Handbook of Electrical and Electronic Insulating Materials

Second Edition

W. Tillar Shugg

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To those developers of insulating materials making possible a century of progress for the electrical and electronics industries.

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Foreword to the Second Edition

When conceived and created nearly a decade ago, this *Handbook of Electrical and Electronic Insulating Materials* fulfilled a compelling need seen by those involved with the insulation of electrical and electronic machines and devices. Early in this century, in the formative years of electrical insulation, several books on the subject were published and widely used. They thoroughly treated the fundamental properties of materials but were less rigorous in the practical and engineering uses of electrical insulation. New insulating materials such as polymers, plastics, gasses, and liquids appeared frequently in this period of phenomenal growth of electrical machines.

The first edition of this handbook addressed these issues, resulting in an extremely useful reference work which presented properties, uses, standards, and specifications of electrical insulating materials. In the years since the book's inception the pace of the development of electrical machines has somewhat diminished while the breakneck pace of the electronics industry continues unabated. The synthesis of new insulating materials also has slowed but innovative composites that utilize the best properties of their individual components have proliferated.

The Dielectrics and Electrical Insulation Society of the Institute of Electrical and Electronic Engineers leads the electrical and electronic industries worldwide in all matters relating to electrical insulation. It is natural for the DEI Society to have a continuing interest in this handbook. Recently, IEEE Press obtained the rights to this book and has worked closely with the DEI Society to support its revision. Tillar Shugg embarked on the strenuous effort to update and strengthen the considerable body of information found within, culminating in this revised second edition.

Like its predecessor, this authoritative second edition of the handbook is not intended for storage on a library shelf. Rather, it is designed as a desk volume to provide quickly accessible data, design input, comparisons, standards, and suppliers for insulating systems and materials. Every practitioner of electrical and electronics insu-

lation science and technology will find this expanded and updated revision to be indispensable and of immediate and practical value. For those entering the industry, it is a fine educational resource.

RONALD N. SAMPSON
Technology Seminars, Inc.

Foreword to the First Edition

A half century of personal perspective over the 100 years of development in electrical insulation provides understanding of the monumental task needed and undertaken in this handbook. Fifty years ago, it was quite easy to catalog and describe the relatively few insulating materials in use. But even then, the electrical industry was concerned that too many insulating materials were available. For example, General Electric used about 12 drying oil-modified, asphalt, phenol and alkyd varnishes, and wanted to standardize on 8 or less!

Signs of change *in the opposite direction* were already apparent. Glass fiber was being introduced to replace asbestos, but instead ultimately largely replaced cotton, linen, and rayon, Mechanically tough polyvinylformal resin could and would replace bulky cotton-wrapped wire insulation. PVC, plasticized polyvinylchloride, allowed the development of a wholly new concept in extruded cable insulation. Electrical equipment could be made smaller, more efficient, and less expensive. It was an exciting time, and the opportunities seemed and proved to be almost endless.

Twenty-five years later, the number of available insulating materials had grown so rapidly that two comprehensive books, *Die Isolierstoffe der Electrotecknik (Insulating Materials for Electrical Practice)* by W. Oburger and *Insulating Materials for Design and Engineering* by Frank Clark, were written to meet the tremendous need. In the last 25 years, the growth has accelerated so fast that the task of providing an up-to-date handbook for electrical insulation appeared overwhelming. The vast number of insulating materials, which are integrated into complex insulation systems in many kinds of electrical equipment for a host of specialized applications with different environments, indeed makes an overall complete description nearly impossible.

It is fortunate that the enormity of the task did not stop the preparation of this handbook, which provides an important step in the overall evaluation of insulation systems and their application. It is necessary, of course, to recognize that the properties

of individual insulating materials vary and also depend upon the way the materials are used. Nevertheless, the ability to compare property values for many insulating materials in a comprehensive fashion provides a base, along with practical application experience, for evaluating insulating materials to be used in the many types of electrical equipment.

KENNETH N. MATHES, P.E.
Consultant on Electrical Insulation
Schenectady, NY

Preface

Prior to this undertaking, there has not been a handbook in print in the United States devoted solely to dielectric materials. This *Handbook of Electrical and Electronic Insulating Materials* is intended to provide a concise but comprehensive reference for all engineers and material specialists in and serving the electrical and electronics industries, as well as those persons with special interest in a particular class of materials. This handbook should fill a wide gap in business, university, and public libraries. It should also be useful as a reference and text in engineering and science courses.

In addition to a word-by-word editing, review, and updating of the first edition, this second edition has been enhanced to include these new and significantly augmented sections:

- Overview of Our Heritage
- Partial Discharge
- Radiation
- Temperature Index of Dielectric Materials
- SI System for Metric Practice
- Definition of Terms Relating to Plastics
- Table showing U.S. consumption of thermoplastics in electrical applications
- Alloys
- Liquid Crystal Polymers
- Conducting Polymers
- Polyacrylate (PAR) Molding Compouneds
- Polyetheretherketone (PEEK) Molding Compounds
- Table showing U.S. consumption of principal thermosetting plastics in electrical applications

- Flooding and Filling Compounds
- Curing Systems
- Polyetherimide (PEI) Film
- Tape Selection
- Hazard Communication Program
- National Institute of Standards and Technology
- Table of Temperature Equivalents

ORGANIZATION OF HANDBOOK

This handbook follows the following format:

- *Preface* (this section), which covers uses for the handbook, its organization, materials covered, sources of information, and acknowledgments.
- *History*, which lists the historical events and personalities of the electrical and electronic industries and presents an overview of our heritage.
- *Fundamentals*, which includes sections on the importance of U.S. and international standards, insulation systems and service life, material aging and breakdown, corona discharge, dipole moment and polarization, material selection steps, temperature index of dielectric materials, standard tests, and the International System of Units (SI).
- Each product group chapter is organized in this way:
  Comprehensive table of contents
  Introduction, including background and overview
  Technology for the group
  Standards and specifications applying to the group
  Manufacturing processes applying to the group
  Development programs
  Market trends
  Summary of properties of materials in the group
- Each insulating material in a product group has this treatment:
  Introduction, including principal producers
  Chemistry (Technology), including formula and manufacturing process
  Standards and specifications applying to this material
  Grades
  Processing methods
  Properties
  End uses
- A chapter on industry activities which lists organizations serving the electrical and electronics industries, summarizing their activities and principal publications. Industry conferences, periodicals, and key reference encyclopedias are also listed.
- A chapter on government activities, including detailed information on Occupational Safety and Health Administration programs relating to worker health and

safety, and Environmental Protection Agency programs aimed at ensuring a clean, safe environment. Also included is information on agencies developing and distributing standards and specifications, and an example of a specification on one of the newer engineering thermoplastics.

- An Appendix, containing conversion factors and formulas, measures and weights, and a sequential listing of key industry and Federal standards and specifications referenced in this handbook. Titles to documents are as they appear on the documents themselves, which may result in some inconsistencies in format.
- Index, comprehensive and cross-referenced for easy use.

MATERIALS COVERED

As shown in the chapter headings listed in the contents, virtually all dielectric materials are discussed according to their broad product group classification, for example, thermoplastic molding compounds, dielectric films, tapes, and coated fabrics. Thus, a certain polymer may be considered in several chapters. For instance, polypropylene appears in these chapters: *Thermoplastic Molding Compounds*, *Extrusion Compounds*, and *Dielectric Films*. And polyesters are included in these chapters: *Thermoplastic Molding Compounds, Embedding Compounds, Magnet Wire Enamels*, and *Insulating Coatings and Impregnants*. This format is employed since a reader is more often interested in considering all candidates for a specific application, say insulating varnishes, than in researching all possible applications for a specific material, say polyesters. Someone with the latter need will find the index more helpful than the chapter titles.

While I have endeavored to include all commonly used insulating materials in this handbook, there are noteworthy exceptions:

- *Asbestos-base materials*, which are being replaced by other products as a result of the Environmental Protection Agency enforcement of the Toxic Substances Control Act (see Chapter 19, *Government Activities*.)
- *Adhesives*, which are covered in the product group chapters where they apply, for example, in these chapters: *Unclad and Clad Structures* and *Tapes and Coated Fabrics* (pressure-sensitive).

TIMELINESS

The information and data in this second edition are current as of 1994.

SOURCES OF INFORMATION

The principal sources of information for this handbook are the following:

- Manufacturers' catalogues, bulletins, and data sheets
- Attendance at insulation conferences

- Personal discussions and correspondence with authorities
- Papers written by authorities
- Books edited or written by authorities
- Encyclopedias
- ASTM, NEMA, and UL standards
- IEEE publications
- Federal (mostly military) specifications
- Trade magazines
- Patents
- The author's experience

W. TILLAR SHUGG

Acknowledgments

During a lifetime of association with the electrical and electronics industries, there have been thousands of contacts, too numerous to mention, who have helped me acquire an interest in and knowledge of insulating materials. My earliest influence was John Shugg, an uncle, who was among the pioneers of insulating varnishes and varnished cambric at General Electric, and also for a while at Schenectady Varnish (now Schenectady International) and Sterling Varnish (now part of P. D. George). It was his varnished cambric business that I ran through World War II.

Later, at General Electric and Continental-Diamond Fibre, it was Harry Collins who provided opportunities to become involved with most of the materials covered in this handbook. E. O. Hausmann, also formerly of Continental-Diamond, was a great help in product manufacturing and technology. An intensive exposure to mica, tubing, and insulated wire was made available by William Brand of the William Brand Company (now Brand-Rex).

Irving Skeist and Jerry Miron of Skeist Laboratories afforded me opportunities to work on many in-depth studies of insulating materials and their markets. Irving was a consulting editor for the first edition of this handbook.

Special thanks go to Tor Orbeck, Ron Sampson, John Tanaka, Ken Mathes, Phil Alexander, and William Bentley, my colleagues at IEEE, for their guidance and encouragement on this project. This second edition would not have been possible without the enthusiastic support of Greg Stone and Ron Sampson of the IEEE Dielectrics and Electrical Insulation Society and Dudley Kay of IEEE Press.

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W. Tillar Shugg

1

History

INTRODUCTION 3
OVERVIEW OF OUR HERITAGE 3

INTRODUCTION

Electrical and electronic insulating materials, also called dielectric materials, are essential to the proper operation of all electrical and electronic equipment. In fact, equipment size and operating limitations are dictated by the type and amount of material required for insulation. In the early days of the electrical industry, engineers had to adapt wood-finishing varnishes, natural resins, coal tars, and petroleum asphaltic residues as saturants and coatings for tapes used to wrap coils and cables. Today, a virtually unlimited number of insulating materials is available, and the problem becomes one of selecting rather than adapting.

Significant events and personalities causing the growth of the electrical and electronics industries (and with them the insulation industry) are shown in Table 1-1.

No listing of people making major contributions would be complete without including these industry giants:

Charles Proteus Steinmetz (1865–1923) who, while at General Electric, developed the mathematics and the theory of the alternating current.

Marchese Gugliemo Marconi (1874–1937) who produced a practical wireless telegraph system in 1895 and the first transatlantic wireless signal in 1901. He received the Nobel prize in physics in 1909.

An overview is also given of the chronology of insulating materials development with an assessment of future market requirements and trends.

OVERVIEW OF OUR HERITAGE

The beginning of human awareness of electromagnetic phenomena dates back into antiquity. Early humans were mystified by lightning and by the magnetic properties of amber when rubbed with fur, and lodestone, or magnetite as it is now known. Ben Franklin began his electrical experiments in 1747, and later postulated the theory that there are two kinds of electricity, positive and negative. In recognition of his scientific contributions he received honorary degrees from the University of Saint Andrews and the University of Oxford. In addition, he became a Fellow of the Royal Society of London for Improving Natural Knowledge.

It was not until the 1800s, however, that electromagnetic induction was studied and explained by Michael Faraday and Joseph Henry. Faraday also established the principle that different dielectric materials have their own specific inductive capacities, more often referred to now as dielectric constants. In 1855, Faraday completed work on his landmark book, *Experimental Researches in Electricity*.

Henry went on to develop electromagnets of the same form later used in dynamos and motors, and in 1831 built one of the first motors. In later years, he became Director of the newly formed Smithsonian Institution and President of the National Academy of Sciences.

As more electrical equipment was developed to service the telegraph communications industry beginning in 1844 with the first public telegram, and in 1877 with the

TABLE 1-1 Historical Events and Personalities of the Electrical and Electronics Industries

DATA	EVENT	INVENTOR OR ORGANIZER	COUNTRY
1828–1832	Electromagnetic induction	Joseph Henry	U.S.
		Michael Faraday	England
1837	Five-needle telegraph	Charles Wheatstone	England
		William Cooke	England
1838	Simple key telegraph	Samuel Morse	U.S.
		Alfred Vail	U.S.
1873	Treatise on Electricity and Magnetism	James C. Maxwell	Scotland
1876	Telephone	Alexander Bell	U.S.
1879	Incandescent lamp	Thomas Edison	U.S.
		Joseph Swan	England
1883	Transformer	L. Goulard	England
		J. D. Gibbs	England
1884	American Institute of Electrical Engineers founded	Nathanial Keith	U.S.
1884	Trolley car	Frank Sprague	U.S.
		Van De Poele	U.S.
1884	Steam turbine	Charles Parsons	England
1886	Electrical resistance welding	Elihu Thompson	U.S.
1887	Induction motor	Nikola Tesla	U.S.
		Galileo Ferraris	Italy
		Friedrich Haselwander	Germany
1892	Electric vehicle	(several)	France
1906	Triode vacuum tube	Lee De Forest	U.S.
1907	Bakelite	Leo Baekeland	Belgium
1912	Radio signal amplifier	Edwin Armstrong	U.S.
1912	Institute of Radio Engineers founded	John Stone	U.S.
		John Hogan	U.S.
1913	Heterodyne radio receiver	Reginald Fessenden	U.S.
1914	High-frequency alternator	E. F. W. Alexanderson	U.S.
		Reginald Fessenden	U.S.
1921	Oil filled power cable	Emanueli	Italy
1927	Electronic television	P. T. Farnsworth	U.S.
1930	Nylon	Wallace Carothers	U.S.
1930	Neoprene	Wallace Carothers	U.S.
1946	Electronic Numerical Integrator and Computer (ENIAC)	John Mauchly	U.S.
		J. Presper	U.S.
1947	Transistor	William Shockley	U.S.
		Walter Brattain	U.S.
		John Bardeen	U.S.
1958	First Electrical/Electronics Insulation Conference		
1961	First commercial integrated circuit	Fairchild Corp.	U.S.
1963	Institute of Electrical and Electronics Engineers (IEEE) formed from American Institute of Electrical Engineers and Institute of Radio Engineers		U.S.

formation of the Bell Telephone Company, it became necessary to also develop improved insulations over those then available, such as paper, woven fabrics, wood, mica, glass, porcelain, shellac, rosin, copal, rubber and gutta percha, asphalt, linseed and China wood drying oils, and petroleum and coal tar distillates. These materials, of course, are still widely used, but in greatly refined forms and with significantly improved purity.

The first synthetic resins, the reaction products of phenol and formaldehyde, were developed by Belgium chemist Leo Baekeland in 1907 and became available a few years later. Today, phenolic resins are widely used as modifiers to improve temperature resistance of other resins, permitting some formulations to qualify as Class 180 C insulations where they offer low-cost alternatives to silicone varnishes. Molded phenolics continue to be used in a wide variety of heavy duty electrical applications.

Aminos were the next thermoset resins to be widely used for electrical insulations. The two principal types of these resins are urea-formaldehyde and melamine-formaldehyde condensation products of the reaction of urea and melamine with formaldehyde. Melamine compounds are generally superior to urea compounds in resistance to acids, alkalis, heat, and boiling water. Parts made of urea shrink on aging and tend to crack around inserts and sharp corners. Melamine exhibits these characteristics to a lesser extent, and is usually preferred for critical applications.

Another early insulating material, still in use, is vulcanized fibre, used for its high mechanical strength where moisture is not a problem, such as in arc barriers, air circuit breakers, lightning arrestors for heavy duty transformers, switch and appliance parts, and slot liners for rotating equipment. Vulcanized fibre is made by saturating rag-base or woodpulp paper, layered to 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 from a nearby stream or river. This process became a problem with the advent of the Clean Water Act of 1977.

The first electrical grade tape, friction tape, was marketed in the late 1920s. It was made by applying to a fabric a soft and extremely tacky mixture of rubber and a softener by means of a three-roll calendar. During World War II, the shortage of natural rubber encouraged the development of synthetic rubber adhesives. 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.

Alkyd saturated polyesters (glyptals) became available in the mid-1920s, and soon became the most widely used coatings and impregnants for application to all types of electrical equipment. Alkyds are produced by partial esterification of a polyhydric alcohol, such as pentaerythitol, with a fatty acid derived from vegetable oils, for example, linseed and China wood (tung) oils, followed by reaction with a dibasic acid, such as phthalic acid. Alkyds may be blended with other varnishes or reacted with other resins, including phenolics for improved water and alkali resistance, epoxies for better adhesion, and silicones for higher thermal and dielectric properties.

Polychlorinated biphenyls (askarels), introduced in the U.S. in 1929 from Europe, soon became the premier liquid dielectric for transformers and certain capacitors. They were, however, phased out in the early 1980s by the Toxic Substances Control Act, although electrical industry leaders in 1994 are asking for a review of the regulations

and urging that PCBs again be permitted for use with adequate safeguards. There is as yet 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, and other synthetic oils.

The 1930s brought forth several polymers still widely used. Du Pont's Wallace Carothers discovered nylon in 1930. Nylon, a polyamide polymer, became commercially available in 1938, and was invaluable as a replacement for silk in parachutes and in ladies' stockings when silk became unavailable in World War II. Despite its tendency to absorb moisture, nylon is used extensively as a jacket over primary wire insulation and in molded parts such as coil forms, insulator blocks, and electrical connectors. Nylon 11, a more expensive, low-moisture-absorption grade, is also used as jacketing for aircraft control cable and for hydraulic tubing and hose. The type designation 6/6 shows the number of carbon atoms in each part of a nylon molecule formed by a dibasic acid and a diamine, in this case, adipic acid and hexamethylene diamine. Type 11 indicates there are 11 carbon atoms in the monomer of a nylon formed by polymerization of the ring compound omega-amino undecanoic acid.

Carothers in 1931 also developed Neoprene™ which, chemically, is polymerized chloroprene, useful as a cable jacket for its high resistance to heat, oils, and gasoline.

From pilot plant production in the early 1930s, polyethylene has become by far the most versatile wire and cable insulation. Low-density polyethylene (LDPE), the first polyethylene resin, is produced by polymerizing ethylene gas into long polymer chains in an autoclave, or tublar, reactor. There followed a number of other polyethylene types with designations describing several different synthesis processes. Some examples are LLDPE (linear low-density polyethylene), HDPE (high-density polyethylene), HMW-HDPE (high-molecular-weight high-density polyethylene), and XLPE (crosslinked polyethylene). Polyethylene is often copolymerized with other resins to form useful products such as ethylene propylene diene rubber (EPDM) and ethylene-vinyl acetate (EVA).

The first successor to plain enamel for magnet wire insulation was polyvinyl formal enamel (Formvar™), in use since 1938 and still used extensively where solderability is not required. Monsanto is the developer of the resin made by condensation of formaldehyde and hydrolyzed polyvinyl acetate.

The first fluoropolymer, polytetrafluoroethylene (PTFE), was discovered at Du Pont in 1938, but because early production was devoted to military products before and during World War II, it was not commercially available until 1947. Since that time, the family of fluoropolymers as grown to include several other materials, including perfluoroalkoxy (PFA), fluorinated ethylene-propylene copolymer (FEP), ethylene-tetrafluoroethylene-(ETFE), polyvinylidene fluoride (PVDF), ethylene-chlorotrifluoro ethylene (ECTFE), and polychlorotrifluoroethylene (PCTFE).

A distinction is sometimes made among the terms *fluoropolymers*, *fluorocarbons*, and *fluoroplastics*. *Fluoropolymers* is the generic term which includes fluorocarbons and fluoroplastics. *Fluorocarbons* consist of polymers with only carbon-fluorine bonds. *Fluoroplastics* may have, in addition to carbon-fluorine bonds, carbon-hydrogen and carbon-chlorine bonds. These materials all have in common the widest operating temperature ranges of all plastics, outstanding resistance to attack to chemicals, excellent

dielectric properties, and virtually no tendency to absorb water. They are, however, high priced.

Polyvinyl chloride (PVC) was first used in wire and cable insulation and jacketing in the late 1930s. During World War II, its use spread as replacement for rubber, then in short supply. Polyvinyl chloride is one of the most widely used materials in extrusion applications, as producers and fabricators have successfully complied with EPA and OSHA standards and regulations, which in 1974 and 1975 appeared to threaten the survival of the industry. Polyvinyl chloride resins alone are inherently hard and brittle at temperatures up to 180°F (82°C). To be useful, they must be compounded with plasticizers and other additives. A typical electrical grade formulation would contain 50 percent polyvinyl chloride, 25 to 35 percent plasticizer, and the rest other additives. Important considerations in selection of a plasticizer are its compatibility, volatility, tendency to migrate to other materials, toxicity, odor, burning characteristics, dielectric properties, weatherability, and efficiency (concentration required to be effective).

Also in the late 1930s, acrylics, or polymethyl methacrylate (PMMA) resins, were produced for commercial use by Rohm and Haas (Plexiglas™) and Du Pont (Lucite™). A decreasing dielectric constant with increasing frequencies makes acrylics attractive candidates for high-frequency applications. High arc resistance makes them suitable for circuit breakers and other high-voltage applications. They are being used increasingly in fiber optics. They are not suitable where flammability may be a problem.

