defects
Packing	Not level specified; not in accordance with contract requirements. Any nonconforming component, component missing, damaged or otherwise defective affecting serviceability. Inadequate application of components such as: incomplete closures of case liners; container flaps, loose or inadequate strappings, bulged or distorted container.
Quantity of material	Less than specified or indicated quantity.
Weight	Gross weight exceeds specified requirements.
Markings	Interior or exterior markings omitted, illegible, incorrect, incomplete, of improper size, location, sequence, method of application, or not in accordance with contract requirements.

4.2.2.1.3 *Inspection levels and acceptable quality levels (AQL's) for examinations.* The inspection levels for determining the sample size and the acceptable quality level (AQL) expressed as defects per 100 units shall be as follows:

Examination paragraph	Inspection level	AQL
4.2.2.1.1	II	2.5
4.2.2.1.2	S-2	2.5

4.2.3 *Testing.* The molding material shall be tested for the characteristics listed in table I and table II, as applicable. Testing shall be in accordance with the test methods specified herein for each lot submitted for inspection. The lot size, for the purpose of determining the sample size for testing shall be expressed in units of 100 pounds of material. The

Exhibit 19-4 (*cont.*)

sample unit of product shall consist of sufficient material to prepare all required specimens. The inspection level shall be S-1, with an acceptance number of 0. The results for each test shall be the averaged results of the specimens, unless only one specimen is required for testing.

4.2.3.1 *Classification of tests*. All tests shall be classified, as follows:

a. Lot acceptance tests (see 4.2.3.2).

b. Periodic lot check tests (see 4.2.3.3).

4.2.3.2 *Lot acceptance tests*. Lot acceptance tests shall be made on each lot of material and shall be the basis for acceptance or rejection of the lot, except when periodic lot check tests are required. Lot acceptance tests shall consist of testing for tensile strength, tensile elongation at break, and hardness. For grade E, lot acceptance tests shall include the additional tests specified in table II.

4.2.3.3 *Periodic lot check tests*. Periodic lot check tests shall be made on the first lot of material furnished under this specification, and on any subsequent lot specified by the procuring agency (see 6.2). If not specified by the procuring agency, periodic lot check tests shall be repeated at least once every year. Periodic lot check tests shall consist of all tests specified in table I and table II, as applicable. When periodic lot check tests are made, they shall be included in the basis for acceptance or rejection of the lot.

4.3 *Test methods*.

4.3.1 *Preparation of specimens*. Unless otherwise specified, test specimens shall be prepared by injection molding. Specimens shall be post cured for 24 ± 0.1 hours at 166° ± 5°C (330° ± 9°F), followed by 24 ± 0.1 hours at 243 ± 3°C (470° ± 5°F), followed by 24 ± 0.1 hours at 257 ± 3°C (495° ± 5°F).

4.3.2 *Test conditions*. Unless otherwise specified, all tests shall be performed at 23° ± 2°C (73.4° ± 3.6°F) and 50 ± 5 percent relative humidity. Specimens shall be conditioned in accordance with procedure A of ASTM D 618. Prior to conditioning, specimens shall be dried for 24 ± 0.1 hours at 166° ± 5°C (330° ± 9°F).

4.3.3 *Specific gravity*. One specimen shall be tested in accordance with method A-1 or A-2 of ASTM D 792 using the test specimen size specified in this method.

4.3.4 *Tensile strength and elongation at break*. Five specimens, each 3.2 ± 0.1 mm (0.125 ± 0.005 inches) thick, shall be tested in accordance with ASTM D 1708.

4.3.5 *Deflection temperature under load*. Three specimens shall be tested in accordance with ASTM D 648 using a fiber stress of 1820 KPa (264 psi). Length and width of test specimens shall be as specified in D 648 and thickness shall be 3.2 ± 0.3 mm (0.125 ± 0.015 inch).

4.3.6 *Hardness*. Five measurements shall be made in accordance with ASTM D 785. The determinations shall be made using procedure A and scale E as specified in ASTM D 785.

4.3.7 *Flammability*. Specimens shall be tested in accordance with Underwriters' Laboratories UL 94 using 1.6 mm (1/16 inch) thick specimens. The number of specimens to be tested and dimensions for length and width shall be as specified in Underwriters' Laboratories UL 94.

4.3.8 *Dielectric constant and dissipation factor*. Three specimens shall be tested in accordance with ASTM D 150, using any electrode system specified in this test method.

4.3.9 *Volume and surface resistivity*. Three specimens, each 3.2 ± 0.3 mm (0.125 ± 0.0125 inches) thick shall be tested in accordance with ASTM D 257. Other specimen dimensions shall be as allowed in ASTM D 257.

5. PACKAGING

Exhibit 19-4 (*cont.*)

Application. The requirements of section 5 apply only to purchase by or direct shipment to the Government.

5.1 *Packing*. Packing shall be level A, B, or Commercial as specified (see 6.2).

5.1.1 *Level A*. Unless otherwise specified, the material shall be packed in one of the following types of containers:

a. Fiber drums conforming to PPP-D-723, type II, grade A, or type III, grade A in quantities of 200 pounds, maximum.
b. Metal drums conforming to PPP-D-729, type III or type IV, in quantities of 400 pounds, maximum.

Insofar as practical, drums shall be of uniform shape and size, with minimum cube and tare consistent with the protection required. Drums shall contain identical quantities and shall be closed in accordance with the applicable container specification. Fiber drums shall be furnished with a 0.004 inch thick polyethylene liner property heat sealed.

5.1.2 *Level B*. Unless otherwise specified, the material shall be packed in one of the following types of containers:

a. Fiber drums conforming to PPP-D-723, type I, grade A in quantities of 200 pounds maximum.
b. Metal drums conforming to PPP-D-729, type III or type IV, in quantities of 400 pounds, maximum.