The first general purpose polystyrene resins were marketed in the U.S. in 1939 by Dow Chemical. The flammability, low impact strength, tendency to craze, and susceptibility to attack by hydrocarbons limit electrical/electronic applications. End uses include computer tape and video cassette reels and compact battery cases. When copolymerized with acrylonitrile, however, styrene-acrylonitrile resin (SAN) is formed with improved toughness, tensile strength, heat distortion, and chemical resistance. When a third monomer is added by grafting SAN on butadiene polymer to make acrylonitrile-butadiene-styrene resin (ABS), a wide range of properties is obtainable, permitting resins to be tailored to specific end uses with emphasis on toughness.

Silicone resins and elastomers, developed by Dow Corning and General Electric, although using different processes, became available in the middle 1940s. The Dow Corning process uses a Grignard reagent, while General Electric employs a direct process. Varnishes and elastomers made from silicones are useful from –50°C (–58°F) to 250°C (486°F), have excellent dielectric properties and moisture resistance, and are among the most resistant of all materials to corona attack. Mechanical properties of silicones are unpretentious.

Epoxies, introduced in 1947, are predominant in embedding compounds and second in usage in insulation varnishes. In combination with phenolics, they make useful novolac thermosetting molding compounds. The basic epoxy resin is the polycondensation product of bisphenol-A and epichlorohydrin, but cycloaliphatic epoxies are also widely used. To be useful, epoxies must be cured by the action of hardeners, including amines, polyamides, anhydrides, and urea-formaldehyde or phenol-formaldehyde resins. The most commonly employed ratio of epoxy resins to hardener is one to one,

but may range as high as 100 parts epoxy resin to one part hardener. Epoxies are noted for their excellent dielectric properties, low shrinkage during cure, superior adhesion to most surfaces, good thermal properties, and good chemical and moisture resistance.

About the same time, polyurethanes (PURs) came into general use in magnet wire enamels where they permit soldering without stripping. PURs are also widely used in coatings for their abrasion resistance, and in embedding compounds where, in combination with butadiene, they have overcome their formerly poor hydrolytic stability. The basic building blocks of PUR resins are di- or polyisocynates which react with polyols to form the PUR resin.

Polypropylene (PP), closely related to polyethylene both chemically and in usage, became commercially available in the mid-1950s. The Rural Electrification Administration and cable manufacturers recognize polypropylene and high-density polyethylene as alternatives for each other. The choice for usage depends heavily on cost. The prophylene homopolymer has a relatively high brittleness temperature, but by copolymerizing propylene with 2 to 20 percent ethylene, a resin is formed with significantly more useful properties.

Polycarbonate (PC) resins were discovered in the U.S. at General Electric and were marketed in 1950. The resin, a polyester of carbonic acid, is obtained from bisphenol A and other polyhydric phenols, reacted with phosgene. Polycarbonate resins are noted for their good dielectric properties and corona resistance. Alloys with other polymers are available and are used for a wide range of commercial applications.

The first commercially available acetal homopolymer resin was introduced by Du Pont in 1959 with the trademark Delrin. Two years later, Celanese, now Hoechst Celanese, marketed an acetal copolymer resin Celcon™, which competes for essentially the same end uses, many of which were formerly served by metals.

About 1960, sulfer hexafluoride (SF_6) became commercially available from Allied Chemical, now AlliedSignal. It is still the premier dielectric gas for use in circuit breakers for current interruption in high-voltage equipment. 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.

The mid-1960s saw commercialization of several resins with outstanding properties: polysulfone developed by Union Carbide (Udel™), noted for its excellent heat and water resistance; modified polyphenylene ether (PPE), formerly called polyphenylene oxide, discovered at General Electric (Noryl™), featuring good dielectric properties over a wide range of humidity and temperature; and polyimide (PI), produced by Du Pont (Pyre ML™ for wire enamel and Kapton™ for film) with one of the highest thermal ratings.

Polybutylene terephthalate (PBT) resins, introduced in 1969, are thermoplastic polyesters widely used, when reinforced with glass fibers, for industrial motor controls, circuit breakers, terminal blocks, and housings for appliances and hand power tools.

Polyphenylene sulfide (PPS), developed by Phillips Chemical (Ryton™), became commercially available in 1972. Its outstanding property is resistance to thermal degradation, which occurs completely only at temperatures over 1300°F (704°C). It is suitable for applications requiring good dimensional stability, chemical resistance, dielectric properties, and resistance to high temperatures.

Polyethersulfone resins were introduced in the United Kingdom and then in the United States in 1972–1973. They were first produced by ICI Americas (Victrex™). Continuous use temperature index rating for unfilled resin by Underwriters Laboratories, 356°F (180°C), is among the highest for any thermoplastic.

Another high-temperature polymer, polyamideimide (PAI), was brought to market by Amoco in 1973 with the trademark Torlon. Resins have stable dielectric and mechanical properties up to 500°F (260°C).

Specialty resins introduced since 1980 includes polyetherimide (PEI) by General Electric (Ultem™), polyacrylate, with several producers, and polyetherether ketone (PEEK), also with several producers.

So much for chronology, but what about future product development and market trends? No doubt, research and development efforts will continue on polymers, although there is now available a multitude of products from which to choose for any given application. The emphasis will probably be on specialty polymers, such as liquid crystal polymers, alloys, blends, and polymers for cryogenic applications.

The search for improved dielectric liquids will certainly continue, but sulfur hexafluoride will remain the premier dielectric gas.

Efforts will increase to eliminate volatile organic compounds (VOCs) from varnishes and wire enamels to stay in compliance with increasingly stringent environregulations.

Insulations for electronics must keep pace with the exciting developments in that technology and in the continuing trend toward miniaturization.

The problem with all this is that insulation technology is an interdisciplinary field involving chemistry, chemical engineering, electrical engineering, mechanical engineering, and quality control. Most practitioners were chemists, electrical engineers, or without formal education, but with a great deal of on-the-job experience, most of which was limited to a few specific applications. With deemphasis on producing electrical insulations by our largest electrical equipment manufacturers, career opportunities in our field are severely limited.

Probably the greatest single opportunity for education and information on new insulating materials and technology is by attending and participating in conferences here and overseas. Only in this way will those involved with dielectric materials have a common forum where ideas and practices can be cross-fertilized with our peers.

2

Fundamentals

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INTRODUCTION

This chapter covers subjects which apply generally to all insulating materials and the reader is encouraged to read it next.

U.S. AND INTERNATIONAL STANDARDS

The real test of the suitability of a material for a specific application is how well the part made from the material performs in actual use when subjected to the full range of conditions it is likely to encounter. This method, however, is usually not practical due to the time (often years) it requires. Manufacturers need quicker ways to determine material suitability. To answer this need, there is an ongoing program to develop and refine tests for selected critical properties to make them more indicative, more useful, more precise, and more reproducible. Thus, users of materials have come to rely on standards as the basis for purchase transactions with producers.

All of the industrialized nations of the world have active standards development programs. The U.S. and Russia each have more than 80,000 active specifications and standards, followed by Germany with 24,000, and the Peoples Republic of China with 14,000.

Standards are important documents in many ways:

- An industrial standard comprises definitions, classifications, requirements, test methods, and recommended practices. (The military uses the word *specification* as nonmilitary organizations use the word *standard*.)
- Standards are intended to establish a common understanding between manufacturers and users regarding requirements for materials and the methods to be employed in determining property values.
- Standards were originally developed for products made and used within a country, but because of increasing international trade, there is a growing need for standards acceptable throughout the world. There are now more than 10,000 international standards, of which about 100, developed by the International Electrotechnical Commission (IEC), are concerned with materials for the electrical and electronics industries.
- Purchases for military products and equipment are virtually all made to specification. Because of this practice and the huge volume of expenditures, the Department of Defense (DOD) is by far the largest developer of specifications in the western world. There are over 9,000 specifications for military products and equipment and over 4,700 specifications for materials. The DOD participates in developing nongovernmental standards and adopts these where possible, cancelling the related military specifications.
- In the U.S., the associations most active in the development of standards for insulating materials are the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), the Institute of Electrical and Electronics Engineers (IEEE),

Underwriters Laboratories (UL), and the Institute for Interconnecting and Packaging Electronic Circuits (IPC), with ASTM having by far the most standards covering the widest variety of products.

Brief descriptions of principal U.S. and international standards preparing organizations, their publications, and their conferences appear in Chapter 18, *Industry Activities*.

Throughout this handbook, a diligent effort has been made to summarize or reference all current (at the time of publication) military specifications and ASTM, NEMA, UL, and IPC standards relating to the materials covered. A complete military specification for a plastic material is included in Chapter 19, *Government Activities*.

INSULATION SYSTEMS AND SERVICE LIFE

An insulation system is an assembly of insulation materials in a particular type of equipment, as defined by Military Specification MIL-E-917, *Electric Power Equipment, Basic Requirements*. Although there are differing opinions on the subject among some authorities, this specification states the case for determining service life of equipment as follows:

> Experience has shown that the thermal life characteristics of composite insulation systems cannot be reliably inferred solely from information concerning component materials. To assure satisfactory service life, insulation specifications need to be supported by service experience or life tests. Accelerated life tests are being used increasingly to evaluate the many new synthetic insulating materials that are available thus shortening the period of service experience required before they can be used with confidence. Tests on complete insulation systems, representative of each type of equipment, are necessary to confirm the performance of materials for their specific functions in the equipment. The electrical insulation of equipment is made up of many different components selected to withstand the widely different electrical, mechanical, and thermal stresses occurring in different parts of the structure. How long an insulation system will be serviceable depends on the effectiveness of the physical support for the insulation, and the severity of the forces acting on it, as well as on the materials themselves and the service environment. Therefore, the length of useful life of the insulation system will depend on the way that its individual components are arranged, the interactions upon each other, and the contribution of each component to the electrical and mechanical integrity of the system.

UL STANDARDS FOR INSULATION SYSTEMS

Underwriters Laboratories has developed the following standards for insulation systems:

- UL 1097, *Double Insulation Systems for Use in Electrical Equipment*
- UL 1446, *Systems of Insulating Materials—General*

• UL 2097, *Reference Standard for Double Insulation Systems for Use in Electronic Equipment*

MATERIAL AGING AND BREAKDOWN

The principal factors generally recognized as causing the aging and deterioration of an insulation are the following:

• *Thermal stresses* occurring in electrical and electronic equipment. These are caused by internal heating due to current overloads plus ambient temperatures. When exposed for prolonged periods above a temperature specific for each material, chemical and physical breakdown rapidly accelerates, aggravated by mismatches in thermal expansion.

• *Electrical stresses* caused by the voltage gradient in the material. Most equipment is designed with ample safety margin for dielectric strength, so under normal operating conditions, high-voltage gradients below the breakdown voltage do not cause detectable aging. However, at elevated temperatures, electrical stresses may act to further accelerate material degradation.

• *Mechanical stresses* caused by assembly configurations, manufacturing techniques, centrifugal forces, and vibration. These stresses tend to physically damage material.

• *Environmental conditions*, such as exposure to oxidation, ozone, radiation, and chemicals. The destructive effects of oxidation and radiation are discussed in this chapter in the section on "Radiation" (p. 18) and in Chapter 3, sections "Antioxidants" and "Ultraviolet Stabilizers" (pp. 45, 46). The resistance of insulating materials to many chemicals is well documented, so in selecting candidates for a specific application, only those materials should be considered that are resistant to attack by chemicals likely to be encountered.

• *Moisture*, either in the form of water or high humidity, a major cause of lowered dielectric properties or even dielectric failure of an insulation system. Some insulating materials, such as papers and organic fabrics, are highly hygroscopic and are not suitable for use alone as electrical insulation in environments where moisture could be present in appreciable amount. Moisture causes the fibers of these materials to swell, thereby affecting their spacing and the thickness of the material. However, up to 6 percent moisture content is necessary for these materials to exhibit their optimum mechanical properties. Each of these materials has a critical water content below which their usefulness deteriorates rapidly, so they cannot be completely dried before use. It is customary to impregnate and/or coat these materials with insulating liquids or varnishes to impede moisture absorption significantly. When so treated effectively, the paper and fabric perform as substrates and the dielectric properties of the system approach those of the impregnant or coating.

Although not as susceptible to moisture absorption to nearly the same degree as papers and organic fabrics, some plastics will pick up moisture much more readily than other plastics. Examples are polyamides (nylons), polyimides, acrylics, polysulfones,

and some polyurethanes. Somewhat lower dielectric properties do not preclude their use for many applications.

Moisture can also form a conductive path on the surfaces of otherwise moisture-resistant materials. This action is exacerbated by the presence of conductive contaminants on a surface, which is often the case with transmission line insulators.

Under certain conditions and at elevated temperatures, moisture may react with some polymers, notably polyurethanes, to cause chemical reversion, thereby destroying the ability to function as a dielectric. This tendency to hydrolyze can be controlled by blending or alloying with less susceptible polymers.

- *Voids and contaminants* within an insulating material providing the location for initiation of destructive action by electrical discharge, moisture, and contaminant reaction with the base material.

Since the aging of insulation systems in service is usually caused by several of the above factors acting simultaneously, testing aging factors independently cannot be expected to portray service life accurately.

Although there is acceptance by most authorities of the avalanche theories on breakdown in gases and liquids (discussed in chapters on *Dielectric Gases* and *Dielectric Liquids*), despite intensive postulation, no theory yet satisfactorily explains all aspects of breakdown in solids. The problem is that dielectric failure in solids is more complex, involving combinations of several breakdown mechanisms. In solids, atoms and molecules are not as free to move or rotate with the application of an electrical field. In functioning electrical equipment, however, impurities, voids, environmental factors, and the configuration of the equipment are more important in determining breakdown than the inherent nature of the material. The probability of breakdown because of these factors is greatly increased by rising temperatures, including localized heating that cannot be effectively dissipated. The *intrinsic (theoretical) dielectric strength* of a material is that value of the electrical field intensity which causes breakdown absent the effect of the above factors.

It is well known that for a given material, the dielectric strength is significantly greater per unit thickness for thin than for thick specimens. The explanation generally given for this phenomenon is that with increased thickness, more dielectrically weaker paths are available, the weakest of which causes breakdown. By similar reasoning, the use of larger area electrodes results in lower dielectric strength values. A rule of thumb states that for homogeneous solids, the dielectric strength varies approximately as the reciprocal of the square root of the thickness of the specimen. However, although this interpretation may satisfy empirical test results, it does not provide an explanation of the true nature of the phenomenon, which awaits the results of further research.

Another factor affecting dielectric strength values is the rate of voltage rise and whether it is continuous or step-by-step. A slow rate of increase usually encourages time-dependent thermal degradation due to local heating, resulting in lower dielectric strength values. To be meaningful, therefore, dielectric breakdown strength values should include a statement of the following:

- Specimen thickness and conditioning
- Method of voltage application

- Type and size of electrodes
- Test temperature
- Any unusual environmental conditions

A phenomenon about which there is little enlightening published information is the significantly higher dielectric breakdown strength perpendicular to laminations of multiple layers of an insulating material compared with the same total thickness of a single layer of the same material. In effect, the boundaries between layers seem to interrupt or lengthen what otherwise would be a breakdown path through a homogeneous material. When tested parallel to laminations, the electrical field has no boundaries to penetrate and the breakdown voltage is significantly lower than for unlaminated material. Here, the boundaries may contain surface discontinuities which present dielectric weaknesses.

PARTIAL DISCHARGE (CORONA)

Although the phenomenon of an electrical discharge which does not completely bridge the insulation between electrodes or conductors is often referred to by both terms, the IEEE prefers *partial discharge*. In general usage, *corona* is accompanied by a faint glow, while *partial discharge* need not be luminous.

Partial discharge may occur in high-voltage transmission lines, resulting in formation of ozone, a highly reactive form of oxygen, and in ionization, often luminous, in the surrounding air. Where conductors are insulated, the insulation may be attacked by ozone and further degraded by electron bombardment.

Partial discharge may also occur in a void within an insulation system where the voltage gradient is sufficiently high. This discharge has a damaging effect on surrounding materials, causing a weakness in the system that can eventually lead to failure. As frequency increases in ac systems, partial discharge damage increases rapidly. Both ac and dc systems are susceptible to ionization attack on insulation surfaces.

Saturated polymers with high resistance to oxidation may have low resistance to ionization attack, as exhibited by polyethylene, polypropylene, and polytetrafluoroethylene. Silicone rubber is rated the best flexible insulation with regard to both ozone and ionization attack for operating temperatures over 130°C (266°F). For lower temperatures, ethylene-propylene copolymer, butyl rubber, nylon, and chlorinated polyolefins are among the least affected polymers. For applications where they are otherwise suitable, paper–oil cables would provide the best protection from both ozone and ionization damage.

SPACE CHARGES

A phenomenon known as *space charges* gained attention and encouraged investigation into their causes and measurement when it was observed that when a positive dc voltage was applied to a cable insulated with crosslinked polyethylene for a significant period of time, the breakdown voltage became perceptibly lower after negative dc voltage was applied. The reason ascribed to this occurrence was that it was caused by a space charge

built up in the insulation by free electrons and negative ions. This was of such magnitude that an undersea power transmission cable with XLPE insulation planned between Hokkaido and Honshu islands in Japan was completed instead with oil-filled cable.[1]

Although there are many theories regarding the causes and effects of space charges in dielectrics, the practical consideration is that traditional dielectric strength tests may not always be relied upon as design criteria in certain applications where space charges may be involved.

See also "Breakdown in Gases," p. 435.

RADIATION

When plastics are subjected to ionizing radiation:

- Free radicals are created by breaking chemical bonds.
- Molecules become crosslinked, thereby improving stress-crack, abrasion, and deformation resistance, raising useful service temperature, and increasing resistance to the action of fluids.

Ionizing radiation also promotes rapid room temperature polymerization of solventless organic coatings and vulcanization of natural and synthetic rubbers other than butyl rubber.

However, excessive ionizing radiation may cause serious degradation in these materials. Each material has its own threshold resistance to ionizing radiation beyond which severe damage occurs.

Ionizing radiation may be produced by ultraviolet light (UV) or electron beam (EB) technology.

See also "Ultraviolet Stabilizers," p. 46, and "Radiation Curing," p. 241.

DIPOLE MOMENT AND POLARIZATION

Dipole moment may be defined as follows:

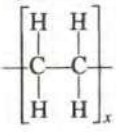
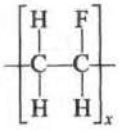
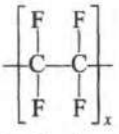
> Molecules in which the atoms and their electrons and nuclei are so arranged that one part of the molecule has a positive electrical charge while the other part is negatively charged. The molecule therefore becomes a small magnet or dipole. Changing electrical or magnetic fields causes the molecule to turn or rotate in one direction or another, depending on the charge of the field. The dipole moment (μ) is the distance between the charges multiplied by the quantity of charge in electrostatic units.[2]

Dipole polarization occurs when normally randomly oriented permanent dipoles of a molecule are aligned by an applied electric field. This phenomenon is facilitated

[1]Y. Li and T. Takada, "Progress in space charge measurement of solid insulating materials in Japan," *IEEE Electrical Insulation Magazine*, vol. 10, no. 5, Sept./Oct. 1994.

[2]Gessner G. Hawley, *Condensed Chemical Dictionary*, 10th ed. New York: Van Nostrand Reinhold, 1981.

at higher temperatures where dipoles are bound less tightly and are more free to align with the field.

The type and arrangement of the atoms in a molecule determine its polarity. In general, the degree of molecular symmetry and the affinity of an atom for its electrons influences polarity. Thus, polyethylene  is nonpolar, polymonofluoroethylene  is strongly polar, and polytetrafluoroethylene  exhibits low polarity (because of symmetry and the high affinity of fluorine for its electrons).

The aligned dipole molecules produce a net polarization across the material which has the effect of increasing the dielectric constant. In general, the dielectric constant at 1 megahertz of nonpolar polymers ranges from 2.2 to 2.6, and for polar polymers from 2.6 to over 6. Examples of nonpolar and polar polymers are shown in Table 2-1.

In addition to polarization by permanent dipoles, other forms of polarization include *electronic polarization* and *atomic polarization*. Arthur von Hippel, in his writing on *Molecular Properties of Dielectrics*, describes these phenomena as follows:

> Matter, electrically speaking, consists of positive atomic nuclei surrounded by negative electron clouds. Upon the application of an external electric field the electrons are displaced slightly with respect to the nuclei; induced dipole moments result and cause the so-called electronic polarization of materials. When atoms of different types form molecules, they will normally not share their electrons symmetrically, as the electron clouds will be displaced eccentrically toward the stronger binding atoms. Thus atoms acquire charges of opposite polarity, and an external field acting on these net charges will tend to change

TABLE 2-1 Typical Nonpolar and Polar Polymers

Nonpolar
Polyethylene
Polyphenylene oxide
Polypropylene
Polystyrene
Polytetrafluoroethylene
Polar
ABS resin
Nylon 6/6
Polycarbonate
Polymethyl methacrylate
Polysulfone
Polyvinyl chloride

the equilibrium positions of the atoms themselves. By this displacement of charged atoms or groups of atoms with respect to each other, a second type of induced dipole moment is created; it represents the atomic polarization of the dielectric. The asymmetric charge distribution between the unlike partners of a molecule gives rise, in addition, to permanent dipole moments which exist also in the absence of an external field. Such moments experience a torque in an applied field that tends to orient them in the field direction. Consequently, an orientation (or dipole) polarization can arise.

All polymers can be polarized by an electric field, but not necessarily by their permanent dipoles. Where all forms of polarization are present, the highest dielectric constant will be observed in a dc or low-frequency ac field. As frequency increases, a point will be reached where a particular polarization does not have time to form, leading to a decrease in dielectric constant. Permanent dipole polarization takes the longest time, requiring the movement of entire molecular segments, and consequently this form is the first to become inactive. Atomic polarization is next, requiring movement of atoms. The last form to become inactive is electronic polarization, which involves only electrons. All forms, however, persist through power frequencies up to at least 1 megahertz (10^6 Hz).

Following this analysis, the dissipation factor (tan δ) is highest when permanent dipole moments are oscillating in phase at maximum frequency, thereby creating frictional heat, just before the frequency becomes too high for them to oscillate in phase or at all.

For a detailed discussion of polarization, see:

Engineering Dielectrics, Volume IIA, Bartnikas/Eichhorn, American Society for Testing and Materials (includes extensive references).

An Introduction to the Theory of Dielectric Loss in Plastics, A. H. Sharbaugh and J. C. Devins, Institute of Electrical and Electronics Engineers Publication 68C6-EI-33.

MATERIAL SELECTION STEPS

In selecting a material for a specific use, these steps are important:

1. All possible environmental conditions to which the material could be exposed should be determined, including (but not necessarily limited to) temperature, humidity, chemicals, and radiation.

2. The list of candidate materials for the application should be reviewed, eliminating from further consideration all materials known not to be sufficiently resistant to these conditions. As an example, for an application requiring continuous operation at 155°C (311°F), all materials with lower thermal class ratings should be screened out.

3. Considering the equipment or part design and the manufacturing process to be used, only materials which possess the required dielectric and mechanical properties should be selected for further review. For example, unreinforced mica paper tape

would not withstand typical coil winding tensions. Glass fabric reinforced mica tape would, however, withstand the winding process, but at the cost of added bulk and expense. Conformability, deformability, and impact strength are important considerations for many applications, such as housings and control equipment. Arc quenching capability without formation of carbon is required for dielectric gases used in circuit breakers.

4. Compatibility with other compounds in an insulation system is a critical factor and should serve to screen materials. For example, transformer liquids should not affect gaskets (a consideration with silicones), films, or laminates used in the transformer insulation system.

5. Manufacturing ease, time, and cost should be considered, together with material cost to determine final suitability for an end use.

6. Building and testing a prototype should be the final step, with redesign and retesting where necessary.

Property values listed in data sheets and tables should serve only for comparisons among candidate materials and as a screening method where differences are significant. Properties of plastics are time-dependent and cannot be predicted from short-time tests. This is especially so for material degradation by oxidation, radiation, and chemicals.

TEMPERATURE INDEX OF DIELECTRIC MATERIALS

Design engineers require some way of selecting dielectric materials for use in electrical equipment for continuous operation at elevated temperatures. The temperature index has been developed for this purpose to serve as a guide to the relative thermal endurance of commonly used dielectric materials. Since it is impractical to test materials for as long as they are expected to remain effective in service, tests are conducted at selected elevated temperatures, and the time plotted to the end point criteria on a graph with the logarithm of time as the ordinate and the reciprocal of the absolute temperature, K, as the abscissa (Arrhenius plot). The graph is then extrapolated, most commonly to 20,000 hours, to determine the temperature index of the material.

Although this index is of practical use to design engineers, it is to be noted that for many dielectric materials which would have satisfactory endurance for 20,000 hours over the full range of operating temperatures of the electrical equipment they insulate, decomposition occurs at elevated temperatures used to determine temperature indexes, indicating (incorrectly) that these materials would be unsuitable where practical experience has shown them to be effective dielectrics.

Although the terms temperature index, temperature classification, and thermal endurance are often used interchangeably in common parlance, distinctions are made in the technical literature (while still leaving room for some confusion):

• *Temperature Classification* is a term reserved for insulating systems as used in specific equipment, and is no longer recognized as a description of the temperature capability of individual insulating materials (IEEE Standard 98-1984). Note: Individual dielectric materials are, however, generally referred to as Class 90, Class 105, etc., materials.

• *Thermal Endurance* is defined as the relationship between temperature and time spent at that temperature, required to produce such degradation of an electrical insulation that it fails under specified conditions of stress, electric or mechanical, in service or under test (*IEEE Standard Dictionary of Electrical and Electronics Terms*).

• *Temperature Index* is an index that allows relative comparisons of the temperature capability of insulating materials or insulation systems based on specified controlled test conditions (*IEEE Standard Dictionary of Electrical and Electronics Terms*). Temperature ranges and their assigned indexes are shown in Table 2-2.

TABLE 2-2 Preferred Temperature Indexes (°C)

TEMPERATURE RANGE OF FAILURE IN 20,000 H	ASSIGNED TEMPERATURE INDEX
90–104	90
105–129	105
130–154	130
155–179	155
180–199	180
200–219	200
220–249	220
250 and above	none established

STANDARD TESTS FOR DIELECTRIC MATERIALS

Specific tests covering all dielectric materials are described in Chapter 3, *Thermoplastic Molding Materials*, where they are most commonly used for comparing polymeric materials.

SI SYSTEM FOR METRIC PRACTICE (ASTM E 380)

This system is intended as a basis for international standardization of measurement units. The designation SI is an acronym for the French name "Le Système International d'Unités."

SI units and quantity symbols are shown in Table 2-3.

TABLE 2-3 SI Units and Quantity Symbols

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
*ampere	A	amp, a	SI unit of electric current, magnetic (scalar) potential, magnetomotive force.	*I* *U* *F*
ampere-hour	Ah, A·h	amp-hr	Quantity of electricity. 1 Ah = $3.6 \cdot 10^3$ C.	
*ampere-turn	A	At	SI unit of magnetomotive force.	*F*
*ampere per meter	A/m		SI unit of linear current density, magnetic field strength (note: interpret as ampere turns per meter).	*A* *H*
*ampere per square meter	A/m^2		SI unit of current density.	*J*
*ampere meter squared	$A \cdot m^2$		SI unit of magnetic (area) moment.	*m*
angstrom	Å	A°, A	Wavelength. Use not recommended. 1 Å = 10^{-10} m.	
atmosphere, standard	atm		Pressure. Use not recommended. 1 atm = 14.7 lb/in^2 = $1.013 \cdot 10^5$ Pa.	
atmosphere, technical	at		Use not recommended. 1 at = 1 kgf/cm^2.	
*atomic mass unit (unified)	u		Atomic mass. The (unified) atomic mass unit is defined as one twelfth of the mass of an atom of the ^{12}C nuclide. Use of the old atomic mass (amu), defined by reference to oxygen, is not recommended.	
*atto	a		SI prefix for 10^{-18}.	
*attoampere	aA		See: ampere.	
*attofarad	aF		See: farad.	
bar	bar	b, barye	Pressure. 1 bar = 10^5 Pa. Use of the bar is strongly discouraged except for limited use in meteorology.	
barn	b		Nuclear capture cross section. In temporary use with SI. 1 b = 10^{-28} m^2.	
barrel	bbl		Volume. 1 bbl = 42 gal_{us} = $1.5899 \cdot 10^{-1}$ m^3.	
barrel per day	bbl/d		Standard barrel used for petroleum, etc. A different standard barrel is used for fruits, vegetables, and dry commodities.	
baud	Bd	baud (w/ prefix)	In telecommunications, a unit of signaling speed equal to one element per second. The signaling speed in bauds is equal to the reciprocal of the signal element length in seconds.	1/*r*

(*continued*)

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
bel	B	b	Ratio of power. Rarely used. 1 B = 10 dB. See decibel and Appendix B of ANSI-IEEE Std 260-1978 for further guidance concerning notation.	
*becquerel	Bq		SI unit of activity of a radionuclide.	
billion electronvolts	GeV	bev, BeV	Energy of accelerated particles. The name *gigaelectronvolt* is preferred for this unit.	
bit	b	bit	In information theory, the bit is a unit of information content equal to the information content of a message, the *a priori* probability of which is one half.	
			In computer science, the bit is a unit of storage capacity. The capacity, in bits, of a storage device is the logarithm to the base two of the number of possible states of the device.	
bit per second	b/s	bit/s, bits/s, bps, bit/sec		
British thermal unit	Btu		Heat, energy. Use of the joule (SI) is preferred. Conversion factors vary with usage. Consult ANSI/IEEE Std 268-1982.	
byte	byte		A group of bits or adjacent binary digits that a computer processes as a unit.	
calorie (International Table calorie)	cal_{IT}		Heat. Use not recommended. 1 cal_{IT} = $4.1868 \cdot 10^3$ J.	
calorie (thermochemical calorie)	cal		Heat. Use not recommended. 1 cal = $4.1840 \cdot 10^3$ J.	
*candela	cd		SI unit of luminous intensity.	I
candela per square foot	cd/ft^2		Luminance. Use of the SI unit cd/m^2 is preferred.	L
candela per square inch	cd/in^2		Luminance. Use of the SI unit cd/m^2 is preferred. 1 $cd/in^2 = 1.55 \cdot 10^3$ cd/m^2.	
*candela per square meter	cd/m^2	nit	SI unit of luminance.	L
candle	cd		The unit of luminous intensity has been given the name *candela*. Use of the name *candle* for this unit is not recommended.	
*centi	c (prefix)		SI prefix for 10^{-2}.	
*centimeter	cm		Length. (Preferred SI unit multiple.)	
*circular mil	cmil		Area (cross section of wire). 1 cmil = $(\pi/4) \cdot 10^{-6}$ $in^2 = 5.067 \cdot 10^{-10}$ m^2.	

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
*coulomb	C	c	SI unit of electric charge, quantity of electricity, electric flux. 1 C = 1 A·s.	Q Ψ
*coulomb per meter	C/m		Linear density of charge (SI).	λ
*coulomb meter	C·m		SI unit of electric dipole moment.	p
*coulomb per square meter	C/m^2		SI unit of electrical flux density.	D
*coulomb per cubic meter	C/m^3		SI unit of volume density of charge.	
*cubic centimeter	cm^3	cc	Volume. (Preferred SI unit multiple.)	
cubic foot	ft^3		Volume. 1 $ft^3 = 2.832 \cdot 10^{-2}$ m^3.	
cubic foot per minute	ft^3/min	cfm	Flow rate. 1 $ft^3/min = 4.719 \cdot 10^{-4}$ m^3/s.	
cubic foot per second	ft^3/s		Flow rate. 1 $ft^3/s = 2.832 \cdot 10^{-2}$ m^3/s.	
cubic inch	in^3		Volume. Section modulus. 1 $in^3 = 1.639 \cdot 10^{-5}$ m^3.	
*cubic meter	m^3		SI unit of volume.	
*cubic meter per second	m^3/s		SI unit of flow rate.	
cubic yard	yd^3		1 $yd^3 = 0.7646$ m^3.	
curie	Ci	C	A unit of activity of radionuclide. Use of the SI unit, the becquerel, is preferred. 1 Ci = $3.7 \cdot 10^{10}$ Bq.	
cycle per second	Hz	c/s, cps, c/sec, cycle	Frequency. See: hertz. The name *hertz* is internationally accepted for this unit; the symbol Hz is used instead of c/s.	
day	d		1 day = 24 hr = 86 400 s.	
deci	d (prefix)		SI prefix for 10^{-1}.	
decibel	dB	db, DB	Noise intensity, gain, power. See Appendix A of ANSI-IEEE Std 260-1978 for further guidance concerning notation.	
decibel referred to 1 mW	dB (1mW)	dBm	See Appendix A of ANSI/IEEE Std 260-1978 for further guidance concerning notation.	
degree	...°	deg	Plane angle.	
degree Celsius	°C	degree centigrade	SI unit of Celsius temperature. The degree Celsius is a special name for the kelvin, for use in expressing Celsius temperatures or temperature intervals. $T_K = t_{°C} + 273.15$.	t
degree Fahrenheit	°F		Temperature. $T_K = (t_{°F} + 459.67)/1.8$. $t_{°C} = (t_{°F} - 32)/1.8$.	

(continued)

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
degree Kelvin			See: kelvin.	
degree Rankine	°R		Use discouraged. $T_K = T_R/1.8$.	
deka	da (prefix)		SI prefix for 10.	
dyne	dyn	dyne	Force. Use not recommended. 1 dyn $= 10^{-5}$ N.	F
*electronvolt	eV	ev	Energy (nuclear physics). 1 eV = $1.602 \cdot 10^{-19}$ J.	
erg	erg		Work, energy. Use not recommended. 1 erg $= 10^{-7}$ J.	
exa	E (prefix)		SI prefix for 10^{18}.	
*farad	F	f, fd	SI unit of capacitance. 1 F = 1 C/V.	C
*farad per meter	F/m		SI unit of capacity, permittivity.	ϵ
*farad, reciprocal	F^{-1}	daraf	Unit of elastance (SI).	S
*femto	f (prefix)		SI prefix for 10^{-15}.	
foot	ft		Length. 1 ft = 0.3048 m.	
foot per minute	ft/min	fpm	Velocity. 1 ft/min = $5.080 \cdot 10^{-3}$ m/s.	
foot per second	ft/s	fps, ft/sec	Velocity. 1 ft/s = 0.3048 m/s.	
foot-pound	ft·lb		A unit of work equal to the work done by a force of one pound acting through a distance of one foot in the direction of the force.	
foot pound-force	ft·lbf		Use joules. 1 ft·lbf = 1.356 J.	
foot poundal (OBSOLETE)	ft·pdl		An absolute unit of work equal to the work done by a force of one poundal acting through a distance of one foot in the direction of the force. Note: No longer used. 1 ft·pdl = $4.214 \cdot 10^{-2}$ J.	
footcandle	fc		Illumination. 1 fc = 1 lm/ft^2. The name *lumen per square foot* is also used for this unit. Use of the SI unit of illuminance, the lux (lumen per square meter), is preferred. 1 fc = 10.764 lx.	
footlambert	fL		Brightness (luminance). 1 fL = $(1/\pi)$ cd/ft^2. One lumen per square foot leaves a surface whose luminance is one footlambert in all directions within a hemisphere. Use of the SI unit, the candela per square meter, is preferred. 1 fL = 3.426 cd/m^2.	
gee	g	G	Acceleration of gravity. Standard acceleration of free fall. Use m/s^2. 1 g = 9.807 m/s^2.	
gal	Gal		Use strongly discouraged. The gal is used only for the quantity g. 1 Gal = 1 cm/s^2 $= 10^{-2}$ m/s^2.	

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
gallon	gal		Volume. Use not recommended. 1 gal_{US} = 231 in^3 = 3.7854 L. 1 gal_{UK} = 4.5461 L.	
gauss	G		Electromagnetic CGS unit of magnetic flux density. Use not recommended. Use tesla. 1 G = 10^{-4} T.	B
*giga	G (prefix)	kM	SI prefix for 10^9.	
*gigabit	Gb		See: bit.	
gigacycle per second	GHz	kMC, Gc/s	Frequency. See: hertz, gigahertz.	f, ν
*gigaelectronvolt	GeV	bev, BeV	Energy. See: electronvolt.	
*gigahertz	GHz	kMHz, KMC, Gc/s	Frequency. (Preferred SI unit multiple.)	f, ν
gilbert	Gb		Electromagnetic CGS unit of magneto-motive force. Use not recommended. 1 Gb = 0.7958 A.	
*gram	g	gm	Mass. (Preferred SI unit multiple.) 1 g = 10^{-3} kg.	m
*gray	Gy		SI unit of absorbed dose in the field of radiation dosimetry.	
*hecto	h		SI prefix for 10^2.	
*henry (pl. henrys)	H	Hy, hy	SI unit of inductance: (self) inductance, permeance. 1 H = 1 Wb/A.	L P, P_m
*henry, reciprocal	H^{-1}		Reciprocal inductance (SI). Reluctance (SI).	Γ R, R_m
*henry per meter	H/m		SI unit of (magnetic) permeability, absolute permeability.	μ
*hertz	Hz	cps, c/s, cycle	SI unit of frequency, bandwidth.	f, ν B
horsepower	hp		Power, rate of work. The horsepower is an anachronism in science and technology. Use of the SI unit of power, the watt, is preferred. Conversion factors vary with usage: 1 hp (electric) = $7.46 \cdot 10^2$ W. 1 hp (metric) = $7.35 \cdot 10^2$ W. 1 hp (U.K.) = $7.45 \cdot 10^2$ W.	
*hour	h	hr	Time. 1 h = $3.6 \cdot 10^2$ s.	
inch	in	in.	Length. 1 in = $2.54 \cdot 10^{-2}$ m.	
inch per second	in/s	ips	Velocity. 1 in/s = $2.54 \cdot 10^{-2}$ m/s.	

(continued)

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
*joule	J		SI unit of energy, work, quantity of heat.	E, W W Q
*joule per degree Celsius	J/°C		SI unit of heat capacity, thermal capacitance.	C_θ
*joule per kelvin	J/K		SI unit of entropy.	S
kelvin	K		SI unit of temperature. Previous to 1967 called *degree kelvin*. Note no symbol ° appears with K. $t_{°C} = T_K - 273.15$.	
*kilo	k(prefix)		SI prefix for 10^3.	
*kilobit	kb		See: bit.	
*kilobyte	kilobyte		See: byte.	
kilocycle per second	kHz	kc/s, kc	Frequency. Use kilohertz. See: hertz.	
kilomegacycle per second	GHz	KMC, kMc/s	Frequency. Use gigahertz. See: hertz.	
kilogauss	kG		Use not recommended. See: gauss.	
*kilogram	kg		SI unit of mass.	
kilogram-force	kgf		Use not recommended. Kilogram is SI unit of mass, newton is SI unit of force. 1 kgf = 9.807 N.	
*kilohertz	kHz		Frequency. (Preferred SI unit multiple.)	
*kilohm	kΩ		Resistance. (Preferred SI unit multiple.)	R
*kilojoule	kJ		See: joule.	
*kilometer	km		Length. (Preferred SI unit multiple.)	
*kilometer per hour	km/h		Velocity.	
*kilotesla	kT		See: tesla.	
*kilovar	kvar		Reactive power. (Preferred SI unit multiple.)	Q
*kilovolt	kV		(Preferred SI unit multiple.) See: volt.	
*kilovoltampere	kVA	KVA, kva	Apparent power. (Preferred SI unit multiple.)	
*kilowatt	kW		(Preferred SI unit multiple.) See: watt.	
kilowatthour	kWh		Temporarily in use with SI as a measure of electric energy. Widely used, but should eventually be replaced by the megajoule. 1 kWh = 3.6 MJ.	
knot	kn		1 kn = 1 nmi/h = 0.514 m/s. Use not generally recommended.	
lambert	L		CGS unit of luminance. Use not recommended. 1 L = $(1/\pi)\cdot 10^4$ cd/m^2 = $3.183 \cdot 10^3$ cd/m^2. One lumen per square	L

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
			centimeter leaves a surface whose luminance is one lambert in all directions within a hemisphere.	
*liter	L	l	Volume. 1 L = 10^{-3} m^3. The letter l has been adopted for *liter* by the CGPM, and it is recommended in a number of international standards. In 1978 the CIPM accepted L as an alternative symbol. Because of frequent confusion with the numeral 1, the letter l is no longer recommended for U.S. use. (Script ℓ also not recommended.)	V, v
liter per second	L/s		Flow rate.	
*lumen	lm		SI unit of luminous flux. 1 lm = 1 cd·sr.	Φ
lumen per square foot	lm/ft^2		Unit of illuminance and also a unit of luminous exitance. Use of the SI unit, lumen per square meter is preferred. 1 lm/ft^2 = 10.764 lm/m^2.	
*lumen per square meter	lm/m^2		SI unit of luminous exitance.	M
*lumen per watt	lm/W		SI unit of spectral luminous efficacy, total luminous efficacy.	$K(\lambda)$ K, K_t
*lumen second	lm·s		SI unit of quantity of light.	Q
*lux	lx		SI unit of illuminance. 1 lx = 1 lm/m^2.	E
maxwell	Mx		CGS electromagnetic unit of magnetic flux. Use not recommended. 1 Mx = 10^{-8} Wb.	
*mega	M (prefix)		SI prefix for 10^6.	
*megabyte	megabyte		See: byte.	
*megaelectronvolt	MeV		See: electronvolt.	
*megahertz	MHz		Frequency. (Preferred SI unit multiple.) See: hertz.	
*megohm	MΩ	M	(Preferred SI unit multiple.) See: ohm.	
*megavolt	MV		(Preferred SI unit multiple.) See: volt.	
*megawatt	MW		(Preferred SI unit multiple.) See: watt.	
*meter	m		SI unit of length, breadth, height, thickness, radius, diameter, length of path, wavelength.	l b h d, δ r d s λ

(*continued*)

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
*meter, reciprocal	m^{-1}	/m	Wavenumber (SI).	σ (also, $\tilde{\nu}$ in spectroscopy only.)
*square meter	m^2		SI unit of area.	A
*cubic meter	m^3		SI unit of volume.	V, v
*meter per second	m/s		SI unit of velocity.	v
*meter per second squared	m/s^2		SI unit of acceleration.	a, g
*meter to the fourth power	m^4		Second (axial) moment of area (SI). Second (polar) moment of area (SI).	I, I_a J, I_p
*(ion) per cubic meter	m^{-3}	ion/m^3	Ion (number) density (SI).	$n^+; n^-$
*square meter per volt second	$m^2/V{\cdot}s$		Mobility (of a charge carrier in a medium) (SI).	μ
*(electron) per cubic meter second	$m^{-3}{\cdot}s^{-1}$		Rate of production of electrons per unit volume (SI).	q
*cubic meter per second	m^3/s		Recombination coefficient (SI).	α
metric ton	t		Use not recommended. 1 t = 1000 kg.	
mho	mho	Ω^{-1}	Formerly used as the name of the siemens (S). Still in use in the U.S.	
*micro	μ (prefix)		SI prefix for 10^{-6}.	
micromicro	p (prefix)	$\mu\mu$	Prefix for 10^{-12}. Do not use. Use pico.	
*microampere	μA		Electric current. See: ampere.	
*microfarad	μF		Capacitance. (Preferred SI unit multiple.)	
*microgram	μg		See: gram.	
*microhenry	μH		Self inductance. (Preferred SI unit multiple.)	
microinch	μin		1 μin = $2.54{\cdot}10^{-8}$ m.	
*microliter	μL		See: liter.	
*micrometer	μm	μ	Length. (Preferred SI unit multiple.) 1 μm = 10^{-6} m.	
micron	μm	μ	Use not recommended. Micron = micrometer. Use micrometer. Change μ to μm.	
*microsecond	μs		Time. (Preferred SI unit multiple.)	
*microsiemens	μS		Conductance. (Preferred SI unit multiple.)	
*microwatt	μW		Power. (Preferred SI unit multiple.)	
mil	mil		1 mil = 0.001 in = $2.54{\cdot}10^{-5}$ m.	
mile (nautical)	nmi		1 nmi = $1.852{\cdot}10^3$ m.	
mile (statute)	mi (statute)		1 mi = 5280 ft = $1.609{\cdot}10^3$ m.	