Insofar as practical, drums shall be of uniform shape and size with minimum cube and tare consistent with the protection required. Drums shall contain identical quantities and shall be closed in accordance with the applicable container specification. Fiber drums shall be furnished with a 0.004 inch thick polyethylene liner properly heat sealed.

5.1.3 *Commercial*. The material shall be packed in accordance with MIL-STD-1188.

5.2 *Marking*. In addition to any special marking required by the contract or purchase order, shipping containers shall be marked in accordance with MIL-STD-129, with the exception that commercial marking in accordance with MIL-STD-1188 applies for commercial packaging only.

6. NOTES

6.1 *Intended use*. The thermoplastic material is intended for use in applications requiring good mechanical and electrical properties at 250°C (500°F). Strength is retained at cryogenic temperatures making possible applications requiring a wide temperature range. The material is resistant to acids, hydrocarbon oils and most common solvents. Stability in vacuum is good and resistance to gamma radiation is excellent.

6.2 *Ordering data*. Procurement documents should specify the following:

a. Title, number and date of this specification.
b. Grade required (see 1.2.1).
c. Color, if different (see 3.4).
d. Specific pellet size, if required (see 3.5).
e. Periodic lot check tests, if required (see 4.2.3.3).
f. Level of packing required (see 5.1).

Custodian:
Army—MR

Preparing activity:
Army—MR

Project No. 9330-A860

Exhibit 19-4 (*cont.*)

Appendix

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CONVERSION FACTORS FOR FREQUENTLY USED UNITS

Measures and Weights

CLASSIFICATION UNIT	EQUIVALENTS IN OTHER UNITS OF SAME SYSTEM	METRIC EQUIVALENT
Weight (*avoirdupois*)		
Grain	0.036 dram	0.0648 gram
	0.002285 ounce	
Dram	27.343 grains	1.771 grams
	0.0625 ounce	
Ounce	16 drams	28.349 grams
	437.5 grains	
Pound	16 ounces	0.453 kilogram
	7,000 grains	
Short ton	2,000 pounds	0.907 metric ton
Long ton	2,240 pounds	1.016 metric ton
(*troy*)		
Grain	0.042 pennyweight	0.0648 gram
	0.002083 ounce	
Pennyweight	24 grains	1.555 grams
	0.05 ounce	
Ounce	20 pennyweight	31.103 grams
	480 grains	
Pound	12 ounces	0.373 kilogram
	240 pennyweight	
	5,760 grams	
(*apothecaries'*)		
Grain	0.05 scruple	0.0648 gram
	0.002083 ounce	
	0.0166 dram	
Scruple	20 grains	1.295 grams
	0.333 dram	
Dram	3 scruples	3.887 grams
	60 grains	
Ounce	8 drams	31.103 grams
	480 grains	
Pound	12 ounces	0.373 kilogram
	5,760 grains	
Volume		
Cubic inch	0.00058 cubic foot	16.378 cubic centimeters
	0.000021 cubic yard	
Cubic foot	1,728 cubic inches	0.028 cubic meter
	0.0370 cubic yard	
Cubic yard	27 cubic feet	0.765 cubic meter
	46,656 cubic inches	

(*continued*)

Measures and Weights (*continued*)

CLASSIFICATION UNIT	EQUIVALENTS IN OTHER UNITS OF SAME SYSTEM	METRIC EQUIVALENT
U.S. liquid measure		
Minim	1/60 fluidram 0.003759	0.061610 milliliters
Fluidram	60 minims 0.225 cubic inch	3.696 milliliters
Fluidounce	8 fluidrams 1.804 cubic inches	29.573 milliliters
Gill	4 fluidounces 7.218 cubic inches	118.291 milliliters
Pint	4 gills 28.875 cubic inches	0.473 liter
Quart	2 pints 57.75 cubic inches	0.946 liter
Gallon	4 quarts 231 cubic inches	3.785 liters
U.S. dry measure		
Pint	33.600 cubic inches	0.550 liter
Quart	2 pints 67.200 cubic inches	1.101 liters
Peck	8 quarts 537.605 cubic inches	8.809 liters
Bushel	4 pecks 2150.42 cubic inches	35.238 liters
Length		
Inch	0.083 foot 0.027 yard	2.540 centimeters
Foot	12 inches 0.333 yard	30.48 centimeters
Yard	3 feet 36 inches	0.914 meter
Rod	5.50 yards 16.5 feet	5.029 meters
Mile	5,280 feet 1,760 yards	1.609 kilometers
Area		
Square inch	0.007 square foot 0.00077 square yard	6.451 square centimeters
Square foot	144 square inches 0.111 square yard	0.093 square meter
Square rod	30.25 square yards 0.006 acre	25.293 square meters
Acre	4,840 square yards 43,560 square feet	0.405 hectare 4,047 square meters
Square mile	640 acres 102,400 square rods	2,590 square kilometers 259.2 hectares

Pressure

atm	psia	in Hg*	mm Hg*	bar	kg/cm²	dyn/cm²	N/m² (pascal)
1	14.6960	29.921	760.0	1.01325	1.03323	1,013,250	101,325

Volume

in³	ft³	gal	L	m³	cm³
1	5.787×10^{-4}	4.329×10^{-3}	0.0163871	1.63871×10^{-5}	16.3871

Density

lb/ft³	lb/gal	g/cm³	kg/m³ = g/L
1	0.133680	0.016018	16.018463

*Mercury.