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
mile per hour	mi/h	mph	Although use of mph as an abbreviation is common, it should not be used as a unit symbol. 1 mi/h = 0.447 m/s = 1.609 km/h.	
*milli	m (prefix)		SI prefix for 10^{-3}.	
*milliampere	mA		See: ampere.	
millibar	mbar		Use of the bar is strongly discouraged, except for limited use in meteorology. 1 mbar = 100 Pa.	
*milligram	mg		Mass. (Preferred SI unit multiple.)	
*millihenry	mH		Self inductance. (Preferred SI unit multiple.)	
*milliliter	mL		See: liter.	
*millimeter	mm		Length. (Preferred SI unit multiple.)	
millimicron	nm		Use of the name millimicron is not recommended. Use nanometer.	
*millipascal second	mPa·s		Dynamic viscosity. (Preferred SI unit multiple.)	
*millisecond	ms		Time. (Preferred SI unit multiple.)	
*millivolt	mV		(Preferred SI unit multiple.) See: volt.	
*milliwatt	mW		Power. (Preferred SI unit multiple.)	
*minute (plane angle)	′		Used to measure plane angles in surveys, plans, electrical calculations. Radians are used to measure plane angles in scientific and engineering calculations.	
*minute (time)	min		Time. Used to measure work time and in statistics. Note: In engineering measurements and calculations, minutes should be used in time derivative functions only when "second" related quantities (such as "millisecond, microsecond") become impractical. Time may also be designated by means of superscripts as in the following example: $9^{h}\ 46^{m}\ 30^{s}$.	
*mole	mol		SI unit of amount of a substance.	
month	mo			
*nano	n (prefix)		SI prefix for 10^{-9}.	
*nanoampere	nA		See: ampere.	
*nanofarad	nF		See: farad.	
*nanometer	nm		Length. (Preferred SI unit multiple.)	
*nanosecond	ns		Time. (Preferred SI unit multiple.)	
*nanowatt	nW		Power. (Preferred SI unit multiple.)	

(*continued*)

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
nat	nat		Natural logarithmic equivalent of the bit.	
nautical mile	nmi		Distance, range. 1 nmi = 1852 m.	
*neper	Np		Natural logarithm of two amounts of power (SI). 1 Np = 8.686 dB.	
*neper per second	Np/s		Damping coefficient (SI).	δ
*neper per meter	Np/m		Attenuation coefficient (SI).	α
*newton	N		SI unit of force. 1 N = 1 kg·m/s^2.	F
*newton meter	N·m		Moment of force (SI).	M
			Torque (SI).	T
*newton per square meter	N/m^2		SI unit of pressure or stress. See: pascal	p, σ, τ
			Young's modulus.	E
			Modulus of elasticity.	E
			Shear modulus.	G
			Bulk modulus.	K
nit			Luminance. The name *nit* is sometimes given to the SI unit of luminance, the candela per square meter. Use of the *nit* is permitted as a name in text but not as a unit symbol. 1 nit = 1 cd/m^2.	L
oersted	Oe	oe	Electromagnetic CGS unit of magnetic field strength. Use not recommended. 1 Oe = 79.57 A/m.	
*ohm	Ω		SI unit of resistance,	R
			impedance,	Z
			reactance.	X
			1 Ω = 1 V/A.	
*ohm meter	Ω·m		SI unit of resistivity.	
ounce (avoirdupois)	oz		1 oz = 2.835·10^{-2} kg.	
*pascal	Pa		SI unit of pressure or stress. 1 Pa = 1 N/m^2.	
*pascal second	Pa·s		SI unit of dynamic viscosity.	
percent	%			
*peta	P (prefix)		SI prefix for 10^{15}.	
*pico	p (prefix)		SI prefix for 10^{-12}.	
*picoampere	pA		See: ampere.	
*picofarad	pF		Capacitance. (Preferred SI unit multiple.)	
*picosecond	ps		Time. (Preferred SI unit multiple.)	
*picowatt	pW		Power. See: watt.	
pint	pt		1 pt (U.K.) = 0.5683 L.	
			1 pt (U.S. dry) = 0.5506 L.	
			1 pt (U.S. liquid) = 0.4732 L.	
pound (avoirdupois)	lb		1 lb (av) = 0.4536 kg.	
pound per cubic foot	lb/ft^3		1 lb/ft^3 = 16.018 kg/m^3.	

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
pound-force	lbf		1 lbf = 4.448 N.	
pound-force foot	lbf·ft		1 lbf·ft = 1.356 N·m.	
pound-force per square foot	lbf/ft^2		1 lbf/ft^2 = 47.88 Pa.	
pound-force per square inch	lbf/in^2	psi	Although use of the abbreviation psi is common, it should not be used as a unit symbol. 1 $lbf/in^2 = 6.895 \cdot 10^3$ Pa.	
quart	qt		1 qt (U.K.) = 1.1365 L. 1 qt (U.S. dry) = 1.1012 L. 1 qt (U.S. liquid) = 0.9464 L.	
rad	rd		Unit of absorbed dose in the field of radiation dosimetry. Use of the SI unit, the gray, is preferred. 1 rd = 0.01 Gy.	
*radian	rad		SI unit of plane angle.	
*radian per second	rad/s		SI unit of angular frequency, angular velocity.	ω
*radian per second squared	rad/s^2		SI unit of angular acceleration.	α
rem	rem		Unit of dose equivalent in the field of radiation dosimetry. Use of the SI unit, the sievert, is preferred. 1 rem = 0.01 Sv.	
revolution per minute	r/min	rpm	Speed of rotation. Although the use of rpm as an abbreviation is common, it should not be used as a unit symbol.	
revolution per second	r/s	rps	Speed of rotation.	
roentgen	R	r	A unit of exposure in the field of radiation dosimetry. 1 R = $2.58 \cdot 10^{-4}$ C/kg.	
*second (plane angle)	..."		1 " = $4.848 \cdot 10^{-6}$ rad.	
*second (time)	s	sec	SI unit of time, period.	t T
*second, reciprocal	s^{-1}	/s, /sec	Complex (angular) frequency oscillation constant (SI).	p
*siemens	S		SI unit of conductance. 1 S = 1 Ω^{-1}. The name mho has been used for this unit in the U.S.	
*sievert	Sv		SI unit of dose equivalent in the field of radiation dosimetry.	
slug	slug		FPS system unit of mass. Use not recommended. 1 slug = 14.59 kg.	
square foot	ft^2		Area. 1 ft^2 = 0.0929 m^2.	
square inch	in^2		Area. 1 in^2 = $6.452 \cdot 10^{-4}$ m^2.	

(continued)

TABLE 2-3 *Continued*

UNIT	UNIT SYMBOL	SOMETIMES OCCURS AS: (DO NOT USE)	APPLICATIONS AND NOTES	QUANTITY SYMBOL (FOR USE AS VARIABLES, ETC.)
*square meter	m^2		SI unit of area.	
*square meter per second	m^2/s		SI unit of kinematic viscosity.	
*square millimeter per second	mm^2/s		Kinematic viscosity. (Preferred SI unit multiple.)	
square yard	yd^2		Area. 1 yd^2 = 0.8361 m^2.	
*steradian	sr	sterad	SI unit of solid angle.	
*tera	T (prefix)	t	SI prefix for 10^{12}.	
*tesla	T		SI unit of magnetic flux density (magnetic induction). 1 T = 1 N/(A·m) = 1 Wb/m^2.	*B*
therm	thm		1 thm = 100 000 Btu. 1 thm (EEC) = $1.0551 \cdot 10^8$ J. 1 thm (U.S.) = $1.0548 \cdot 10^8$ J.	
ton (short)	ton		1 ton = 2000 lb = 907.2 kg.	
ton, metric	t		1 t = 1000 kg. Use of this name in the U.S. is not recommended.	
torr	torr	Torr	1 torr = $1/760 = 1.333 \cdot 10^2$ Pa. Use not recommended.	
*(unified) atomic mass unit	u		See: atomic mass unit, unified.	
*var	var	VA reactive	SI unit of reactive power.	*Q*
*volt	V	v	SI unit of voltage, electromotive force. 1 V = 1 W/A.	*V*, *E*
*voltampere	VA	va	SI unit of apparent power.	*S*
*volt per meter	V/m		SI unit of electric field strength.	*E*
*watt	W	w	SI unit of power. 1 W = 1 J/s.	*P*
*watt per meter kelvin	W/(m·K)		SI unit of thermal conductivity.	λ
*watt per steradian	W/sr		SI unit of radiant intensity.	*I*
*watt per steradian square meter	$W/sr \cdot m^2$		SI unit of radiance.	*L*
watthour	Wh		1 Wh = 3600 J.	
*watt per square meter	W/m^2		Poynting vector (SI).	*S*
*weber	Wb		SI unit of magnetic flux, magnetic flux linkage. 1 Wb = 1 V·s.	Φ Λ
*weber per meter	Wb/m		SI unit of magnetic vector potential.	*A*
weight percent	wt%		Concentration.	
yard	yd		1 yd = 0.9144 m.	
year	a		In the English language, generally yr. 1 yr (365 days) = $3.1536 \cdot 10^7$ s.	

Note: Asterisks (*) indicate SI units, preferred multiples of SI units, or other units acceptable for use with SI.

3

Thermoplastic Molding Compounds

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INTRODUCTION

Today, the availability and use of thermoplastics is taken for granted. In fact, it would be difficult to imagine life without them, since they are essential to virtually every phase of our daily lives in the home, in commerce, and in industry, as well as being in the forefront of high-technology research and development. Yet, thermoplastics were a novelty as recently as the 1930s, and have since grown to a multibillion dollar industry with a high probability that this astonishing growth rate will continue.

This chapter focuses on the principal engineering thermoplastics used for making parts by injection molding. Thermoplastics used primarily for extrusion are covered in a separate chapter.

As used in this handbook, *thermoplastic* refers to an organic polymer which softens on heating below its decomposition temperature and hardens to its original state on cooling.

DEFINITIONS OF TERMS RELATING TO PLASTICS

Commonly used terms relating to plastics are defined in this section.

A-stage. An early stage in the preparation of certain thermosetting resins in which the material is still soluble in certain liquids, and may be liquid or capable of becoming liquid upon heating.[1]

Addition Polymerization. Polymerization in which monomers are linked together without the splitting off of water or other simple molecules.[1]

Aging. (1) The effect on materials of exposure to an environment for an interval of time. (2) The process of exposing materials to an environment for an interval of time.[1]

Alloy (in plastics). Two or more immiscible polymers united, usually by another component, to form a resin having enhanced performance properties.[1]

Aromatic Polyester. A polyester derived from monomers in which all the hydroxyl and carboxyl groups are linked directly to aromatic nuclei.[1]

B-stage. An intermediate stage in the reaction of certain thermosetting resins in which the material swells when in contact with certain liquids and softens when heated, but may not entirely dissolve or fuse.[1]

Biodegradable Plastic. A degradable plastic in which the degradation results from the action of naturally-occurring microorganisms such as bacteria, fungi, and algae.[1]

Block Copolymer. An essentially linear copolymer in which there are repeated sequences of polymeric segments of different chemical structure.[1]

Blocking. Unintentional adhesion between plastic films or between a film and another surface.[1]

Bloom. A visible exudation or efflorescence on the surface of a material.[1]

C-stage. The final stage in the reaction of certain thermosetting materials in which they have become insoluble and infusible.[1]

Chalking. A powdery residue on the surface of a material resulting from degradation or migration of an ingredient, or both.[1]

Cold Molding. A process of compression molding in which the molding is formed at room temperature and subsequently baked at elevated temperatures.[1]

Compression Molding. The method of molding a material already in a confined cavity by applying pressure and (usually) heat.[1]

Condensation Polymerization. Polymerization in which monomers are linked together with the splitting off of water or other simple compounds.[1]

Crosslinking. The formation of a three-dimensional polymer by means of interchain reactions resulting in changes in physical properties.[1]

Degradation. A deleterious change in the chemical structure, physical properties, or appearance of a plastic.[1]

Elastomer. A macromolecular material that at room temperature returns rapidly to approximately its initial dimensions and shape after substantial deformation by a stress and release of that stress.[1]

Engineering Plastics. See the section "Engineering Thermoplastics," p. 41 in this chapter.

Extrusion. A process in which heated or unheated plastic is forced through a shaping orifice (a die) in one continuously formed shape, as a film, sheet, rod, or tubing.[1]

Filler. A relatively inert material added to a plastic to modify its strength, permanence, working properties, or other qualities, or to lower costs.[1]

Gel. A colloid in which the dispersed phase has combined with the continuous phase to produce a viscous or jelly-like product.[2]

Glass Transition Temperature (T_g). The temperature at which an amorphous material changes from or to a brittle, vitreous state to or from a viscous or rubbery condition.[1,2]

Graft Copolymer. A copolymer in which polymeric side chains have been attached to the main chain of a polymer of different structure.[1]

Homopolymer. A polymer resulting from polymerization of a single monomer.[1]

Injection Molding. The process of forming a material by forcing it, in fluid state and under pressure, through a runner system (sprue, gate) into the cavity of a closed mold.[1]

Novolac (Novolak). A phenol or ortho-cresol-formaldehyde resin which remains thermoplastic until reacted with a source of methylene groups such as hexamethylenetetramine.[1]

Oligomer. A polymer molecule consisting of only a few monomer units (dimer, trimer, tetramer).[2]

Organosol. A suspension of a finely divided polymeric resin in a plasticizer together with a volatile organic liquid.[1]

Plastics. Materials which contain one or more organic polymeric resins of large molecular weight and which are capable of being shaped by flow into finished articles or their component parts.[1]

Plasticizer. A substance incorporated in a high polymer to improve its workability, flexibility, or distensibility.[1, 2]

Plastisol. A dispersion of finely divided resin in a plasticizer. It becomes an organisol if a volatile organic solvent is included.[1, 2]

Polymer. A chemical compound formed by polymerization of a monomer or monomers of different types.

Polymerization. A chemical reaction in which the molecules of monomers are linked together.[1]

Polyol. An alcohol having several hydroxyl groups.[1]

Polyolefin. A group name for thermoplastic polymers such as polyethylene and polypropylene.[2]

Pot Life. The period of time during which a reacting thermosetting composition remains suitable for its intended processing after mixing with reaction-initiating agents.[1]

Prepolymer. A polymer of degree of polymerization between that of the monomer and the final polymer.[1]

Prepreg. In reinforced thermosetting plastics, the admixture of resin, reinforcements, fillers, etc., in a substrate ready for molding.[1]

Resin. A natural or synthetic polymeric material, usually of high molecular weight. Synthetic resins are classed as either thermoplastic or thermosetting, depending on whether or not they liquefy or soften on heating.

Runner. The feed channel in an injection or transfer mold that runs from the inner end of the sprue or pot to the cavity gate. Also, the piece formed in this channel.[1]

Sheet Molding Compound. A fiber-reinforced thermosetting compound in sheet form.[1]

Shrink Mark. An undesired depression in the surface of a molded piece formed on cooling after molding.[1]

Sprue. The feed channel that runs from the outer face of an injection or transfer mold to the mold gate in a single cavity mold. Also, the piece formed in this channel.[1]

Stress-cracking. External or internal cracking, often evidenced by fine lines, caused by tensile stresses or environmental factors acting on a plastic material.

Thermoplastic. A high-molecular-weight polymer that may be softened repeatedly when heated after returning to its original condition when cooled to room temperature.[2]

Thermosetting Plastic. A plastic capable of being changed into an infusible or insoluble substance when cured by heat or other means.[1]

Transfer Molding. The process for making thermosetting parts in which a measured charge of suitably preheated material is placed in a chamber from which it is forced through channels into a closed cavity (mold) where it is cured at a controlled temperature.

Vacuum Forming. A forming process in which a heated plastic sheet is drawn against the mold surface by evacuating the air between it and the mold.[1]

Viscosity. The internal resistance to flow exhibited by a fluid.[2]

Vulcanization. The irreversible process resulting from crosslinking of the unsaturated hydrocarbon chain in rubber with sulfur, usually with the application of heat.[2]

[1]ASTM D 883, *Standard Terminology Relating to Plastics*.

[2]Gessner G. Hawley, *Condensed Chemical Dictionary*, 10th ed. New York: Van Nostrand Reinhold, 1981.

PLASTICS INDUSTRY

Since the early 1930s, thermoplastic technology has experienced steady, strong growth, resulting in one of the world's major industries comprised of companies ranging in size from among the world's largest to the smallest. The plastics industry is comprised of the following:

- *Monomer and polymer manufacturers*, mostly large chemical companies that convert basic raw materials from coal and petroleum into intermediate chemicals, and from these make monomers and polymers.
- *Additive, reinforcement, and filler manufacturers*, a diversified group making catalysts, stabilizers, antioxidants, flame retardants, fiber reinforcements, and fine particles which, when mixed with polymers, make them more suitable for specific end uses.
- *Compounders*, including most polymer manufacturers, independent specialists, and in-house operations that formulate resins from polymers, additives, reinforcements, and fillers.

TABLE 3-1 1993 U.S. Consumption for Thermoplastics in Electrical and Electronic Applications

MATERIAL	MILLION POUNDS
Acrylonitrile-butadiene-styrene	126
Polyamide (nylon)	108
Polyacetal	4
Polycarbonate	39
Polyester	58
Polyethylene	
High density	140
Low density	389
Polyphenylene alloys	29
Polypropylene	28
Polystyrene	300
Polyvinyl chloride	530
Styrene acrylonitrile	4
Total	1,755

Source: Modern Plastics Magazine.

- *Processors*, including companies engaged in molding, extruding, casting, calendering, and laminating plastics.
- *Finishers*, companies that assemble, decorate, and otherwise make plastic products suitable for marketing.

Most of these companies employ specialists whose job it is to help prospective customers in the area of their expertise.

Table 3-1 shows the estimated electrical and electronic industries' consumption of widely used thermoplastics. These figures include materials used for dielectric films and extruded wire and cable insulations.

ENGINEERING THERMOPLASTICS

Most of the polymers discussed in this chapter are classed as *engineering thermoplastics*, a designation that at best is loosely defined. Generally speaking, these polymers can be molded with close tolerances into complex precision parts. The implication here is that other (commodity) polymers lack this capability, which is not necessarily so. Under certain conditions, some engineering thermoplastics also do not satisfy this generalization. For example, polyamide parts may change dimensions significantly as they absorb moisture, which they do more readily than other engineering or commodity polymers.

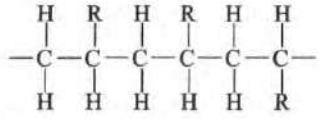
A broader definition of engineering thermoplastics states that these materials have a good balance of properties which is retained over a wide range of environmental conditions. Yet, as shown in the section of this chapter entitled "Summary of Rankings of Thermoplastic Polymers," no polymer has a monopoly on high or low rankings for all key properties, and there is little consistency in the rankings of any polymer vis-à-vis any other polymer.

However defined, there is general agreement on the polymers classed as engineering thermoplastics. These polymers are identified in the section of this chapter entitled "Principal Thermoplastic Polymers for Electrical/Electronic Uses" (p. 68).

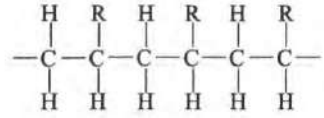
POLYMERIZATION

Homopolymerization is a chemical reaction in which molecules of a simple structure (monomer) link together to form large, often complex, molecules (macromolecules) in a chainlike configuration. When two or more different monomers are involved, the process is termed *copolymerization* or *heteropolymerization*.