Temperature Formulas

To convert from	to	
Degrees Celsius	Kelvin	$T_K = T_C + 273.15$
Degrees Fahrenheit	Kelvin	$T_K = (T_F + 459.67)/1.8$
Degrees Rankine	Kelvin	$T_K = T_R/1.8$
Degrees Fahrenheit	Celsius	$T_C = (T_F - 32)/1.8$
Degrees Kelvin	Celsius	$T_C = T_K - 273.15$

Temperature Equivalents

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
—	-458	-272.22	—	-422	-252.22
—	-456	-271.11	—	-420	-251.11
—	-454	-270.00	—	-418	-250.00
—	-452	-268.89	—	-416	-248.89
—	-450	-267.78	—	-414	-247.78
—	-448	-266.67	—	-412	-246.67
—	-446	-265.56	—	-410	-245.56
—	-444	-264.44	—	-408	-244.44
—	-442	-263.33	—	-406	-243.33
—	-440	-262.22	—	-404	-242.22
—	-438	-261.11	—	-402	-241.11
—	-436	-260.00	—	-400	-240.00
—	-434	-258.89	—	-398	-238.89
—	-432	-257.78	—	-396	-237.78
—	-430	-256.67	—	-394	-236.67
—	-428	-255.56	—	-392	-235.56
—	-426	-254.44	—	-390	-234.44
—	-424	-253.33	—	-388	-233.33

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
—	-386	-232.22	—	-292	-180.00
—	-384	-231.11	—	-290	-178.89
—	-382	-230.00	—	-288	-177.78
—	-380	-228.89	—	-286	-176.67
—	-378	-227.78	—	-284	-175.56
—	-376	-226.67	—	-282	-174.44
—	-374	-225.56	—	-280	-173.33
—	-372	-224.44	—	-278	-172.22
—	-370	-223.33	—	-276	-171.11
—	-368	-222.22	—	-274	-170.00
—	-366	-221.11	-457.6	-272	-168.89
—	-364	-220.00	-454.0	-270	-167.78
—	-362	-218.89	-450.4	-268	-166.67
—	-360	-217.78	-446.8	-266	-165.56
—	-358	-216.67	-443.2	-264	-164.44
—	-356	-215.56	-439.2	-262	-163.33
—	-354	-214.44	-436.0	-260	-162.22
—	-352	-213.33	-432.4	-258	-161.11
—	-350	-212.22	-428.8	-256	-160.00
—	-348	-211.11	-425.2	-254	-158.89
—	-346	-210.00	-421.6	-252	-157.78
—	-344	-208.89	-418.0	-250	-156.67
—	-342	-207.78	-414.4	-248	-155.56
—	-340	-206.67	-410.8	-246	-154.44
—	-338	-205.56	-407.2	-244	-153.33
—	-336	-204.44	-403.6	-242	-152.22
—	-334	-203.33	-400.0	-240	-151.11
—	-332	-202.22	-396.4	-238	-150.00
—	-330	-201.11	-392.8	-236	-148.89
—	-328	-200.00	-389.2	-234	-147.78
—	-326	-198.89	-385.6	-232	-146.67
—	-324	-197.78	-382.0	-230	-145.56
—	-322	-196.67	-378.4	-228	-144.44
—	-320	-195.56	-374.8	-226	-143.33
—	-318	-194.44	-371.2	-224	-142.22
—	-316	-193.33	-367.6	-222	-141.11
—	-314	-192.22	-364.0	-220	-140.00
—	-312	-191.11	-360.4	-218	-138.89
—	-310	-190.00	-356.8	-216	-137.78
—	-308	-188.89	-353.2	-214	-136.67
—	-306	-187.78	-349.6	-212	-135.56
—	-304	-186.67	-346.0	-210	-134.44
—	-302	-185.56	-342.4	-208	-133.33
—	-300	-184.44	-338.8	-206	-132.22
—	-298	-183.33	-335.2	-204	-131.11
—	-296	-182.22	-331.6	-202	-130.00
—	-294	-181.11	-328.0	-200	-128.89

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
-324.4	-198	-127.78	-155.2	-104	-75.56
-320.8	-196	-126.67	-151.6	-102	-74.44
-317.2	-194	-125.56	-148.0	-100	-73.33
-313.6	-192	-124.44	-144.4	-98	-72.22
-310.0	-190	-123.33	-140.8	-96	-71.11
-306.4	-188	-122.22	-137.2	-94	-70.00
-302.8	-186	-121.11	-133.6	-92	-68.89
-299.2	-184	-120.00	-130.0	-90	-67.78
-295.6	-182	-118.89	-126.4	-88	-66.67
-292.0	-180	-117.78	-122.8	-86	-65.56
-288.4	-178	-116.67	-119.2	-84	-64.44
-284.8	-176	-115.56	-115.6	-82	-63.33
-281.2	-174	-114.44	-112.0	-80	-62.22
-277.6	-172	-113.33	-108.4	-78	-61.11
-274.0	-170	-112.22	-104.8	-76	-60.00
-270.4	-168	-111.11	-101.2	-74	-58.89
-266.8	-166	-110.00	-97.6	-72	-57.78
-263.2	-164	-108.89	-94.0	-70	-56.67
-259.6	-162	-107.78	-90.4	-68	-55.56
-256.0	-160	-106.67	-86.8	-66	-54.44
-252.4	-158	-105.56	-83.2	-64	-53.33
-248.8	-156	-104.44	-79.6	-62	-52.22
-245.2	-154	-103.33	-76.0	-60	-51.11
-241.6	-152	-102.22	-72.4	-58	-50.00
-238.0	-150	-101.11	-68.8	-56	-48.89
-234.4	-148	-100.00	-65.2	-54	-47.78
-230.8	-146	-98.89	-61.6	-52	-46.67
-227.2	-144	-97.78	-58.0	-50	-45.56
-223.6	-142	-96.67	-54.4	-48	-44.44
-220.0	-140	-95.56	-50.8	-46	-43.33
-216.4	-138	-94.44	-47.2	-44	-42.22
-212.8	-136	-93.33	-43.6	-42	-41.11
-209.2	-134	-92.22	-40.0	-40	-40.00
-205.6	-132	-91.11	-36.4	-38	-38.89
-202.0	-130	-90.00	-32.8	-36	-37.78
-198.4	-128	-88.89	-29.2	-34	-36.67
-194.8	-126	-87.78	-25.6	-32	-35.56
-191.2	-124	-86.67	-22.0	-30	-34.44
-187.6	-122	-85.56	-18.4	-28	-33.33
-184.0	-120	-84.44	-14.8	-26	-32.22
-180.4	-118	-83.33	-11.2	-24	-31.11
-176.8	-116	-82.22	-7.6	-22	-30.00
-173.2	-114	-81.11	-4.0	-20	-28.89
-169.6	-112	-80.00	-0.4	-18	-27.78
-166.0	-110	-78.89	+3.2	-16	-26.67
-162.4	-108	-77.78	+6.8	-14	-25.56
-158.8	-106	-76.67	+10.4	-12	-24.44

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+14.0	−10	−23.33	+100.4	+38	+3.33
+17.6	−8	−22.22	+102.2	+39	+3.89
+19.4	−7	−21.67	+104.0	+40	+4.44
+21.2	−6	−21.11	+105.8	+41	+5.00
+23.0	−5	−20.56	+107.6	+42	+5.56
+24.8	−4	−20.00	+109.4	+43	+6.11
+26.6	−3	−19.44	+111.2	+44	+6.67
+28.4	−2	−18.89	+113.0	+45	+7.22
+30.2	−1	−18.33	+114.8	+46	+7.78
+32.0	±0	−17.78	+116.6	+47	+8.33
+33.8	+1	−17.22	+118.4	+48	+8.89
+35.6	+2	−16.67	+120.2	+49	+9.44
+37.4	+3	−16.11	+122.0	+50	+10.00
+39.2	+4	−15.56	+123.8	+51	+10.56
+41.0	+5	−15.00	+125.6	+52	+11.11
+42.8	+6	−14.44	+127.4	+53	+11.67
+44.6	+7	−13.89	+129.2	+54	+12.22
+46.4	+8	−13.33	+131.0	+55	+12.78
+48.2	+9	−12.78	+132.8	+56	+13.33
+50.0	+10	−12.22	+134.6	+57	+13.89
+51.8	+11	−11.67	+136.4	+58	+14.44
+53.6	+12	−11.11	+138.2	+59	+15.00
+55.4	+13	−10.56	+140.0	+60	+15.56
+57.2	+14	−10.00	+141.8	+61	+16.11
+59.0	+15	−9.44	+143.6	+62	+16.67
+60.8	+16	−8.89	+145.4	+63	+17.22
+62.6	+17	−8.33	+147.2	+64	+17.78
+64.4	+18	−7.78	+149.0	+65	+18.33
+66.2	+19	−7.22	+150.8	+66	+18.89
+68.0	+20	−6.67	+152.6	+67	+19.44
+69.8	+21	−6.11	+154.4	+68	+20.00
+71.6	+22	−5.56	+156.2	+69	+20.56
+73.4	+23	−5.00	+158.0	+70	+21.11
+75.2	+24	−4.44	+159.8	+71	+21.67
+77.0	+25	−3.89	+161.6	+72	+22.22
+78.8	+26	−3.33	+163.4	+73	+22.78
+80.6	+27	−2.78	+165.2	+74	+23.33
+82.4	+28	−2.22	+167.0	+75	+23.89
+84.2	+29	−1.67	+168.8	+76	+24.44
+86.0	+30	−1.11	+170.6	+77	+25.00
+87.8	+31	−0.56	+172.4	+78	+25.56
+89.6	+32	±0.00	+174.2	+79	+26.11
+91.4	+33	+0.56	+176.0	+80	+26.67
+93.2	+34	+1.11	+177.8	+81	+27.22
+95.0	+35	+1.67	+179.6	+82	+27.78
+96.8	+36	+2.22	+181.4	+83	+28.33
+98.6	+37	+2.78	+183.2	+84	+28.89

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+185.0	+85	+29.44	+269.6	+132	+55.56
+186.8	+86	+30.00	+271.4	+133	+56.11
+188.6	+87	+30.56	+273.2	+134	+56.67
+190.4	+88	+31.11	+275.0	+135	+57.22
+192.2	+89	+31.67	+276.8	+136	+57.78
+194.0	+90	+32.22	+278.6	+137	+58.33
+195.8	+91	+32.78	+280.4	+138	+58.89
+197.6	+92	+33.33	+282.2	+139	+59.44
+199.4	+93	+33.89	+284.0	+140	+60.00
+201.2	+94	+34.44	+285.8	+141	+60.56
+203.0	+95	+35.00	+287.6	+142	+61.11
+204.8	+96	+35.56	+289.4	+143	+61.67
+206.6	+97	+36.11	+291.2	+144	+62.22
+208.4	+98	+36.67	+293.0	+145	+62.78
+210.2	+99	+37.22	+294.8	+146	+63.33
+212.0	+100	+37.78	+296.6	+147	+63.89
+213.8	+101	+38.33	+298.4	+148	+64.44
+215.6	+102	+38.89	+300.2	+149	+65.00
+217.4	+103	+39.44	+302.0	+150	+65.56
+219.2	+104	+40.00	+303.8	+151	+66.11
+221.0	+105	+40.56	+305.6	+152	+66.67
+222.8	+106	+41.11	+307.4	+153	+67.22
+224.6	+107	+41.67	+309.2	+154	+67.78
+226.4	+108	+42.22	+311.0	+155	+68.33
+228.2	+109	+42.78	+312.8	+156	+68.89
+230.0	+110	+43.33	+314.6	+157	+69.44
+231.8	+111	+43.89	+316.4	+158	+70.00
+233.6	+112	+44.44	+318.2	+159	+70.56
+235.4	+113	+45.00	+320.0	+160	+71.11
+237.2	+114	+45.56	+321.8	+161	+71.67
+239.0	+115	+46.11	+323.6	+162	+72.22
+240.8	+116	+46.67	+325.4	+163	+72.78
+242.6	+117	+47.22	+327.2	+164	+73.33
+244.4	+118	+47.78	+329.0	+165	+73.89
+246.2	+119	+48.33	+330.8	+166	+74.44
+248.0	+120	+48.89	+332.6	+167	+75.00
+249.8	+121	+49.44	+334.4	+168	+75.56
+251.6	+122	+50.00	+336.2	+169	+76.11
+253.4	+123	+50.56	+338.0	+170	+76.67
+255.2	+124	+51.11	+339.8	+171	+77.22
+257.0	+125	+51.67	+341.6	+172	+77.78
+258.8	+126	+52.22	+343.4	+173	+78.33
+260.6	+127	+52.78	+345.2	+174	+78.89
+262.4	+128	+53.33	+347.0	+175	+79.44
+264.2	+129	+53.89	+348.8	+176	+80.00
+266.0	+130	+54.44	+350.6	+177	+80.56
+267.8	+131	+55.00	+352.4	+178	+81.11