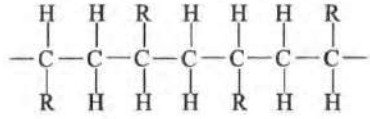
Linear or *straight-chain* polymers, typified by polyethylene, form long, virtually continuous chains, theoretically without crosslinking between chains. Chains, however, are not one-dimensional, but rather three-dimensional and always changing in configuration because of molecular motion. Chain components may have side groups attached to a main chain, thereby modifying polymer properties. Polymers of this type are called *branched* polymers. When side groups (R) are arranged randomly along the backbone chain, the polymer is termed *atatic*:



An *isotatic* polymer has side groups located on one side of the backbone chain:



A *syndotatic* polymer has side groups arranged in a symmetrical and recurring pattern on both sides of the backbone chain:



Polymerization may also proceed by *step growth*, in which linear polymers with intermediate degree of polymerization interact to form macromolecules:

—A—A—A—A— —(A—A—A)—(A—A—A)—

chain growth step growth

Crosslinked, or *network* polymers are formed when linear chains are interconnected as chain growth proceeds as a result of interaction of reactive sites on separate linear chains.

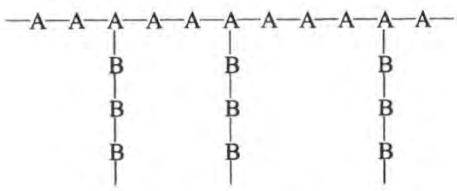
Addition polymers are polymers in which free radicals are the initiating agents that react with the double bond of the monomer by adding to it on one side while producing a new free electron on the other side, thereby making the chain self-propagating.

Polymers may also be formed by *polycondensation*, a chemical reaction in which two or more monomers combine to form large molecules giving off water, salt, or other simple compounds. This process is typified by the reaction between phenol and formaldehyde, as shown in "Phenolics" (p. 128) of Chapter 4, *Thermosetting Molding Compounds*.

When two or more polymers are arranged in alternating sections, or blocks, along the backbone chain, the polymer is referred to as a *block* copolymer:

——(A—A—A—A)——(B—B—B)——(A—A—A—A)——(B—B—B)——

The term *graft* copolymer is used to describe a backbone chain formed from monomers (A) to which side chains formed from other monomers (B) are attached (grafted) at various points. Thus, a graft copolymer is similar in structure to a branched polymer where the side group is replaced with a polymer:



Polymer *alloys* are formed by physically blending two or more polymers of different properties into a homogeneous mixture through addition of special wetting agents and compounding under high shear conditions to prevent phase separation.

Polymer properties are significantly affected by polymer structure and molecular weight. Branched molecules are usually less crystalline with lower melting points. Chains that can crystallize and which have polar groups have high melting points. Longer chains have high melt viscosities. Increasing molecular weight imparts greater toughness characteristics. Polymer structures may be determined by infrared, X-ray diffraction, and nuclear magnetic resonance techniques.

The five common polymerization techniques are:

1. *Gas phase* polymerization requires high pressures and elevated temperatures. The process is usually initiated by a free radical source. Some grades of polyethylene and polypropylene are made by this method employing pressures up to 45,000 psi.

2. *Bulk*, *mass*, or *batch* polymerization, usually in liquid phase, is carried out at normal pressure and at elevated temperatures, with or without catalysts. Polyvinyl chloride may be made by this method. The reaction is exothermic, and removal of heat becomes a significant problem as viscosity increases. Control of molecular weight is difficult using this process, and the resins produced usually have a broad molecular weight distribution.

3. *Solution* polymerization employs a suitable solvent for the monomer and polymer, thereby facilitating removal of reaction heat. Reaction temperature must remain below the boiling point of the solvent, which may lengthen reaction time significantly. Other possible disadvantages are solvent flammability, toxicity, and the problems associated with solvent recovery. High-molecular-weight polymers are difficult to produce using this method. Acrylic resins may be made by this process.

4. *Emulsion* polymerization requires the monomer to be dispersed in water containing an emulsifying agent and a water-soluble initiator. This method obviates solvent problems and permits faster reaction rates than bulk or solution processes. Emulsion polymerization is suitable for making high-molecular-weight copolymers with narrow molecular weight distribution. Resins require a drying step, necessary to remove all moisture before use.

5. *Suspension* polymerization is a method in which a monomer is mechanically dispersed in a nonsolvent without use of an emulsifying agent, and linking is catalyst-initiated or by free-radical addition. This process facilitates control over the reaction variables and the final particle size of the polymer. This method is used to make high-molecular-weight polymers with relatively narrow molecular weight distributions. Resin particles must be washed and dried before use.

REINFORCEMENTS AND FILLERS

Thermoplastic resin properties are often improved significantly by compounding polymers with reinforcements and fillers.

Glass is the most common reinforcing fiber. It is low in cost and contributes to improve mechanical strength and electrical insulation properties with reduced flammability. Chopped strands of "E" glass in lengths of $^1/_8$–$^1/_4$ inch comprise 10–40 percent of compound weight for optimum results. Glass-fiber-reinforced grades may be purchased from resin suppliers or compounded by the molder at the injection molding machine. Other fibers often used in combination with glass for special applications include *aramid*, *boron*, *sisal*, *polyester*, and *carbon*.

Since all polymers are not affected to the same degree by the addition of fibers, reference should be made to manufacturers' data sheets for a particular polymer to determine advantages and limitations of reinforced versus general purpose grades.

Fillers, sometimes called *extenders*, *fine particles*, and *nonfibrous property enhancers*, also are important ingredients in thermoplastic resin compounds. Proper use of fillers has the following effects:

- Increased flexural modulus
- Increased dimensional stability
- Increased heat deflection temperature
- Reduced tensile strength
- Reduced creep
- Improved dielectric properties
- Reduced flammability
- Higher thermal conductivity
- Increased melt viscosity
- Improved processing
- Higher part weight

Commonly used fillers for electrical grades include:

- *Calcium carbonate* (also contains small amounts of magnesium carbonate and oxides of aluminum, iron, silicon, and manganese) which lowers cost, modifies flow characteristics, and improves chemical resistance and some mechanical properties
- *Alumina trihydrate* which reduces flammability
- *Kaolin*, or clay (mostly oxides of aluminum and silicon), which controls flow and improves chemical resistance and some mechanical properties
- *Mica flake* which has a much lower cost than glass fiber, contributes to arc resistance, tensile and flexural strength, and to modulus, but reduces impact strength
- *Talc* (hydrous magnesium silicate) which imparts impact strength and modulus

To achieve maximum effectiveness, filler particles, often submicron in size, must be uniformly dispersed throughout the compound and wet by the polymer. With judi-

cious use, fillers permit resin cost to be reduced without sacrifice of essential properties in many applications. Filler concentrates, purchased from custom compounders, provide a convenient way for molders to incorporate fillers.

FLAME RETARDANTS

Each thermoplastic polymer is unique in its flammability characteristics. Some polymers, such as polyamide-imide, polyarylate, polyetheretherketone, polyetherimide, polyethersulfone, and polyphenylene sulfide are inherently resistant to burning and require no further treatment. Other polymers, such as polyamides, polycarbonate, and polysulfone, are somewhat less resistant, and several polymers burn readily. However, the flammability of these polymers may be significantly reduced by compounding with reactive and nonreactive halogenated compounds, phosphate esters, and antimony oxide.

Examples of reactive halogenated compounds include tetrabromo- and tetrachlorobisphonol A for polycarbonates.

Nonreactive halogenated compounds include chloroparaffins and halogenated biphenyls used in styrenics and polyamides (nylons).

Phosphate esters with flame-retardant properties include triaryl phosphate, tricresyl phosphate, isodecyl diphenyl phosphate, and trioctyl phosphate. Styrenics and modified polyphenylene oxide use these compounds.

Antimony oxide (antimony trioxide) is used in conjunction with halogenated compounds forming antimony oxychloride which greatly enhances flame-retardant properties.

A principal objective in developing flame-retardant grades is to minimize the degradation in polymer properties which invariably occurs.

Hazards other than the flammability of a polymer or its flame-retardant resin grade are smoke generation and its toxicity, and tendency to melt drip.

Two of the most widely used tests for flammability with reported results are UL 94 and Oxygen Index, described under "Standard Tests" (p. 47) in this chapter.

ANTIOXIDANTS

Oxidation is the principal degrading reaction that limits the useful life of a plastic. This process is inherent with plastics, and is often initiated by the presence of impurities with exposure to oxygen or other oxidizing agent. Oxidation is accelerated by heat, light, humidity, and radiation.

Oxidative degradation causes polymer chain scission and/or crosslinking. In the process hydroxyl, carbonyl, acid, and ester groups are formed and polar groups may develop. Unstable peroxide radicals resulting from the oxidative process themselves decompose, initiating further degradation and significant polymer breakdown.

Effective antioxidants include hindered phenolics and secondary aryl amines with reactive OH or NH functional groups, respectively. These groups act to transfer hydrogen to free radicals, principally peroxy radicals, thereby limiting further degradation. Amines, additionally, act as chain terminators, but may cause discoloration of the plas-

tic. Phenolic antioxidants include butylated hydroxytoluene, polyphenolics, and thiobisphenolics. Substituted para-phenylene-diamine and diphenylamines are examples of amine antioxidants.

Another type of antioxidant includes phosphites and thioesters which act to decompose hydroperoxides before they form free radicals. Phosphites reduce hydroperoxides to alcohols and are themselves oxided to phosphates. Thioesters act to make phenolic and amine antioxidants more effective. Examples of this type of antioxidant include tris(monononylphenyl) phosphite, disteryl pentaerythritol diphosphite, and dialkyl thiodiproprionates.

Antioxidants are effective in the range of 0.1–0.5 percent of polymer weight. However, since other ingredients in a recipe may affect antioxidant action, the precise amount of antioxidant for optimum effectiveness for a given plastic should be determined for that plastic's specified formulation.

ULTRAVIOLET STABILIZERS

As noted above, the degradation process in plastics is accelerated by radiation. Ultraviolet (UV) light from the sun and fluorescent lamps is a common type of radiation to which plastics are exposed. Most plastics contain light-absorbing chemical groups (often formed in processing) such as hydroperoxides and carbonyl groups (chromophores). On absorbing UV energy, these groups form free radicals, which then react with other base polymer and additive polymer groups, initiating further degradation, much as in oxidative degradation.

Certain additives will retard this UV action because they have higher UV absorptivity than chromophores, thereby preventing most of the UV energy from affecting these groups. Examples of UV absorbers include 2-hydroxybenzophenones, 2-hydroxybenzotriazoles, acrylic esters, salicylates, and oxanilides. Hindered amines and phosphites, described previously in the "Antioxidants" section, also act as UV stabilizers in much the same way as they retard oxidative degradation.

Polyethylene is a plastic whose UV resistance (which is inherently poor) can be dramatically improved by addition of UV stabilizers along with 2–3 percent carbon black.

UV stabilizers are effective in the range of 0.25–1.0 percent of polymer weight.

INJECTION MOLDING

The process for forming thermoplastic resins into parts is injection molding. Compression molding, used for thermosetting resins, could also be used, but this method is not as efficient, requiring more energy and slower cycles.

Injection molding consists of these basic steps:

1. Dried thermoplastic compound is fed from a hopper into a heating chamber.
2. After reaching a viscous state, the plastic is forced (injected) by a plunger or screw into a water-cooled mold of the desired shape.

3. After cooling to the point where it can be handled without deformation, the part is ejected from the mold cavity, and sprues and runners (used to convey the plastic from the chamber to the mold) are trimmed.

Early injection molding machines used a reciprocating plunger, or ram, to inject plastic into the mold. While satisfactory parts may be made with this type of machine, there are several inherent disadvantages:

- There is virtually no mixing action to homogenize the plastic.
- Uniform heating throughout the charge, or "shot," is difficult to achieve in thick sections.
- Nozzle pressures tend to be erratic.
- Metering of material is not precise.

Newer injection molding machines now in common use employ a screw instead of a plunger. Compound is mixed and fed from the hopper through the screw tip backflow stop valve by the rotating screw. Accumulation of melt in front of the screw tip forces the screw to back up in the barrel. After the desired amount of melt has accumulated, the screw is powered forward hydraulically as an injection piston to shoot the charge into the mold. This type of machine, shown in Fig. 3-1, overcomes the disadvantages of machines using plunger feeds. A more complex machine employs two intermeshing screws, which provide even better mixing with reduced backflow along the screw flight.

The screw is divided into three zones: feed, compression, and metering. The feed section transports the resin from the hopper to the heated portion of the barrel. Flight volume is constant past adjacent flights. The compression section compacts the material from its powder or granular state into a melt. The volumes of the flight in this section decrease in the direction of the nozzle, compensating for the increasing density of the material as it melts. The melting characteristics of the resin determine the geometry of the screw, the sharper the melting point of the resin, the more abrupt the compression. In the metering zone, the plastic is mixed and heated into a homogeneous melt. A large amount of heat is generated by the action of the screw, and external heating must be adjusted accordingly. This zone has constant flight volume.

The objective is to determine the optimum balance of temperatures and pressures throughout the molding process. Mold and screw design are critical. Inadequate processing techniques may cause molecular weight degradation and buildup of low molecular weight ends to polymer chains resulting in significant property loss.

STANDARD TESTS

Selected standard tests described below are used to compare plastics and indicate their suitability for proposed applications. The accompanying tables rank polymers in descending order of their desirability. Values are obtained from the tables of key properties included in the polymer sections of this chapter.

Fig. 3-1. Single-screw injection molding machine. (*Courtesy ICI Americas Inc.*)

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Since these values are typical of standard grades without additives, it is noteworthy that higher or lower values would apply to other grades and, within limits, could change the rankings. The values shown indicate the inherent properties of the polymers and are significant when differences in values are appreciable.

A designation of na in the tables means data are not available.

Useful and convenient manuals on testing are published by Underwriters Laboratories:

- UL 746A, *Polymeric Materials—Short Term Property Evaluations*
- UL 746B, *Polymeric Materials—Long Term Property Evaluations*
- UL 746C, *Polymeric Materials—Use in Electrical Equipment Evaluations*

Practice for Conditioning Plastics and Electrical Insulating Materials for Testing (ASTM D 618)

Since moisture and temperature affect the properties of electrical insulating materials, it is essential that test specimens be uniformly conditioned before they are tested to ensure comparability of test results. This test calls for conditioning test specimens in standard laboratory atmosphere of 50% ± 2% relative humidity, 73.4° ± 1.8°F (23° ± 1°C), with adequate air circulation:

SPECIMEN THICKNESS	HOURS
0.25 in or under	40
over 0.25 in	88

Specific Gravity and Density (ASTM D 792)

Weight per unit volume is the value needed to calculate how many parts can be molded from a given weight of resin. Thus, it is as important as price in determining the cost of a molded part. Production and purchase specifications for a resin include an acceptable value or range for specific gravity.

The terms *specific gravity* and *density* both refer to weight/volume relationships and are often used interchangeably, although in property tables for electrical insulating materials, *specific gravity* is more often encountered.

Specific gravity is the ratio of the weight of a given volume of material at 73.4°F (23°C) to that of an equal volume of water at the same temperature. It is properly expressed as *Specific Gravity, 23/23°C.*

Density is the weight per unit volume of a material at 23°C and is expressed as *D23C, g/cm*^{3}. Specific gravity and density values for the same material differ slightly because water at 23°C has a density slightly less than one: D23C, g/cm^3 = Specific Gravity 23/23°C × 0.99756.

To determine specific gravity, a piece of molded or extruded part is held by a fine wire, weighed, and submerged in water at 73.4°F (23°C). While it is in the water, it is weighed again. The difference in weight equals the weight of an equal volume of water.

TABLE 3-2 Specific Gravity of Thermoplastic Polymers (23/23°C) (ASTM D 792)

RANK	POLYMER	VALUE
1	Polypropylene	0.90
2	Acrylonitrile-butadiene-styrene	1.03
2	Polystyrene-butadiene	1.03
4	Polystyrene	1.04
4	Nylon 11	1.04
6	Modified polyphenylene oxide	1.06
7	Styrene-acrylonitrile	1.07
8	Nylon 6/6	1.14
9	Acrylic	1.19
10	Polycarbonate	1.20
11	Polysulfone	1.25
12	Polyetherimide	1.27
13	Polybutylene terephthalate	1.31
14	Polyphenylene sulfide	1.34
15	Polyethersulfone	1.37
16	Polyamide-imide	1.40
17	Acetal copolymer	1.41
18	Acetal homopolymer	1.42

Specific gravity equals the weight of the piece in air divided by the weight of an equal volume of water.

Specific gravities of commonly used thermoplastic polymers are listed and ranked in Table 3-2.

Dielectric Strength (ASTM D 149)

Dielectric strength, expressed as volts per mil, is the voltage gradient at which a continuous arc is formed through the specimen. To be comparable, specimens of different materials must be identical in geometry and conditioning, since values decrease as specimen thicknesses increase and are adversely affected with increasing moisture content and test environment temperature.

Specimens are thin sheets having parallel plane surfaces with sufficient area to prevent arc flashover. Published tables often show values for $^1/_8$ inch thick specimens for comparability. Specimens are placed between electrodes of prescribed size. There are two ways to conduct the test:

1. *Short-Time Test* (often published in comparison tables). The voltage is increased from zero to breakdown at a uniform specified rate from 0.5 to 1.0 kilovolt per second.

2. *Step-by-Step Test.* The initial voltage applied is 50 percent of the breakdown voltage determined by the short-time test. Voltage is increased in stated increments and at prescribed rates until breakdown occurs.

Dielectric strengths of commonly used thermoplastic polymers are listed and ranked in Table 3-3.

TABLE 3-3 Dielectric Strength of Thermoplastic Polymers (Short Time, 125 mils, volts/mil) (ASTM D 149)

RANK	POLYMER	VALUE*
1	Polypropylene	600
1	Nylon 6/6	600 (dry)
3	Polyamide-imide	580
4	Modified polyphenylene oxide	550
5	Polystyrene	500
5	Acrylic	500
7	Polyetherimide	480
8	Nylon 11	425 (dry)
8	Polysulfone	425
8	Styrene-acrylonitrile	425
8	Acrylonitrile-butadiene-styrene	425
11	Polybutylene terephthalate	420
12	Polyethersulfone	400
12	Polystyrene-butadiene	400
15	Acetal homopolymer	380
15	Acetal copolymer	380
15	Polyphenylene sulfide	380
15	Polycarbonate	380

*At room temperature and 60 Hz.

Dielectric Constant, Permittivity, Specific Inductive Capacity (ASTM D 150)

Dielectric constant, permittivity, and specific inductive capacity (SIC) are different names for the same property. Since values for this property of an insulating material change with temperature and frequency, the term *constant* is really not appropriate, and *permittivity* or *relative permittivity* have come to be the preferred terms and are so designated by ASTM. SIC is no longer a widely used term. Because *dielectric constant* values and references still appear more commonly in the literature and in data tables, this term is used throughout this handbook.

Dielectric constant is a critical property in the selection of an insulating material for a specific end use. Where the primary function of an insulation is to minimize electric power losses, a low dielectric constant is required. For a capacitor dielectric, however, a high value is desirable to enable the capacitor to be designed as small as possible. For most insulating materials, dielectric constant values increase with temperature. The effect of increasing frequency is unique with each insulating material. Dry air has a dielectric constant of one (lowest) under normal conditions. The value for another material is determined by calculating the ratio of the capacitance of a capacitor with the material as dielectric to the capacitance of the same electrode system with air as dielectric. Frequencies commonly used are 60 Hertz and 10^6 Hertz.

Dielectric constants of commonly used thermoplastic polymers are listed and ranked in Table 3-4.

TABLE 3-4 Dielectric Constant of Thermoplastic Polymers (ASTM D 150)

RANK	POLYMER	DIELECTRIC CONSTANT* (60 Hz)	DIELECTRIC CONSTANT* (10^6 Hz)
1	Polypropylene	2.2	2.2
2	Polystyrene	2.5	2.4
2	Polystyrene-butadiene	2.5	2.4
4	Styrene-acrylonitrile	2.6	2.6
4	Acrylonitrile-butadiene-styrene	2.6	2.6
4	Modified polyphenylene oxide	2.6	2.6
7	Polysulfone	3.1	3.0
8	Polyphenylene sulfide	3.1	3.2
9	Polycarbonate	3.2	3.0
10	Polyetherimide	3.2	3.1
11	Polybutylene terephthalate	3.3	3.1
12	Polyethersulfone	3.5	3.5
13	Acrylic	3.7	2.2
14	Acetal homopolymer	3.7	3.7
14	Acetal copolymer	3.7	3.7
16	Nylon 11	3.9	3.1
17	Polyamide-imide	4.3	3.9
18	Nylon 6/6	8.0	4.6

*At room temperature.

Dissipation Factor, Loss Tangent, Tan Delta (δ) (ASTM D 150)

Dissipation factor, loss tangent, and tan (δ) are commonly used terms for the same property. For consistency, *dissipation factor* is the term used throughout this handbook.

Numerically, this property is the tangent of the loss angle. The charging current of a perfect dielectric will lead the applied voltage by 90 degrees. The angle by which the current vector of a less-than-perfect dielectric is less than 90 degrees is called the loss angle.

Power factor, a similar property, is determined by dividing the number of watts indicated by a wattmeter in a circuit, by the number of watts calculated by multiplying the reading on an ammeter times the reading on a voltmeter in the same circuit. The apparent wattage must be multiplied by that factor to give the power available for use. When the dissipation factor is less than 0.1, the power factor differs from the dissipation factor by less than 0.5 percent.