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+354.2	+179	+81.67	+449.6	+232	+111.11
+356.0	+180	+82.22	+453.2	+234	+112.22
+357.8	+181	+82.78	+456.8	+236	+113.33
+359.6	+182	+83.33	+460.4	+238	+114.44
+361.4	+183	+83.89	+464.0	+240	+115.56
+363.2	+184	+84.44	+467.6	+242	+116.67
+365.0	+185	+85.00	+471.2	+244	+117.78
+366.8	+186	+85.56	+474.8	+246	+118.89
+368.6	+187	+86.11	+478.4	+248	+120.00
+370.4	+188	+86.67	+482.0	+250	+121.11
+372.2	+189	+87.22	+485.6	+252	+122.22
+374.0	+190	+87.78	+489.2	+254	+123.33
+375.8	+191	+88.33	+492.8	+256	+124.44
+377.6	+192	+88.89	+496.4	+258	+125.56
+379.4	+193	+89.44	+500.0	+260	+126.67
+381.2	+194	+90.00	+503.6	+262	+127.78
+383.0	+195	+90.56	+507.2	+264	+128.89
+384.8	+196	+91.11	+510.8	+266	+130.00
+386.6	+197	+91.67	+514.4	+268	+131.11
+388.4	+198	+92.22	+518.0	+270	+132.22
+390.2	+199	+92.78	+521.6	+272	+133.33
+392.0	+200	+93.33	+525.2	+274	+134.44
+393.8	+201	+93.89	+528.8	+276	+135.56
+395.6	+202	+94.44	+532.4	+278	+136.67
+397.4	+203	+95.00	+536.0	+280	+137.78
+399.2	+204	+95.56	+539.6	+282	+138.89
+401.0	+205	+96.11	+543.2	+284	+140.00
+402.8	+206	+96.67	+546.8	+286	+141.11
+404.6	+207	+97.22	+550.4	+288	+142.22
+406.4	+208	+97.78	+554.0	+290	+143.33
+408.2	+209	+98.33	+557.6	+292	+144.44
+410.0	+210	+98.89	+561.2	+294	+145.56
+411.8	+211	+99.44	+564.8	+296	+146.67
+413.6	+212	+100.00	+568.4	+298	+147.78
+415.4	+213	+100.56	+572.0	+300	+148.89
+417.2	+214	+101.11	+575.6	+302	+150.00
+419.0	+215	+101.67	+579.2	+304	+151.11
+420.8	+216	+102.22	+582.8	+306	+152.22
+422.6	+217	+102.78	+586.4	+308	+153.33
+424.4	+218	+103.33	+590.0	+310	+154.44
+426.2	+219	+103.89	+593.6	+312	+155.56
+428.0	+220	+104.44	+597.2	+314	+156.67
+431.6	+222	+105.56	+600.8	+316	+157.78
+435.2	+224	+106.67	+604.4	+318	+158.89
+438.8	+226	+107.78	+608.0	+320	+160.00
+442.4	+228	+108.89	+611.6	+322	+161.11
+446.0	+230	+110.00	+615.2	+324	+162.22

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+618.8	+326	+163.33	+791.6	+422	+216.67
+622.4	+328	+164.44	+795.2	+424	+217.78
+626.0	+330	+165.56	+798.8	+426	+218.89
+629.6	+332	+166.67	+802.4	+428	+220.00
+633.2	+334	+167.78	+806.0	+430	+221.11
+636.8	+336	+168.89	+809.6	+432	+222.22
+640.4	+338	+170.00	+813.2	+434	+223.33
+644.0	+340	+171.11	+816.8	+436	+224.44
+647.6	+342	+172.22	+820.4	+438	+225.56
+651.2	+344	+173.33	+824.0	+440	+226.67
+654.8	+346	+174.44	+827.6	+442	+227.78
+658.4	+348	+175.56	+831.2	+444	+228.89
+662.0	+350	+176.67	+834.8	+446	+230.00
+665.6	+352	+177.78	+838.4	+448	+231.11
+669.2	+354	+178.89	+842.0	+450	+232.22
+672.8	+356	+180.00	+845.6	+452	+233.33
+676.4	+358	+181.11	+849.2	+454	+234.44
+680.0	+360	+182.22	+852.8	+456	+235.56
+683.6	+362	+183.33	+856.4	+458	+236.67
+687.2	+364	+184.44	+860.0	+460	+237.78
+690.8	+366	+185.56	+863.6	+462	+238.89
+694.4	+368	+186.67	+867.2	+464	+240.00
+698.0	+370	+187.78	+870.8	+466	+241.11
+701.6	+372	+188.89	+874.4	+468	+242.22
+705.2	+374	+190.00	+878.0	+470	+243.33
+708.8	+376	+191.11	+881.6	+472	+244.44
+712.4	+378	+192.22	+885.2	+474	+245.56
+716.0	+380	+193.33	+888.8	+476	+246.67
+719.6	+382	+194.44	+892.4	+478	+247.78
+723.2	+384	+195.56	+896.0	+480	+248.89
+726.8	+386	+196.67	+899.6	+482	+250.00
+730.4	+388	+197.78	+903.2	+484	+251.11
+734.0	+390	+198.89	+906.8	+486	+252.22
+737.6	+392	+200.00	+910.4	+488	+253.33
+741.2	+394	+201.11	+914.0	+490	+254.44
+744.8	+396	+202.22	+917.6	+492	+255.56
+748.4	+398	+203.33	+921.2	+494	+256.67
+752.0	+400	+204.44	+924.8	+496	+257.78
+755.6	+402	+205.56	+928.4	+498	+258.89
+759.2	+404	+206.67	+932.0	+500	+260.00
+762.8	+406	+207.78	+935.6	+502	+261.11
+766.4	+408	+208.89	+939.2	+504	+262.22
+770.0	+410	+210.00	+942.8	+506	+263.33
+773.6	+412	+211.11	+946.4	+508	+264.44
+777.2	+414	+212.22	+950.0	+510	+265.56
+780.8	+416	+213.33	+953.6	+512	+266.67
+784.4	+418	+214.44	+957.2	+514	+267.78
+788.0	+420	+215.56	+960.8	+516	+268.89

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+964.4	+518	+270.00	+1133.6	+612	+322.22
+968.0	+520	+271.11	+1137.2	+614	+323.33
+971.6	+522	+272.22	+1140.8	+616	+324.44
+975.2	+524	+273.33	+1144.4	+618	+325.56
+978.8	+526	+274.44	+1148.0	+620	+326.67
+982.4	+528	+275.56	+1151.6	+622	+327.78
+986.0	+530	+276.67	+1155.2	+624	+328.89
+989.6	+532	+277.78	+1158.8	+626	+330.00
+993.2	+534	+278.89	+1162.4	+628	+331.11
+996.8	+536	+280.00	+1166.0	+630	+332.22
1000.4	+538	+281.11	+1169.6	+632	+333.33
+1004.0	+540	+282.22	+1173.2	+634	+334.44
+1007.6	+542	+283.33	+1176.8	+636	+335.56
+1011.2	+544	+284.44	+1180.4	+638	+336.67
+1014.8	+546	+285.56	+1184.0	+640	+337.78
+1018.4	+548	+286.67	+1187.6	+642	+338.89
+1022.0	+550	+287.78	+1191.2	+644	+340.00
+1025.6	+552	+288.89	+1194.8	+646	+341.11
+1029.2	+554	+290.00	+1198.4	+648	+342.22
+1032.8	+556	+291.11	+1202.0	+650	+343.33
+1036.4	+558	+292.22	+1205.6	+652	+344.44
+1040.0	+560	+293.33	+1209.2	+654	+345.56
+1043.6	+562	+294.44	+1212.8	+656	+346.67
+1047.2	+564	+295.56	+1216.4	+658	+347.78
+1050.8	+566	+296.67	+1220.0	+660	+348.89
+1054.4	+568	+297.78	+1223.6	+662	+350.00
+1058.0	+570	+298.89	+1227.2	+664	+351.11
+1061.6	+572	+300.00	+1230.8	+666	+352.22
+1065.2	+574	+301.11	+1234.4	+668	+353.33
+1068.8	+576	+302.22	+1238.0	+670	+354.44
+1072.4	+578	+303.33	+1241.6	+672	+355.56
+1076.0	+580	+304.44	+1245.2	+674	+356.67
+1079.6	+582	+305.56	+1248.8	+676	+357.78
+1083.2	+584	+306.67	+1252.4	+678	+358.89
+1086.8	+586	+307.78	+1256.0	+680	+360.00
+1090.4	+588	+308.89	+1259.6	+682	+361.11
+1094.0	+590	+310.00	+1263.2	+684	+362.22
+1097.6	+592	+311.11	+1266.8	+686	+363.33
+1101.2	+594	+312.22	+1270.4	+688	+364.44
+1104.8	+596	+313.33	+1274.0	+690	+365.56
+1108.4	+598	+314.44	+1277.6	+692	+366.67
+1112.0	+600	+315.56	+1281.2	+694	+367.78
+1115.6	+602	+316.67	+1284.8	+696	+368.89
+1119.2	+604	+317.78	+1288.4	+698	+370.00
+1122.8	+606	+318.89	+1292.0	+700	+371.11
+1126.4	+608	+320.00	+1295.6	+702	+372.22
+1130.0	+610	+321.11	+1299.2	+704	+373.33

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+1302.8	+706	+374.44	+1468.4	+798	+425.56
+1306.4	+708	+375.56	+1472.0	+800	+426.67
+1310.0	+710	+376.67	+1475.6	+802	+427.78
+1313.6	+712	+377.78	+1479.2	+804	+428.89
+1317.2	+714	+378.89	+1482.8	+806	+430.00
+1320.8	+716	+380.00	+1486.4	+808	+431.11
+1324.4	+718	+381.11	+1490.0	+810	+432.22
+1328.0	+718	+381.11	+1493.6	+812	+433.33
+1328.0	+720	+382.22	+1497.2	+814	+434.44
+1331.6	+722	+383.33	+1500.8	+816	+435.56
+1335.2	+724	+384.44	+1504.4	+818	+436.67
+1338.8	+726	+385.56	+1508.0	+820	+437.78
+1342.4	+728	+386.67	+1511.6	+822	+438.89
+1346.0	+730	+387.78	+1515.2	+824	+440.00
+1349.6	+732	+388.89	+1518.8	+826	+441.11
+1353.2	+734	+390.00	+1522.4	+828	+442.22
+1356.8	+736	+391.11	+1526.0	+830	+443.33
+1360.4	+738	+392.22	+1529.6	+832	+444.44
+1364.0	+740	+393.33	+1533.2	+834	+445.56
+1367.6	+742	+394.44	+1536.8	+836	+446.67
+1371.2	+744	+395.56	+1540.4	+838	+447.78
+1374.8	+746	+396.67	+1544.0	+840	+448.89
+1378.4	+748	+397.78	+1547.6	+842	+450.00
+1382.0	+750	+398.89	+1551.2	+844	+451.11
+1385.6	+752	+400.00	+1554.8	+846	+452.22
+1389.2	+754	+401.11	+1558.4	+848	+453.33
+1392.8	+756	+402.44	+1562.0	+850	+454.44
+1396.4	+758	+403.33	+1565.6	+852	+455.56
+1400.0	+760	+404.44	+1569.2	+854	+456.67
+1403.6	+762	+405.56	+1572.8	+856	+457.78
+1407.2	+764	+406.67	+1576.4	+858	+458.89
+1410.8	+766	+407.78	+1580.0	+860	+460.00
+1414.4	+768	+408.89	+1583.6	+862	+461.11
+1418.0	+770	+410.00	+1587.2	+864	+462.22
+1421.6	+772	+411.11	+1590.8	+866	+463.33
+1425.2	+774	+412.22	+1594.4	+868	+464.44
+1428.8	+776	+413.33	+1598.0	+870	+465.56
+1432.4	+778	+414.44	+1601.6	+872	+466.67
+1436.0	+780	+415.56	+1605.2	+874	+467.78
+1439.6	+782	+416.67	+1608.8	+876	+468.89
+1443.2	+784	+417.78	+1612.4	+878	+470.00
+1446.8	+786	+418.89	+1616.0	+880	+471.11
+1450.4	+788	+420.00	+1619.6	+882	+472.22
+1454.0	+790	+421.11	+1623.2	+884	+473.33
+1457.6	+792	+422.22	+1636.8	+886	+474.44
+1461.2	+794	+423.33	+1630.4	+888	+475.56
+1464.8	+796	+424.44	+1634.0	+890	+476.67