Electrical Resistance (ASTM D 257)

Electrical resistance is expressed in ohms: 1 ohm equals the resistance of a circuit in which a potential difference of 1 volt produces a current of 1 ampere. A high resistance is a desirable property in an electrical insulation. This property is adversely affected by increasing moisture content in the specimen and by higher humidity and higher temperature in the test environment. Surface condition of the specimen is another impor-

TABLE 3-5 Dissipation Factor of Thermoplastic Polymers (ASTM D 150)

RANK	POLYMER	DISSIPATION FACTOR* (60 HZ)	DISSIPATION FACTOR* (10^6 HZ)
1	Polystyrene	0.0001	0.0001
2	Polyphenylene sulfide	0.0003	0.0007
3	Modified polyphenylene oxide	0.0004	0.0009
4	Polypropylene	<0.0005	<0.0005
5	Polysulfone	0.0008	0.0034
6	Polyethersulfone	0.001	0.004
7	Acetal homopolymer	na	0.0048
8	Acetal copolymer	0.001	0.006
9	Styrene-butadiene	0.002	0.002
10	Polybutylene terephthalate	0.002	0.02
11	Polyetherimide	0.004	0.006
12	Acrylonitrile-butadiene-styrene	0.004	0.007
13	Styrene-acrylonitrile	0.007	0.007
14	Polycarbonate	0.009	0.010
15	Polyamide-imide	0.025	0.031
16	Nylon 11	0.04	0.05
17	Acrylic	0.05	0.3
18	Nylon 6/6	0.2	0.1

*At room temperature.

tant factor affecting resistance values. For test results to be comparable and meaningful, it is essential that test conditions be defined and controlled.

There are several indicators of electrical resistance.

Insulation resistance is the ratio of direct voltage applied to electrodes embedded in the test material to the total current between them. Both volume and surface resistance are factors.

Volume resistivity, a more widely published property, measures the electrical resistance between opposite faces of a unit cube of material.

Surface resistivity is the resistance between two opposite edges of a unit square of material.

ASTM D 257 describes test methods for determining these and other electrical resistance properties.

Electrical resistances of commonly used thermoplastic polymers are listed and ranked in Table 3-6.

Arc Resistance (ASTM D 495)

Higher values of arc resistance indicate greater resistance to surface breakdown caused by arcing or tracking. Values are determined by the time in seconds for breakdown along the surface of the test material. Thus, the condition of the surface and the humidity present in the test environment significantly affect values.

TABLE 3-6 Volume Resistivity of Thermoplastic Polymers (ASTM D-257)

RANK	POLYMER	Ω·cm*
1	Acrylic	1×10^{18}
2	Polyetherimide	6.7×10^{17}
3	Polyethersulfone	$>1 \times 10^{17}$
4	Polycarbonate	8.2×10^{16}
5	Polyamide-imide	8×10^{16}
6	Polysulfone	5×10^{16}
7	Polybutylene terephthalate	4×10^{16}
8	Acrylonitrile-butadiene-styrene	2×10^{16}
9	Polystyrene	$>1 \times 10^{16}$
9	Styrene-acrylonitrile	$>1 \times 10^{16}$
9	Polypropylene	$>1 \times 10^{16}$
12	Styrene-butadiene	1×10^{16}
12	Polyphenylene sulfide	1×10^{16}
12	Modified polyphenylene oxide	1×10^{16}
15	Acetal homopolymer	1×10^{15}
16	Acetal copolymer	1×10^{14}
16	Nylon 11	1×10^{14}
18	Nylon 6/6	1×10^{13}

*At room temperature.

Test specimens are 0.125 inches thick and have a flat surface. Two electrodes are placed on the surface of the specimen so that an arc occurs when sufficient voltage is applied between them. The arc is caused to occur intermittently with decreasing intervals between arcing. In later stages of the test, the current is also increased. The time of arcing remains constant. There are several distinct types of failure:

- A conductive fine line, or track is formed between electrodes
- The surface of the specimen carbonizes to the point where it carries the current
- The specimen bursts into flame
- Some inorganic dielectrics become incandescent and conduct current, but regain their dielectric properties on cooling.

Arc resistances of commonly used thermoplastic polymers are listed and ranked in Table 3-7.

Water Absorption (ASTM D 570)

The amount of water which a plastic absorbs affects its properties, lowering electrical values and dimensional stability, and is a key indicator of the suitability of a plastic for electrical/electronic applications.

For molding materials, specimens are disks of 2 inches in diameter by $^1/_8$ inch thick. For sheet materials, specimens are 3 inches long by 1 inch wide by the thickness of the sheet. Specimens are conditioned for 24 hours at 122.0°F (50°C), cooled in a desiccator,

TABLE 3-7 Arc Resistance of Thermoplastic Polymers (ASTM D 495)

RANK	POLYMER	SECONDS
1	Acrylic	no tracking
2	Acetal copolymer	240 (burns)
3	Polyamide-imide	230
4	Acetal homopolymer	220
5	Polybutylene terephthalate	184
6	Polypropylene	150
7	Nylon 6/6	130
8	Polyetherimide	128
9	Nylon 11	123
10	Polysulfone	122
11	Polycarbonate	120
12	Styrene-acrylonitrile	115
13	Acrylonitrile-butadiene-styrene	100
14	Modified polyphenylene oxide	75
15	Polyethersulfone	70
16	Polystyrene	65
17	Polystyrene-butadiene	50
18	Polyphenylene sulfide*	34

*Reinforced and filled grades have much higher values.

and immediately weighed. The specimen is immersed in water at 73.4°C (23°C) for 24 hours. Upon removal, the specimen is wiped dry and immediately weighed. The increase in weight is reported as percentage gained. For materials which lose soluble matter during immersion, the specimen must be redried and reweighed, from which percent the soluble matter is calculated. The percent gain in weight plus the percent soluble matter lost equals the percent water absorption. Specimens may be tested at other temperatures, such as 212°F (100°C), and for other periods of immersion, including equilibrium.

Water absorption of commonly used thermoplastic polymers are listed and ranked in Table 3-8.

Deflection Temperature (ASTM D 648)

Deflection temperature is the temperature at which a specified deflection occurs in a specimen under a selected load. This test is useful in indicating the temperature at which a plastic distorts under test conditions, although it does not necessarily indicate its high temperature usage limit.

A specimen 5 inches long by $^1/_2$ inch wide by thickness in the $^1/_8$–$^1/_2$ range is placed on supports 4 inches apart. A load of 66 or 264 pounds per square inch is applied at the center of the specimen. The temperature in the chamber of the testing device is raised at the rate of 3.6° ± 0.36°F (2° ± 0.2°C) per minute. The temperature at which the specimen deflects 0.010 inch is the deflection temperature at the selected load. (See Fig. 3-2.)

Deflection temperatures of commonly used thermoplastic polymers are listed and ranked in Table 3-9.

TABLE 3-8 Water Absorption of Thermoplastic Polymers (1/8 in Thick Specimen) (ASTM D 570)

RANK	POLYMER	% GAIN IN WEIGHT AFTER 24 h @ 73°F (23°C)
1	Polypropylene	0.01
2	Polystyrene	0.02
2	Polyphenylene sulfide	0.02
4	Polystyrene-butadiene	0.06
4	Modified polyphenylene oxide	0.06
6	Polybutylene terephthalate	0.08
7	Polycarbonate	0.15
8	Styrene-acrylonitrile	0.20
9	Acrylonitrile-butadiene-styrene	0.22
9	Acetal copolymer	0.22
11	Acetal homopolymer	0.25
11	Polyetherimide	0.25
13	Polyamide-imide	0.30
13	Polysulfone	0.30
13	Nylon 11	0.30
13	Acrylic	0.30
17	Polyethersulfone	0.43
18	Nylon 6/6	1.20

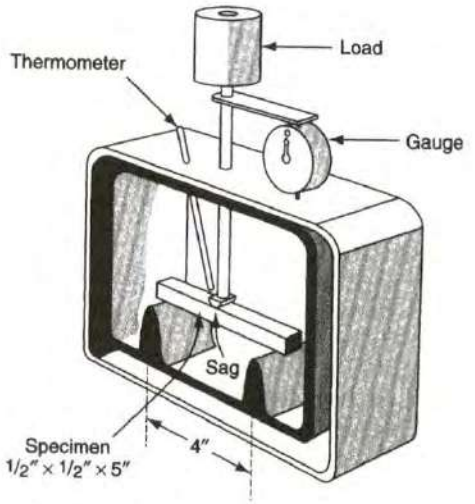


Fig. 3-2 Deflection temperature device. (*Courtesy Celanese.*)

TABLE 3-9 Deflection Temperature of Thermoplastic Polymers (ASTM D 648)

RANK	POLYMER	FLEXURAL LOAD 264 psi °F	°C
1	Polyamide-imide	532	278
2	Polyether sulfone	397	203
3	Polyetherimide	392	200
4	Polysulfone	345	174
5	Polyphenylene sulfide	275	135
6	Polycarbonate	265	129
6	Modified polyphenylene oxide	265	129
8	Acetal homopolymer	255	124
9	Acetal copolymer	230	110
10	Acrylonitrile-butadiene-styrene	210*	99*
11	Styrene-acrylonitrile	200	93
11	Polystyrene	200	93
11	Polystyrene-butadiene	200	93
11	Acrylic	200	93
15	Nylon 6/6	194	90
16	Polypropylene	140	60
17	Nylon 11	131	55
18	Polybutylene terephthalate	130	54

*Annealed.

Tensile Properties (ASTM D 638)

Tensile strength is one of the key mechanical properties, measuring in pounds per square inch the force necessary to elongate and break the specimen and in percent how much the material stretches before breaking. The tensile (elastic) modulus is the ratio of the applied stress to the strain it produces in the region in which strain is linearly proportional to stress. The modulus is usually expressed in terms of pounds per square inch values. Parts with little elongation and high tensile strength would tend to be brittle. Hence, moderate elongation is necessary for toughness. High elongation, however, indicates parts would be rubbery.

Specimens with dimensions shown below are prepared by injection molding or by machining from compression-molded plaques. Specimens may also be rod-shaped or tubular, depending on the shape of the end product. An Inston tensile testing machine is employed in which both ends of the specimen are tightly clamped in the machine heads. One jaw is fixed and the other is movable at rates of 0.05, 0.2, 2, or 20 inches/minute. The machine automatically plots stress against strain on graph paper. (See Fig. 3-3.)

Tensile strengths of commonly used thermoplastic polymers are listed and ranked in Table 3-10.

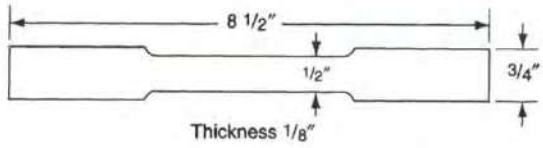


Fig. 3-3 Tensile test specimen.

Izod Impact Resistance (ASTM D 256)

The degree to which a plastic is notch-sensitive may be determined by measuring the energy required to break notched specimens under standard conditions. In designing parts made with plastics with low impact resistance, care should be taken in their design to avoid sharp corners and grooves. It is noteworthy that some otherwise tough plastics (nylon and acetals are examples) are notch-sensitive and exhibit relatively low Izod impact resistance.

Specimens are usually $2^1/_2$ inches long by $^1/_2$ inch wide by $^1/_8$ inch thick, although thicknesses up to $^1/_2$ inch may be used. A notch is cut in the middle of the narrow face of the specimen, which is then clamped in the base of a pendulum testing machine with the notch facing the direction of impact. The pendulum is released and the force required to break the specimen is calculated from the height the pendulum reaches on

TABLE 3-10 Tensile Strength of Thermoplastic Polymers (ASTM D 638)

RANK	POLYMER	psi AT BREAK*
1	Polyamide-imide	27,800
2	Polyetherimide	15,200
3	Polyethersulfone	12,200
4	Nylon 6/6	11,200
5	Polysulfone	10,200
6	Acrylic	10,000
6	Acetal homopolymer	10,000
8	Modified polyphenylene oxide	9,600
9	Polyphenylene sulfide**	9,500
9	Styrene-acrylonitrile	9,500
11	Polycarbonate	9,000
12	Acetal copolymer	8,800
13	Nylon 11	8,200
14	Polybutylene terephthalate	8,200
15	Acrylonitrile-butadiene-styrene	7,000
16	Polystyrene	6,000
16	Polystyrene-butadiene	6,000
18	Polypropylene	5,400

*At room temperature

**Reinforced and filled grades have much higher values.

the follow-through. Izod impact strength is expressed as foot pounds per inch of notch. (See Figs. 3-4 and 3-5.)

Izod impact strengths of commonly used thermoplastic polymers are listed and ranked in Table 3-11.

Flammability (UL 94)

Flammability of a plastic material depends on part size and shape, as well as the tendency of the plastic to burn. Important characteristics are ease of ignition, burning rate, time to extinguish, and products of combustion. UL 94 is intended to indicate the suitability of a plastic for applications where flammability is a factor.

Specimens are 5 inches long by $^1/_2$ inch wide by thickness usually in the 0.030–0.250 inch range. In the UL 94HB test procedure, specimens are conditioned for 48 hours at 73.4° ± 3.6°F (23° ± 2°C) in relative humidity of 50 ± 5 percent prior

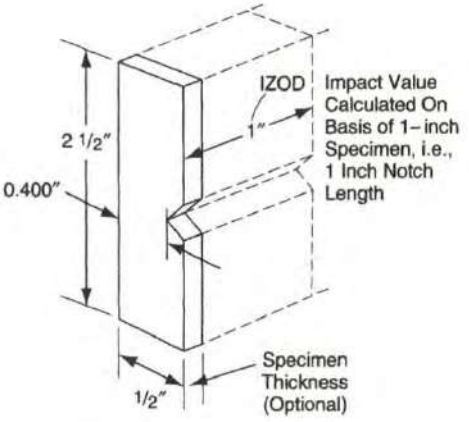


Fig. 3-4 Izod specimen. (*Courtesy Celanese.*)

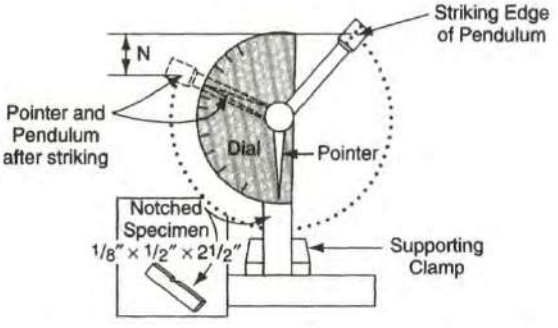


Fig. 3-5 Impact testing machine. (*Courtesy Celanese.*)

TABLE 3-11 Izod Impact Strength of Thermoplastic Polymers (Foot pounds per inch notched 1/8 in specimen) (ASTM D 256)

RANK	POLYMER	VALUE*
1	Polycarbonate	12
2	Acrylonitrile-butadiene-styrene	6.0
3	Modified polyphenylene oxide	5.0
4	Polyamide-imide	2.7
5	Polystyrene-butadiene	2.5
6	Nylon 6/6	2.1
7	Acetal copolymer	1.4
8	Acetal homopolymer	1.3
8	Polysulfone	1.3
10	Polyethersulfone	1.2
11	Polybutylene terephthalate	1.0
11	Polyetherimide	1.0
13	Nylon 11	0.75
14	Polypropylene	0.50
15	Styrene acrylonitrile	0.40
15	Acrylic	0.40
15	Polystyrene	0.40
18	Polyphenylene sulfide**	0.30

*At room temperature.

**Reinforced and filled grades have much higher values.

to testing. A specimen is clamped horizontally and canted at a 45° angle to horizontal. A wire gauze is positioned beneath the specimen at a distance of 3/8 inch. The free end of the specimen is ignited with a Bunsen burner and the burning rate is measured. The material is classed 94HB if:

- Burning rate does not exceed 1.5 inches/minute over a 3.0 inch span for specimens having a thickness of 0.120–0.500 inch
- Burning rate does not exceed 3.0 inches/minute over a 3 inch span for specimens having a thickness less than 0.12 inch
- Burning ceases before the flame reaches a reference mark 4.0 inches along the specimen.

For a 94V classification, a set of specimens is conditioned as above and another set is conditioned in an air-circulating oven for 168 hours at 158° ± 1.8°F (70° ± 1°C), after which the set is immediately placed in a desiccator for at least 4 hours prior to testing. The burning test consists of clamping a specimen from either set vertically with its lower end 12 inches above a layer of dry cotton. A Bunsen burner is placed under the lower end of the specimen for 10 seconds. After the flame is removed, the duration of flaming of the specimen is noted. The procedure is repeated on the same specimen.

Table 3-12 shows the test criteria for 94V-0, V-1, and V-2 classifications.

TABLE 3-12 UL 94 Flammability Test Criteria

	94 CLASSIFICATIONS		
	V-0	V-1	V-2
Maximum time of flaming after either test (seconds)	10	30	30
Maximum total flaming time for each set of 5 specimens (2 flame applications each specimen) (seconds)	30	250	250
Number of specimens that burn to clamp	0	0	0
Number of specimens that drip flaming particles igniting cotton 12 in below specimen	0	0	some
Maximum number of seconds with glowing combustion for any specimen after second removal of flame	30	60	60

For a 94-5V classification, a set of specimens (or plaques 6 inches × 6 inches × 0.5 inch) is conditioned for at least 48 hours at 73.4° ± 3.6°F (23° ± 2°C) and relative humidity of 50 ± 5 percent prior to testing. Another set is conditioned in a circulating air oven for 60 days at 249.8° ± 1.8°F (121° ± 1°C), then cooled in a desiccator for at least 4 hours prior to testing. A specimen from either set is clamped vertically. Then a flame from a Bunsen burner is applied for 5 seconds to a lower corner of the specimen and removed for 5 seconds. The procedure is repeated five times. After the fifth removal of the flame, no specimen shall burn for more than 60 seconds or drip any particles.

Flammability ratings of commonly used thermoplastic polymers are listed and ranked in Table 3-13.

TABLE 3-13 Typical Flammability Ratings of Thermoplastic Polymers. Based on UL Standard 94 ($^1/_{16}$ in Specimen)

	POLYMER	STANDARD GRADE	FLAME-RETARDANT GRADE
1	Polyamide-imide	V-0	not needed
1	Polyetherimide	V-0	not needed
1	Polyethersulfone	V-0	not needed
1	Polyphenylene sulfide	V-0	not needed
5	Nylon 6/6	V-2	V-0
5	Nylon 11	V-2	none
5	Polycarbonate	V-2	V-0
5	Polysulfone	V-2	V-0
9	Acrylonitrile-butadiene-styrene	HB	V-0/5V
9	Polybutylene terephthalate	HB	V-0
9	Modified polyphenylene oxide	HB	V-0
9	Polystyrene	HB	V-0
9	Polystyrene-butadiene	HB	V-0
9	Styrene-acrylonitrile	HB	V-0
9	Polypropylene	HB	V-0
16	Acetal homopolymer	HB	none
16	Acetal copolymer	HB	none
16	Acrylic	HB	none

The Oxygen Index (OI) (ASTM D 2863)

This test is designed to provide a graduated, numerical measure of flammability, rather than a classification (UL 94), and to improve the reproducibility of tests.

The oxygen index is the percent oxygen in an oxygen–nitrogen mixture that will just sustain combustion of a vertically mounted bar specimen that has been ignited by application of a gas flame to its *upper* end (as a candle). The oxygen content of air at sea level, approximately 20 percent, is considered the reference point in determining specimen susceptibility to burning. An index of 100 means the specimen could not be ignited or would not continue to burn after ignition in 100 percent oxygen. Materials with OI greater than 28 are usually classed UL 94V-0.

Oxygen indexes of commonly used thermoplastic polymers are listed and ranked in Table 3-14.

TABLE 3-14 Oxygen Index of Thermoplastic Polymers (ASTM D 2863)

RANK	POLYMER	STANDARD GRADE	FLAME-RETARDANT GRADE
1	Polyetherimide	47	not needed
2	Polyphenylene sulfide	46	not needed
3	Polyamide-imide	43	not needed
4	Polyethersulfone	38	not needed
5	Nylon 6/6	31	na
6	Polysulfone	30	32
7	Polycarbonate	25	35
8	Nylon 11	24.5	none
9	Polybutylene terephthalate	22	29
10	Acrylonitrile-butadiene-styrene	19	na
11	Polystyrene-butadiene	18	28
12	Polypropylene	18	27
13	Polystyrene	18	none
14	Acetal homopolymer	15	none
15	Acetal copolymer	14.9	none
16	Modified polyphenylene oxide	na	30
17	Acrylic	na	none
17	Styrene-acrylonitrile	na	na

MAXIMUM SERVICE TEMPERATURE OF THERMOPLASTIC POLYMERS

All properties of thermoplastic resins are affected by temperature, and each resin has a useful thermal range beyond which it will not perform satisfactorily. Each resin is unique in its reaction to temperature. For some resins, some property values hold up well throughout this range, but beyond it, deteriorate rapidly. For other resins, some property values steadily worsen with increasing temperature, making it more difficult

to define the point beyond which the resin is no longer useful. In selecting a resin for a specific application, it is important not only to determine the expected operating temperature range of a part, but also to consider how resin characteristics change within that range.

Table 3-15 lists maximum service temperatures below which manufacturers predict their resins will retain effective dielectric and mechanical properties.