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+1637.6	+892	+477.78	+1806.8	+986	+530.00
+1641.2	+894	+478.89	+1810.4	+988	+531.11
+1644.8	+896	+480.00	+1814.0	+990	+532.22
+1648.4	+898	+481.11	+1817.6	+992	+533.33
+1652.0	+900	+482.22	+1821.2	+994	+534.44
+1655.6	+902	+483.33	+1824.8	+996	+535.56
+1659.2	+904	+484.44	+1828.4	+998	+536.67
+1662.8	+906	+485.56	+1832.0	+1000	+537.78
+1666.4	+908	+486.67	+1850.0	+1010	+543.33
+1670.0	+910	+487.78	+1868.0	+1020	+548.89
+1673.6	+912	+488.89	+1886.0	+1030	+554.44
+1677.2	+914	+490.00	+1904.0	+1040	+560.00
+1680.8	+916	+491.11	+1922.0	+1050	+565.56
+1684.4	+918	+492.22	+1940.0	+1060	+571.11
+1688.0	+920	+493.33	+1958.0	+1070	+576.67
+1691.6	+922	+494.44	+1976.0	+1080	+582.22
+1695.2	+924	+495.56	+1994.0	+1090	+587.78
+1698.8	+926	+496.67	+2012.0	+1100	+593.33
+1702.4	+928	+497.78	+2030.0	+1110	+598.89
+1706.0	+930	+498.89	+2048.0	+1120	+604.44
+1709.6	+932	+500.00	+2066.0	+1130	+610.00
+1713.2	+934	+501.11	+2084.0	+1140	+615.56
+1716.8	+936	+502.22	+2102.0	+1150	+621.11
+1720.4	+938	+503.33	+2120.0	+1160	+626.67
+1724.0	+940	+504.44	+2138.0	+1170	+632.22
+1727.6	+942	+505.56	+2156.0	+1180	+637.78
+1731.2	+944	+506.67	+2174.0	+1190	+643.33
+1734.8	+946	+507.78	+2192.0	+1200	+648.89
+1738.4	+948	+508.89	+2210.0	+1210	+654.44
+1742.0	+950	+510.00	+2228.0	+1220	+660.00
+1745.6	+952	+511.11	+2246.0	+1230	+665.56
+1749.2	+954	+512.22	+2264.0	+1240	+671.11
+1752.8	+956	+513.33	+2282.0	+1250	+676.67
+1756.4	+958	+514.44	+2300.0	+1260	+682.22
+1760.0	+960	+515.56	+2318.0	+1270	+687.78
+1763.6	+962	+516.67	+2336.0	+1280	+693.33
+1767.2	+964	+517.78	+2354.0	+1290	+698.89
+1770.8	+966	+518.89	+2372.0	+1300	+704.44
+1774.4	+968	+520.00	+2390.0	+1310	+710.00
+1778.0	+970	+521.11	+2408.0	+1320	+715.56
+1781.6	+972	+522.22	+2426.0	+1330	+721.11
+1785.2	+974	+523.33	+2444.0	+1340	+726.67
+1788.8	+976	+524.44	+2462.0	+1350	+732.22
+1792.4	+978	+525.56	+2480.0	+1360	+737.78
+1796.0	+980	+526.67	+2498.0	+1370	+743.33
+1799.6	+982	+527.78	+2516.0	+1380	+748.89
+1803.2	+984	+528.89	+2534.0	+1390	+754.44