TABLE 3-15 Maximum Recommended Service Temperatures of Thermoplastic Polymers

RANK	POLYMER	°F	°C
1	Polyamide-imide	500	260
2	Polyphenylene sulfide	400	205
3	Polyethersulfone	355	180
4	Polyetherimide	340	170
5	Polysulfone	300	150
5	Polybutylene terephthalate*	300	150
7	Nylon 6/6	265	130
8	Polycarbonate	240	115
9	Modified polyphenylene oxide	220	105
9	Acetal copolymer	220	105
9	Polypropylene	220	105
12	Acrylonitrile-butadiene-styrene (heat stabilized)	200	95
12	Acrylic	200	95
14	Acetal homopolymer	195	90
15	Styrene-acrylonitrile	180	80
16	Polystyrene	160	70
17	Polystyrene-butadiene	150	65
18	Nylon 11*	150	65

*Reinforced grades have much higher values.

RELATIVE COSTS OF THERMOPLASTIC POLYMERS

There are many factors to be considered in determining part cost, among which are the following:

- Resin price per pound
- Specific gravity (determines the number of cubic inches per pound)
- Part design (can make use of superior resin properties to reduce wall thickness)
- Molding cycle and machine capabilities
- Number of mold cavities

Thus, it is possible for a high-priced resin with relatively low specific gravity to compete successfully with a low-priced resin having relatively high specific gravity,

especially if the high-priced resin has a significantly shorter molding cycle and superior properties permitting design economies.

In selecting a resin for a specific application, these steps should be taken:

1. Candidates with appropriate properties should first be determined.
2. Resin cost per cubic inch should be obtained from suppliers or calculated by dividing the resin price per pound by cubic inches per pound for the resin (see Table 3-16).
3. Part design and resin properties should be reviewed to see which resin permits the most economical design.
4. Molding cycles should be estimated in consultation with resin suppliers and machine manufacturers.
5. Calculate finishing costs when comparing thermoplastic and thermosetting resins (which typically cost more to finish).
6. Decide on the number of mold cavities, considering part volume needed to supply forecast market demand, and production constraints such as machine capabilities and availability.

Table 3-16 shows cubic inches per pound for selected thermoplastic polymers, from which are calculated price advantages of lighter polymers. For example, if the resin price of nylon 6/6 were 25 percent higher than acetal, part cost would be equal due to the higher specific volume of nylon 6/6 (24.3 versus 19.5).

TABLE 3-16 Specific Volume and Cost Factor of Thermoplastic Polymers

	CUBIC* INCHES PER LB	% PRICE/LB DIFFERENCE FOR EQUAL PART COST
1. Polypropylene	30.8	58
2. Acrylonitrile-butadiene-styrene	27.4	41
3. Polystyrene-butadiene	26.9	38
4. Polystyrene	26.6	36
5. Nylon 11	26.6	36
6. Modified polyphenylene oxide	26.1	34
7. Styrene-acrylonitrile	25.9	33
8. Nylon 6/6	24.3	25
9. Acrylic	23.7	22
10. Polycarbonate	23.1	18
11. Polysulfone	22.1	13
12. Polyetherimide	21.8	12
13. Polybutylene terephthalate	21.1	8
14. Polyphenylene sulfide	20.6	6
15. Polyethersulfone	20.2	4
16. Polyamide-imide	19.8	2
17. Acetal copolymer	19.6	—
18. Acetal homopolymer	19.5	—

ALLOYS

Alloys are formed by interfacial adhesion between selected polymers during extrusion to form homogeneous melt. Alloys differ from blends in that, in blends, distinct polymer phases remain within the resin matrix. Although alloys exhibit many of the properties of a macromolecule, the close affinity of component polymers is physical and not chemical. Producers include Dexter, Du Pont, General Electric, Miles, Rohm & Haas, and Union Carbide.

Also described as alloys are elastomeric products consisting of a continuous phase of a polyolefin in which is dispersed a finely divided highly vulcanized elastomer, for example, ethylene propylene diene rubber (EPDM). Monsanto (Santoprene™, Geolast™) and Du Pont (Alcrym™) are producers of this type of elastomeric alloy.

The key to successful alloying is the role of compatibilizers which must be miscible with all the ingredient polymers acting to bond them together. Compatibilizing agents are highly proprietary with alloy manufacturers. Examples of successful agents include maleic anhydride, isocyanate, stearic acid, ethylene-vinyl acetate, styrene-ethylene/butylene-styrene block copolymer (Kraton™, Shell Chemical), and nitrile-butadiene elastomer (Chemigum P-83™, Goodyear).

Possible combinations of polymers to produce alloys are virtually limitless. Properties of highly miscible polymer alloys may be better than those of component polymers.

See also the "Polymerization" section, p. 41 in this chapter.

LIQUID CRYSTAL POLYMERS (LCPS)

Among the newest and most intriguing of materials, liquid crystal polymer resins have been commercially available since 1984 from Dartco (Xydar™), now Amoco Performance Products. Other producers now include Hoechst Celanese (Vectra™) and Montedison (Granlar™).

Liquid crystal polymers comprise a family of thermoplastic aromatic copolyesters with outstanding high-temperature performance and excellent resistance to chemicals, radiation, and burning.

Chemistry

Vectra resins are made from p-dihydroxybenzoic acid and 6,2 hydroxynaphthoic acid monomers. Xydar resins are polyesters based on terephthalic acid, isophthalic acid, dihydroxybiphenyl, and p-dihydroxybenzoic acid. Granlar resins are reported to be made from substituted hydroquinones and terephthalic acid monomers.

Liquid crystal polymers are classed as engineering thermoplastics.

Grades

Available grades for electrical/electronic applications include unreinforced, up to 40 percent glass-reinforced, and mineral-filled grades. Low-viscosity grades permit very thin sections.

Processing

Liquid crystal polymers may be injection molded on modified conventional equipment. Molding conditions vary widely with the grade and type of resin used. Resins must be thoroughly dried before use.

Properties

The polymer is comprised of densely packed fibrous chains that account for exceptional mechanical strength. Continuous use temperature is in the range of –60° to 465°F (–51°–240°C). Dimensional stability is excellent and creep resistance is superior to most other plastics.

Parts made from liquid crystal polymers are resistant to attack by virtually all chemicals, except sodium hydroxide in concentrations of 30 percent or higher. They are unaffected by exposure to most solvents and radiation. Polymers possess Oxygen Index ratings in the 35 to 47 range and do not burn in air.

Electrical/Electronic Uses

Where property requirements justify their relatively high price, liquid crystal polymer resins are suitable for connectors, chip carriers, sockets, automotive underhood electrical parts, and air conditioning electrical parts.

CONDUCTING POLYMERS

Although still in the early stages of commercial development, conducting polymers are of intense interest for high-technology applications such as batteries for watches, timers for video-cassette recorders, and TV remote controls. A possible high-volume application and one which would greatly advance the evolution of electric vehicles is the development of a practical conducting polymer type battery which would have high power density, long service life, adequate mechanical strength, and rapid rechargeability. The organization spearheading this program is the U.S. Advanced Battery Consortium (USABC), Detroit, Michigan.

Other applications with commercial potential include solder replacements, biomedical devices, electrolytic capacitors, and conducting skins for military equipment such as tanks and aircraft.

Conducting polymers are prepared at Westinghouse from conventional polymers which have considerable delocalization of electrons along polymer chains. Next, the polymers are reacted with an oxidizing or reducing agent which withdraws or adds electrons. These dopants include halogens (iodine, bromine), organic oxidizing agents (chloramil, dicholorocyanoquinone), and alkali metals (sodium, potassium).

At the outset, conductivity rises sharply with increasing dopant content to a point where additional dopant causes only incremental conductivity increase. A major problem of considerable concern is that conductivity decreases on exposure to elevated temperatures and on normal aging. Some conducting polymers (most are proprietary) may

be blended with polymers such as polyethylene or polyvinyl chloride, forming a readily processible partially conducting material.

An earlier and still used method for making conducting polymers is to add to conventional polymers conducting fillers such as carbon black, or copper or aluminum flakes.

DEVELOPMENT PROGRAMS

Polymers with a wide range of properties and prices are available to design and materials engineers. While research and development for new polymers continues, the efforts of many key resin producers and compounders are directed toward modifying existing polymers in these ways:

- Physically blending, or "alloying," different polymers
- Copolymerization or polycondensation of two or more monomers by addition reaction (see "Polymerization" (p. 41) in this chapter)
- Graft copolymerization in which side chains of one polymer are attached to another polymer serving as backbone
- Block copolymerization in which a row, or "block," of units of one polymer are joined with a row of units of another polymer (—AAAA—BBBB—)
- Compounding polymers with reinforcements and fillers (see "Reinforcements and Fillers" (p. 44) in this chapter)

The development of resins formulated with styrene, butadiene, and acrylonitrile and their blends, or alloys, with polycarbonate, polysulfone, and polyvinyl chloride are successful examples of these programs. Blending ratios may be designed to achieve certain properties required for a specific end use.

Underway at several companies are intensive development programs for new alloys, liquid crystal polymers, and conducting polymers, all covered separately in this chapter.

The focus of reinforcement and filler technology is on improving wetting characteristics by surface treatment of fibers or particles with stearates, resinates, silanes and titanates.

For those resins not inherently flame retardant, efforts continue to develop improved FR grades with minimal sacrifice of other properties.

MARKET TRENDS

In high-volume electrical/electronic applications for thermoplastic molding resins (such as transportation, appliances, and computers) where minimal dielectric properties are acceptable, cost effectiveness and design ingenuity are primary concerns. A goal of design engineers is to make the most practical use of materials so that the lowest possible manufacturing cost is attained consistent with specified performance standards. In this regard, where there are no overriding cost factors, plastics with low specific gravity, such as styrenics and nylons, are favored.

In applications requiring flame-retardant properties, likely candidates are compounds with UL 94V-0 or 5V ratings having combustion products with minimal toxicity. These would include imide, polyarylate, polycarbonate, polyetheretherketone, and modified polyphenylene oxide compounds.

Where optimum dielectric properties are required, styrenics and modified polyphenylene oxide have the lowest dielectric constant, nylon 6/6 and polyamide-imide have the highest dielectric strength, and acrylics, acetals, and polyamide-imides are best for arc resistance.

Usage of conducting polymers is growing rapidly.

SUMMARY OF RANKINGS OF THERMOPLASTIC POLYMERS

Table 3-17 ranks thermoplastic polymers according to key properties for each polymer. Rankings range from 1, most favorable from an electrical insulation viewpoint, to 18, least favorable. Note that no polymer ranks either highest or lowest in all properties. This table is intended as an aid to design engineers desiring to investigate polymers potentially suitable to meet critical criteria. Values are for basically unmodified polymers. Polymers with reinforcements (usually glass fibers), fillers (often mineral), and additives (flame retardants, antioxidants, UV inhibitors, etc.) may have significantly higher or lower values for each property.

PRINCIPAL THERMOPLASTIC POLYMERS FOR ELECTRICAL/ ELECTRONIC USES

The chemistry, grades, processing, properties, and electrical/electronic uses of principal thermoplastic polymers are described in the sections which follow. The values shown in tables are for general purpose grades, unreinforced, except as noted.

The following polymers are covered:

- Acetals: Homopolymer
- Acetals: Copolymer
- Acrylic (PMMA)
- Amide Polymers: Nylon 6/6
- Amide Polymers: Nylon 11
- Imide Polymers: Polyamide-Imide (PAI)
- Imide Polymers: Polyetherimide
- Polyarylate (PAR)
- Polybutylene Terephthalate (BPT)
- Polycarbonate (PC)
- Polyetheretherketone (PEEK)
- Modified Polyphenylene Oxide

TABLE 3-17 Ranking of Thermoplastic Polymers by Key Property Values

POLYMER	SPECIFIC GRAVITY	DIELEC-TRIC STRENGTH	DIELEC-TRIC CONSTANT	DISSIPA-TION FACTOR	VOLUME RESIS-TIVITY	ARC RESIS-TANCE	WATER ABSORP-TION	DEFLEC-TION TEMPERA-TURE	MAXI-MUM SERVICE TEMPERA-TURE	TENSILE STRENGTH	IZOD IMPACT STRENGTH
Acetal homo-polymer	18	15	14	7	15	4	11	8	14	6	8
Acetal copolymer	17	15	14	8	16	2	9	9	9	12	7
Acrylic	9	5	13	17	1	1	13	11	12	6	15
Nylon 6/6	8	1	18	18	18	7	18	15	7	4	6
Nylon 11	4	8	16	16	16	9	13	17	17	13	13
Polyamide-imide	16	3	17	15	5	3	13	1	1	1	4
Polyetherimide	12	7	10	11	2	8	11	3	4	2	11
Polybutylene terephthalate	13	11	11	10	7	5	6	18	5	14	11
Polycarbonate	10	15	9	14	4	11	7	6	8	11	1
Modified poly-phenylene oxide	6	4	4	3	12	14	4	6	9	8	3
Polyphenylene sulfide	14	15	8	2	12	18	2	5	2	9	18
Polypropylene	1	1	1	4	9	6	1	16	9	18	14
Polystyrene	4	5	2	1	9	16	2	11	16	16	15
Polystyrene-butadiene	2	12	2	9	12	17	4	11	17	16	5
Styrene-acrylonitrile	7	8	4	13	9	12	8	11	15	9	15
Acrylonitrile-butadiene-styrene	2	8	4	12	8	13	9	10	12	15	2
Polysulfone	11	8	7	5	6	10	13	4	5	5	8
Polyethersulfone	15	12	12	6	3	15	17	2	3	3	10

- Polyphenylene Sulfide (PPS)
- Polypropylene (PP)
- Styrenics: Polystyrene (PS)
- Styrenics: Polystyrene-Butadiene
- Styrenics: Styrene-Acrylonitrile (SAN)
- Styrenics: Acrylonitrile-Butadiene-Styrene (ABS)
- Sulfone Polymers: Polysulfone
- Sulfone Polymers: Polyethersulfone

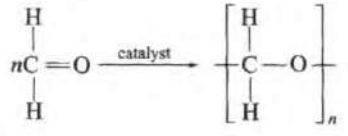
Note: A designation of "na" in the tables means data are not available.

Acetals: Homopolymer (Molding Resin)

The first commercially available acetal homopolymer resin was introduced in 1959 by Du Pont with the trademark Delrin. Two years later, Celanese (now Hoechst Celanese) marketed an acetal copolymer resin, Celcon™, which competes for essentially the same end uses, many of which were formerly served by metals.

Chemistry

Acetal homopolymers are linear polymers formed by polymerizing formaldehyde in the presence of a catalyst to polyoxymethylene:



An acid anhydride may be used to terminate the ends of the molecule, giving the polymer greater stability.

Acetal homopolymer is classed as an engineering thermoplastic.

Grades

Several injection molding grades of Delrin resin are produced:

- General purpose molding grade
- Higher melt flow grade with lower impact strength and elongation
- High-productivity, high-flow, fast-molding grades
- 20% glass fiber-filled general purpose grade
- Low-wear/low-friction, lubricated grade
- Lowest-wear/low friction, 21% Teflon™ TFE fluoroplastic fibers-filled grade

No flame-retardant grades are available.

The related standard for both military and commercial purposes is ASTM D 4181, *Specification for Acetal (POM) Molding and Extrusion Materials.*

Processing

Acetal homopolymer resins may be injection molded in conventional equipment. Resins do not require drying prior to molding.

Properties

Acetal homopolymer resin is superior to the copolymer resin in mechanical properties, but has lower processability and resistance to heat, hot water, and strong alkalis. Resistance is good to aliphatics, but poor to aromatics. Sonic welding may be used in finishing operations.

Table 3-18 shows key property values for both acetal homopolymer and copolymer resins.

TABLE 3-18 Key Properties of Acetal Homopolymer and Copolymer Molding Resins

	ASTM TEST METHOD	HOMOPOLYMER VALUE	COPOLYMER VALUE
Specific gravity*	D 792	1.42	1.41
Dielectric strength, 125 mils, short time, V/mil*	D 149	380	380
Dielectric constant*	D 150		
60 Hz		3.7	3.7
10^6 Hz		3.7	3.7
Dissipation factor*	D 150		
60 Hz		na	0.001
10^6 Hz		0.0048	0.006
Volume resistivity, Ω·cm*	D 257	1×10^{15}	1×10^{14}
Arc resistance*	D 495	220	240 (burns)
Water absorption, 1/8 in thick specimen, %	D 570		
24 h @ 73°F (23°C)		0.25	0.22
Deflection temperature, 264 psi °F (°C)	D 648	255 (124)	230 (110)
Maximum recommended service temperature °F (°C)		195 (90)	220 (104)
Tensile strength at break, psi*	D 638	10,000	8,800
Izod impact strength	D 256		
Foot pounds per inch notched 1/8 in specimen*		1.3	1.4
Flammability ratings			
UL Standard 94, 1/16 in specimen			
Standard grade		HB	HB
FR grade		none	none
Oxygen index, %	D 2863		
Standard grade		15	14.9
FR grade		none	none

*At room temperature

Electric/Electronic Uses

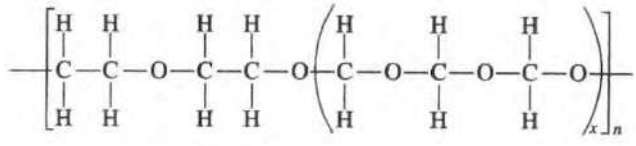
Applications of this resin are limited to components where good FR properties and chemical resistance are not required, including cut-out switches by utilities.

Acetals: Copolymer (Molding Resin)

Acetal copolymer (Celcon™) was introduced in 1961 by Celanese (now Hoechst Celanese) as a competitor to Du Pont's Delrin™, an acetal homopolymer with similar but not identical properties. BASF is now also a producer of the copolymer Ultraform™.

Chemistry

Acetal copolymer is produced from two cyclic ethers: trioxane plus a small proportion of dioxane. Each trioxane molecule yields three oxyethylene linkages, while each dioxane molecule provides two oxyethylene linkages, resulting in a polymer with the structure:



The occasional presence of two adjacent carbons is sufficient to prevent the disastrous "unzipping" of the polymer which might otherwise occur at high temperatures.

Acetal copolymer is classed as an engineering thermoplastic.

Grades

Celcon is available in an internally lubricated injection molding grade, a higher flow grade for parts with thin walls or small gates, a UV-stabilized grade, and a 25% short glass-fibers-reinforced grade for parts requiring high-temperature load-bearing properties. No flame-retardant grades are available. As with the homopolymer, ASTM D 4184 applies.

Processing

All types of injection molding machines may be used in molding acetal copolymer resins. A separate drying step is not required. Shot weight should be in the range of 50–75 percent of rated capacity. Optimum compound temperatures are 370° to 400°F (188°–204°C) with mold temperatures in the 150° to 200°F (66°–93°C) range.

Properties

Compared with acetal homopolymer, the copolymer resin is easier to process and more resistant to attack by chemicals, but mechanical properties are generally lower. Both resins are combustible.

Acetal copolymer resins have good room temperature resistance to:

- Alcohols
- Aliphatic hydrocarbons
- Alkalis
- Carbon tetrachloride
- Detergents
- Ketones
- Mineral oil
- Motor oil

Acetal copolymer resins are attacked by:

- Aromatic hydrocarbons
- Diethyl ether
- Ethyl acetate
- Ethylene dichloride
- Oxidizing agents
- Strong mineral acids

Table 3-18 shows key property values for both acetal copolymer and homopolymer resins.

Electrical/Electronic Uses

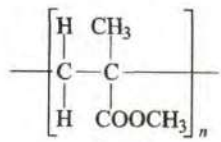
Because of its flammability, this resin is not suitable for applications requiring FR properties, which significantly limits electrical/electronic end uses to products such as radio and TV coil forms, control knobs, etc.

Acrylic (PMMA) (Molding Resin)

Acrylics are noteworthy for superlative optical properties and weatherability. Acrylic molding compounds have been commercially available since their introduction in the late 1930s. The first producers were Rohm and Haas (now AtoHaas) (Plexiglas™) and Du Pont (Lucite™). They are still the largest suppliers, but are now joined by several other companies including ICI Acrylics, Cyro Industries (Perspex™), and Novacor Chemicals (Zylar™).

Chemistry

Acrylics are produced by polymerizing methyl methacrylate alone or combined with other unsaturated monomers. The monomer is the reaction product of acetone and hydrogen cyanide, forming acetone cyanohydrin, which is then heated with methanol in the presence of sulfuric acid. A newer process is based on the oxidation of isobutylene. The homopolymer has the following structure:



Polymerization methods include bulk, solution, emulsion, and suspension techniques. Molecular weight may be controlled by polymerization method and conditions. Higher molecular weight contributes better mechanical properties, but makes processing more difficult. Improvements in various characteristics are attained by copolymerizing methyl methacrylate with styrene (lower cost), acrylonitrile (higher heat resistance), or ethyl acrylate (easier processing). Improvements are also made by blending methyl methacrylate with vinyls or butadiene-based elastomers (greater impact strength) or polyester resins (easier processing).

Grades

Acrylic resins are supplied as pellets and beads. Grades may differ in molecular weight, with higher molecular weight resins having lower melt flow rates, but better resistance to cracking during ejection. Resins with low molecular weight have high melt flow rates and feature better mold-filling characteristics in complex cavities.

Impact strength up to five times greater than obtainable in general purpose grades is available in grades modified with butadiene or other elastomers. These blends, however, have reduced clarity and weather resistance. Grades with UV stabilizers added have improved UV resistance, but noticeably increased edge color. No flame-retardant molding grades are yet commercially available. Military purchases are made to L-P-380, *Plastic Molding Material, Methacrylate*.