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+2552.0	+1400	+760.00	+3398.0	+1870	+1021.1
+2570.0	+1410	+765.56	+3416.0	+1880	+1026.7
+2588.0	+1420	+771.11	+3434.0	+1890	+1032.2
+2606.0	+1430	+776.67	+3452.0	+1900	+1037.8
+2624.0	+1440	+782.22	+3470.0	+1910	+1043.3
+2642.0	+1450	+787.78	+3488.0	+1920	+1048.9
+2660.0	+1460	+793.33	+3506.0	+1930	+1054.4
+2678.0	+1470	+798.89	+3524.0	+1940	+1060.0
+2696.0	+1480	+804.44	+3542.0	+1950	+1065.6
+2714.0	+1490	+810.00	+3560.0	+1960	+1071.1
+2732.0	+1500	+815.56	+3578.0	+1970	+1076.7
+2750.0	+1510	+821.11	+3596.0	+1980	+1082.2
+2768.0	+1520	+826.67	+3614.0	+1990	+1087.8
+2786.0	+1530	+832.22	+3632.0	+2000	+1093.3
+2804.0	+1540	+837.78	+3650.0	+2010	+1098.9
+2822.0	+1550	+843.33	+3668.0	+2020	+1104.4
+2840.0	+1560	+848.89	+3686.0	+2030	+1110.0
+2858.0	+1570	+854.44	+3704.0	+2040	+1115.6
+2876.0	+1580	+860.00	+3722.0	+2050	+1121.1
+2894.0	+1590	+865.56	+3740.0	+2060	+1126.7
+2912.0	+1600	+871.11	+3758.0	+2070	+1132.2
+2930.0	+1610	+876.67	+3776.0	+2080	+1137.8
+2948.0	+1620	+882.22	+3794.0	+2090	+1143.3
+2966.0	+1630	+887.78	+3812.0	+2100	+1148.9
+2984.0	+1640	+893.33	+3830.0	+2110	+1154.4
+3002.0	+1650	+898.89	+3848.0	+2120	+1160.0
+3020.0	+1660	+904.44	+3866.0	+2130	+1165.6
+3038.0	+1670	+910.00	+3884.0	+2140	+1171.1
+3056.0	+1680	+915.56	+3902.0	+2150	+1176.7
+3074.0	+1690	+921.11	+3920.0	+2160	+1182.2
+3092.0	+1700	+926.67	+3938.0	+2170	+1187.8
+3110.0	+1710	+932.22	+3956.0	+2180	+1193.3
+3128.0	+1720	+937.78	+3974.0	+2190	+1198.9
+3146.0	+1730	+943.33	+3992.0	+2200	+1204.4
+3164.0	+1740	+948.89	+4010.0	+2210	+1210.0
+3182.0	+1750	+954.44	+4028.0	+2220	+1215.6
+3200.0	+1760	+960.00	+4046.0	+2230	+1221.1
+3218.0	+1770	+965.56	+4064.0	+2240	+1226.7
+3236.0	+1780	+971.11	+4082.0	+2250	+1232.2
+3254.0	+1790	+976.67	+4100.0	+2260	+1237.8
+3272.0	+1800	+982.22	+4118.0	+2270	+1243.3
+3290.0	+1810	+987.78	+4136.0	+2280	+1248.9
+3308.0	+1820	+993.33	+4154.0	+2290	+1254.4
+3326.0	+1830	+998.89	+4172.0	+2300	+1260.0
+3344.0	+1840	+1004.4	+4190.0	+2310	+1265.6
+3362.0	+1850	+1010.0	+4208.0	+2320	+1271.1
+3380.0	+1860	+1015.6	+4226.0	+2330	+1276.7

Temperature Equivalents (*continued*)

°F	READING IN °F OR °C TO BE CONVERTED	°C	°F	READING IN °F OR °C TO BE CONVERTED	°C
+4244.0	+2340	+1282.2	+4946.0	+2730	+1498.9
+4262.0	+2350	+1287.8	+4964.0	+2740	+1504.4
+4280.0	+2360	+1293.3	+4982.0	+2750	+1510.0
+4298.0	+2370	+1298.9	+5000.0	+2760	+1515.6
+4316.0	+2380	+1304.4	+5018.0	+2770	+1521.1
+4334.0	+2390	+1310.0	+5036.0	+2780	+1526.7
+4352.0	+2400	+1315.6	+5054.0	+2790	+1532.2
+4370.0	+2410	+1321.1	+5072.0	+2800	+1537.8
+4388.0	+2420	+1326.7	+5090.0	+2810	+1543.3
+4406.0	+2430	+1332.2	+5108.0	+2820	+1548.9
+4424.0	+2440	+1337.8	+5126.0	+2830	+1554.4
+4442.0	+2450	+1343.3	+5144.0	+2840	+1560.0
+4460.0	+2460	+1348.9	+5162.0	+2850	+1565.6
+4478.0	+2470	+1354.4	+5180.0	+2860	+1571.1
+4496.0	+2480	+1360.0	+5198.0	+2870	+1576.7
+4514.0	+2490	+1365.6	+5216.0	+2880	+1582.2
+4532.0	+2500	+1371.1	+5234.0	+2890	+1587.8
+4550.0	+2510	+1376.7	+5252.0	+2900	+1593.3
+4568.0	+2520	+1382.2	+5270.0	+2910	+1598.9
+4586.0	+2530	+1387.8	+5288.0	+2920	+1604.4
+4604.0	+2540	+1393.3	+5306.0	+2930	+1610.0
+4622.0	+2550	+1398.9	+5324.0	+2940	+1615.6
+4640.0	+2560	+1404.4	+5342.0	+2950	+1621.1
+4658.0	+2570	+1410.0	+5360.0	+2960	+1626.7
+4676.0	+2580	+1415.6	+5378.0	+2970	+1632.2
+4694.0	+2590	+1421.1	+5396.0	+2980	+1637.8
+4712.0	+2600	+1426.7	+5414.0	+2990	+1643.3
+4730.0	+2610	+1432.2	+5432.0	+3000	+1648.9
+4748.0	+2620	+1437.8	+5450.0	+3010	+1654.4
+4766.0	+2630	+1443.3	+5468.0	+3020	+1660.0
+4784.0	+2640	+1448.9	+5486.0	+3030	+1665.6
+4802.0	+2650	+1454.4	+5504.0	+3040	+1671.1
+4820.0	+2660	+1460.0	+5522.0	+3050	+1676.7
+4838.0	+2670	+1465.6	+5540.0	+3060	+1682.2
+4856.0	+2680	+1471.1	+5558.0	+3070	+1687.8
+4874.0	+2690	+1476.7	+5576.0	+3080	+1693.3
+4892.0	+2700	+1482.2	+5594.0	+3090	+1698.9
+4910.0	+2710	+1487.8	+5612.0	+3100	+1704.4
+4928.0	+2720	+1493.3			

INDUSTRY AND FEDERAL STANDARDS AND SPECIFICATIONS

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