Processing

Acrylic resins may be injection or compression molded using standard techniques. Depending on the formulation and mold design, start-up mold temperatures range from 120° to 200°F (49°–93°C). Recommended cylinder temperatures range from 375° to 430°F (191°–221°C) for single-stage plunger machines and from 310° to 560°F (154°–293°C) for reciprocating screw machines. The newer reciprocating screw machines provide improved feed control, faster cycles, lower pressures, and easier cleaning. Mold shrinkage is in the 2–6 mil per inch range. Optimum processing conditions are unique for each mold, and depend on formulation, machine characteristics, and cavity size and configuration. A drying step is required when not using a vented barrel machine.

Properties

Acrylic resins exhibit outstanding arc resistance, even after immersion in water or long-term outdoor exposure. Impact strength remains unimpaired over a wide portion of the resins' useful temperature range, including subzero temperatures. Clarity is excellent. Surface hardness is much lower than glass. Flammability is relatively high.

Acrylics are resistant to attack by:

- Aliphatic hydrocarbons
- Mineral oils
- Vegetable oils
- Weak acids
- Weak bases

Acrylics are attacked by:

- Alcohols
- Chlorinated hydrocarbons
- Ethers
- Strong inorganic acids

Acrylics are dissolved by:

- Acetone
- Aniline
- Benzene
- Dimethyl formamide
- Ethyl acetate
- Ethylene dichloride
- Toluene

Table 3-19 shows key property values for this resin.

Electrical/Electronic Uses

Major uses for acrylics take advantage of their superior optical properties. They are being used increasingly in fiber optics. High arc resistance makes acrylics suitable for high-voltage applications such as circuit breakers. A decreasing dielectric constant with increasing frequencies makes acrylics attractive candidates for high frequency applications. Acrylics are not suitable where flammability may be a problem.

Amide Polymers: Nylon 6/6 (Molding Resin)

Polyamide polymers were introduced in the U.S. by Du Pont about 1938. They were given the name *nylon*, which is now used generically by all producers, the principal ones being:

PRODUCER	TRADE NAME	TYPE
AlliedSignal	Capron	6, 6/6
Elf Autochem	Rilsan	11, 12
BASF	Ultramid	6, 6/6
Hoechst Celanese	Celanese	6/6
Du Pont	Zytel	6, 6/6, 6/12
Monsanto	Vydyne	6/6

TABLE 3-19 Key Properties of Typical Acrylic Molding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.19
Dielectric strength, 125 mils, short time, V/mil*	D 149	500
Dielectric constant*	D 150	
60 Hz		3.7
10^6 Hz		2.2
Dissipation factor*	D 150	
60 Hz		0.05
10^6 Hz		0.03
Volume resistivity, Ω·cm*	D 257	1×10^{18}
Arc resistance*	D 495	no tracking
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.3
Deflection temperature, 264 psi, °F (°C)	D 648	212 (100)
Maximum recommended service temperature °F (°C)		200 (95)
Tensile strength at break, psi*	D 638	10,000
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		0.4
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		HB
FR grade		none
Oxygen index, %	D 2863	
Standard grade		na
FR grade		none

*At room temperature.

The type designation, for example 6/6, shows the number of carbon atoms in each part of a nylon molecule formed by a dibasic acid and a diamine, in this case adipic acid and hexamethylene diamine. Type 11 indicates there are 11 carbon atoms in the monomer of a nylon formed by polymerization of the ring compound omega-amino undecanoic acid. Nylon 6/6, the highest volume type, and nylon 11, a specialty, low moisture type, are described in this section and the following section.

Chemistry

There are two basic processes for making nylons: polymerization of ring monomers where the monomer has both acid and amine groups (nylon 6), and condensation of a dibasic acid and a diamine, for example, nylon 6/6, obtained by heating adipic acid (6 carbons) with hexamethylene diamine (6 carbons):

$$H_2N(CH_2)_6NH_2 + HOOC(CH_2)_4COOH \xrightarrow[-H_2O]{\text{heat}} —[NH(CH_2)_6NHCO(CH_2)_4CO]_x—$$

Nylon 6/6 is classed as an engineering thermoplastic, although it exhibits an inherent tendency to absorb moisture, resulting in changes in dimensions.

Grades

A large number of grades of nylon 6/6 are available. Nylons are inherently slow burning, but may be made flame retardant with appropriate additives such as halogenated aromatics or cycloaliphatics in conjunction with antimony oxide. Grade modifications to meet specific end uses are obtained through changing molecular weight, copolymerization with other nylon types, and blending with additives and fillers. Modification of nylon 6/6 by copolymerization with nylon 6 provides a resin with improved impact and elongation, but with lower thermal properties. Military purchases are to ASTM D 4066, *Specification for Nylon Injection and Extrusion Materials*.

Processing

For good results, it is essential that nylon resins be dried to less than 0.3 percent moisture content at 140°F (60°C) before molding. Care must be taken to keep resins dry under all conditions of storage and manufacture. Nylons mold readily in conventional equipment that can adequately plasticate and heat the resin to the melt temperatures required of 500° to 580°F (260°–304°C). As noted above, dimensional changes in parts can be expected from changing humidity.

Properties

All nylons are characterized by toughness and abrasion resistance, and are slow burning. Nylon 6/6 has the highest thermal and tensile properties of the common nylon types. It is, however, highly moisture absorbent, as shown in Table 3-20, with the effect on the dielectric constant as shown in Fig. 3-6.

Nylon 6/6 is resistant to attack by:

- Acetone
- Aliphatics
- Ammonia
- Aromatics
- Benzene
- Carbon disulfide
- Carbon tetrachloride
- Chlorobenzene
- Ether
- Ethyl acetate
- Detergents
- Formaldehyde
- Gasoline
- Methyl ethyl ketone

TABLE 3-20 Key Properties of Typical Nylon 6/6 and Nylon 11 Molding Resins

	ASTM TEST METHOD	NYLON 6/6 VALUE**	NYLON 11 VALUE
Specific gravity*	D 792	1.14	1.04
Dielectric strength, 125 mils, short time, V/mil*	D 149	600 (dry)	750 (dry)
Dielectric constant*	D 150		
60 Hz		8.0	3.9
10^6 Hz		4.6	3.1
Dissipation factor*	D 150		
60 Hz		0.2	0.04
10^6 Hz		0.1	0.05
Volume resistivity, Ω·cm*	D 257	1×10^{13}	1×10^{14}
Arc resistance*	D 495	130	123
Water absorption, 1/8 in thick specimen, %	D 570		
24 h @ 73°F (23°C)		1.2	0.3
Deflection temperature, 264 psi, °F (°C)	D 648	194 (90)	131 (55)
Maximum recommended service temperature °F (°C)		265 (130)	149 (65)
Tensile strength at break, psi*	D 638	11,200	8,200
Izod impact strength	D 256		
Foot pounds per inch notched 1/8 in specimen*		2.1	0.75
Flammability ratings			
UL Standard 94, 1/16 in specimen			
Standard grade		V-2	V-2
FR grade		V-0	none
Oxygen index, %	D 2863		
Standard grade		31	24.5
FR grade		na	none

*At room temperature.

**At 50% relative humidity unless otherwise indicated.

- Mineral oils
- Silicone fluids
- Soaps
- Tetrachloroethylene
- Vegetable oils
- Vinyl chloride

Nylon 6/6 is attacked by:

- Acids, both organic and inorganic
- Bases (strong)
- Bleaching lye
- Chloroform
- Phenol

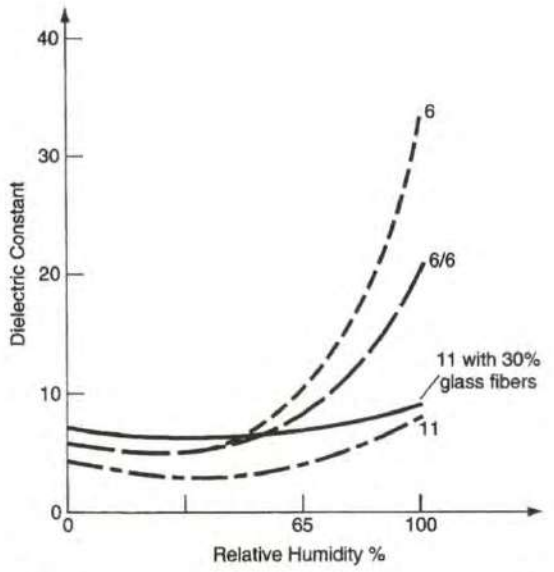


Fig. 3-6 Dielectric constant of selected nylon types as a function of relative humidity at 20°C and under a voltage of 30 V.

Nylon 6/6 dissolves in cresol and cresylic acid.

Table 3-21 shows key property values for both nylon 6/6 and nylon 11 resins.

Electrical/Electronic Uses

The tendency to absorb moisture with harmful effects on dielectric properties limits nylon 6/6 to noncritical electrical/electronic applications. As described in Chapter 7, *Magnet Wire Enamels*, nylon 6/6 is used extensively as a jacket over primary wire insulation. Parts molded from nylon 6/6 include coil forms, insulator blocks, and electrical connectors.

TABLE 3-21 Water Absorption of Selected Nylon Types

NYLON TYPE	% WATER ABSORPTION 24 h (ASTM D 570)
6	1.3–1.9
6/6	1.0–1.3
6/9	0.5
6/12	0.4
11	0.3
12	0.25

Amide Polymers: Nylon 11 (Molding Resin)

Nylon 11, a specialty, low moisture absorption type, was developed in France by ATO and first marketed there in the late 1940s. It is now produced in the U.S. only by Elf Autochem North America, Engineering Polymers, with the trademark "Rilsan."

Chemistry

Nylon 11 is produced by polycondensation from omega–amino undecanoic acid under nitrogen at 419°F (215°C) for several hours. It has the following structure:

$$—[NH(CH_2)_{10}CO]_x—$$

Nylon 11 is classed as an engineering thermoplastic.

Grades

There are several grades of Rilsan:

- Standard grades in a range of flexibility
- Self-lubricated grades (graphite)
- Reinforced grades (glass fibers)
- Temperature-resistant or heat-stabilized grades

Processing

See discussion in previous section on "Amide Polymers: Nylon 6/6."

Properties

Nylon 11 has significantly lower tendency to absorb water than most other nylon types.

The lower susceptibility to moisture results in less change in dielectric properties and greater dimensional stability with increased humidity than for most other nylon types. Thermal and tensile properties of nylon 11 are, however, much lower than for other nylons with fewer carbons in the molecule. Chemical properties are approximately the same as for nylon 6/6.

Table 3-21 shows key properties for both nylon 11 and nylon 6/6.

Electrical/Electronic Uses

Although dielectric properties of nylon 11 qualify it for many electrical/electronic applications, high price and low thermal properties relative to other nylons have limited it to specialty end uses such as jacketing for aircraft control cable and hydraulic tubing and hose.

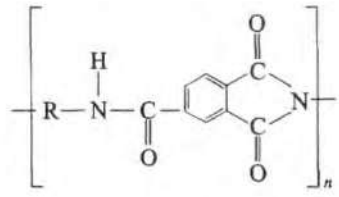
Imide Polymers: Polyamide-Imide (PAI) (Molding Resin)

Polyamide-imide, like other imide polymers, is characterized by high heat resistance. It has stable dielectric and mechanical properties up to 500°F (260°C). Amoco Perfor-

mance Products is the producer of injection-molded grades, trademarked Torlon, first marketed in 1973.

Chemistry

Polyamide-imide is the product of the condensation reaction of trimellitic anhydride and aromatic diamines, with the chemical structure:



It is classed as an engineering thermoplastic.

Grades

Injection molding grades include four general purpose grades and reinforced grades with 30% and 40% glass fibers, and up to 30% graphite fibers. Improved processability is obtained by adding a small amount of polytetrafluoroethylene or by copolymerization. Grades approved for military use are listed in MIL-P-46179, included in Chapter 19, *Government Activities*.

Processing

Polyamide-imides are among the most difficult of resins to process, which limits their use to applications where their high temperature properties make them the only choice. Resins are highly shear sensitive and require a low compression screw. Temperature control is difficult because of heat generated by the high viscosity of these thixotropic resins. Molding cycles are very fast. Immediately after molding, parts must be cured in ovens for up to three days to achieve optimum properties. Resins should be thoroughly dried before molding.

Properties

Polyamide-imide has good dielectric properties and radiation resistance, but its outstanding features are superior high-temperature resistance and tensile strength, which is 7,500 psi at 500°F (260°C) and as high as 31,500 psi at –320°F (–160°C). Its UL flammability rating for general purpose grade is V-0, and Oxygen Index is 43 percent. Polyamide-imide does not drip and produces very little smoke on burning. It is, however, adversely affected by high humidity and should not be used in environments where steam could be a problem. It has better thermal and mechanical properties than polyetherimide, but is much more difficult to process.

Polyamide-imide has good resistance to:

- Aliphatic hydrocarbons
- Aromatic hydrocarbons

- Halogenated solvents
- Most dilute acid solutions
- Most dilute base solutions

Polyamide-imide is attacked by:

- High-temperature caustic solutions
- Concentrated sulfuric acid
- *n,n*-dimethyl acetamide
- Ethylene diamine
- Steam

Table 3-22 shows key property values for both polyamide-imide and polyetherimide resins.

TABLE 3-22 Key Properties of Typical Polyamide-Imide and Polyetherimide Molding Resins

	ASTM TEST METHOD	POLYAMIDE-IMIDE VALUE	POLYETHER-IMIDE VALUE
Specific gravity*	D 792	1.40	1.27
Dielectric strength, 125 mils, short time, V/mil*	D 149	580	480
Dielectric constant*	D 150		
60 Hz		4.3	3.2
10^6 Hz		3.9	3.1
Dissipation factor*	D 150		
60 Hz		0.025	0.004
10^6 Hz		0.031	0.006
Volume resistivity, Ω·cm*	D 257	8×10^{16}	6.7×10^{17}
Arc resistance*	D 495	230	128
Water absorption, 1/8 in thick specimen, %	D 570		
24 h @ 73°F (23°C)		0.30	0.25
Deflection temperature, 264 psi °F (°C)	D 648	532 (278)	392 (200)
Maximum recommended service temperature °F (°C)		450 (232)	340 (170)
Tensile strength at break, psi*	D 638	22,000	15,200
Izod impact strength	D 256		
Foot pounds per inch notched 1/8 in specimen*		2.7	1.0
Flammability ratings			
UL Standard 94, 1/16 in specimen			
Standard grade		V-0	V-0
FR grade		none needed	none needed
Oxygen index, %	D 2863		
Standard grade		43	47
FR grade		none needed	none needed

*At room temperature.

Electrical/Electronic Uses

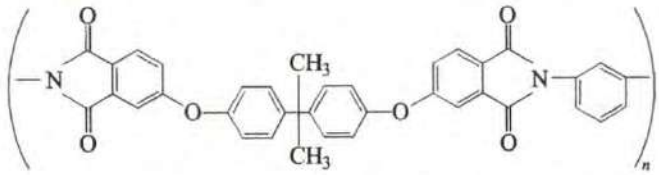
Because of high price and processing difficulty, polyamide-imide is considered where no other commercially available resin qualifies for an application. Its flame resistance and low smoke generation make the resin suitable for aerospace applications, including electrical/electronic parts and replacement of metal parts with important weight reduction. Polyamide-imide is used in silicon chip manufacture, where it reduces burn-in time significantly because of its high processing temperature, 482°F (250°C). Other applications include metal replacement in compressor valve plates and in parts for automotive transmissions and engines.

Imide Polymers: Polyetherimide (PEI) (Molding Resin)

Polyetherimide is one of the most recent engineering plastics developed in General Electric's polymer technology program. G.E. is the only producer of polyetherimide resin "Ultem™," which became commercially available in 1982. Although not as resistant to high temperatures as polyamide-imide, polyetherimide is more readily processible.

Chemistry

Polyetherimide has a basic imide molecule incorporated into an amorphous polymer through ether linkages, resulting in an engineering thermoplastic resin with the following chemical structure:



The aromatic imide group provides rigidity, creep resistance, and high deflection temperature. The ether moiety contributes chain flexibility for good flow and processability.

Grades

The grades of polyetherimide resin now available include unreinforced, and 10–40 percent glass-reinforced grades. Military purchases are governed by MIL-P-46184, *Plastic Molding and Extrusion Material, Polyetherimide (PEI)*.

Processing

Polyetherimide resin has outstanding melt flow, melt stability over a wide processing temperature range, and suitability for conversion using all standard injection molding techniques. Prior to processing, moisture should be reduced to 0.05 percent by drying 4 hours at 300°F (149°C), 5 hours at 280°F (138°C), 6 hours at 265°F (129°C), or 7 hours at 250°F (121°C). Mold temperatures should be 150° to 350°F (66°–177°C).

High temperatures improve flow necessary for filling thin-wall and complex parts. Both conventional and laser techniques may be used to machine molded parts. Bonding may be accomplished by adhesives, solvent assembly, and ultrasonic methods.

Properties

Noteworthy properties of polyetherimide include the following:

- High heat resistance
- High dielectric strength
- Stable dielectric constant and dissipation factor over a wide range of temperatures and frequencies
- High mechanical properties
- Outstanding processability
- Inherent flame resistance with low smoke evolution
- UV radiation resistance

Polyetherimide is highly notch-sensitive. Although lower in thermal and mechanical properties, polyetherimide has much better resistance to steam exposure than polyamide-imide and is far easier to process.

Polyetherimide has high gloss/colorability and is resistant to attack by:

- Aircraft and auto fuels, lubricants, and antifreeze
- Transmission and brake fluids
- Alcohols
- Aromatic hydrocarbons
- Detergents
- Ethers
- Freon
- Ketones
- Mineral acids
- Vegetable oils and fats

The resin is soluble in partially halogenated hydrocarbons such as methylene dichloride and trichloroethane.

Table 3-22 shows key property values for both polyetherimide and polyamide-imide resins.

Electrical/Electronic Uses

Heat resistance to wave and vapor-phase soldering, intricate design potential, dimensional stability, and flame resistance make polyetherimide attractive for circuit boards, terminal bases, connectors, fuses, and integrated circuit test devices. The resin is used for automotive and aerospace applications requiring high heat resistance, resistance to attack by fluids, creep resistance, mechanical strength with light weight, dimensional stability under load, and high electrical insulation values. It is well suited for microwave appliances.

Polyarylate (PAR) (Molding Resin)

First marketed in the U.S. in 1978 by Union Carbide as an import from Japan, electrical grades of polyarylate are now produced in the U.S. by Amoco Performance Products (Ardel™), Du Pont (Arylon™), and Hoechst Celanese (Durel™). These polymers are aromatic polyesters with amophorous molecular structure. The resin lends itself to blending and alloying, and this may be a strong growth area.

Chemistry

There are at least five processes for making the resin, most of which are proprietary, yielding varying degrees of clarity and ranging in color from straw to amber. Common manufacturing ingredients include diphenyl isophthalate and diphenyl terephthalate blends reacted with bisphenyol A.

Polyarylate is classed as an engineering thermoplastic.

Grades

Polyarylate resins are available in unreinforced grades (some meeting requirements for a UL 94 V-0 rating) and in 30 percent glass-reinforced grades.

Processing

Polyarylates require thorough drying before processing. Recommended melt temperatures range from 640° to 735°F (338°–390°C). Mold shrinkage is uniform in all directions, similar to polycarbonate or polysulfone.

Properties

Suitable for high-temperature applications, polyarylate resins, with heat deflection temperature of 310°F (154°C) are positioned between polycarbonate with HDT of 265°F (129°C) and polysulfone with HDT of 345°F (174°C). Polyarylates have inherently good flame retardancy (UL 94V-0) and generate little smoke during burning. They are little affected by humidity under normal service conditions. Good dielectric properties are retained over a broad range of temperature and frequency. Resistance to chemicals and solvents is not noteworthy.

Electrical/Electronic Uses

Flame retardancy and the ability to withstand high operating temperatures while maintaining good dielectric properties make polyarylates suitable for diverse applications including molded three-dimensional wiring boards, wire jacketing, connectors, switchgear, and fuses.

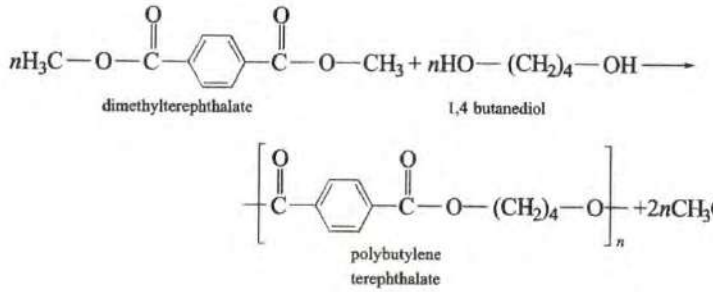
Polybutylene Terephthalate (PBT) (Molding Resin)

Useful for its good dielectric properties, low moisture absorption, and chemical resistance, this thermoplastic polyester, also known as polytetramethylene terephthalate

(PTMT), became commercially available in 1969. Producers include BASF (Ultradur™), General Electric (Valox™), Hoechst Celanese (Celanex™), and Huls American. Polyethylene terephthalate (PET) resin, used primarily for fiber, filament, and film production, is discussed in Chapter 10, *Dielectric Films*, p. 132.

Chemistry

Polybutylene terephthalate is a product of the polycondensation of 1,4-butanediol and dimethylterephthalate:



Grades

Commercially available grades include unreinforced general purpose and flame-retardant grades, and reinforced grades for improved stiffness with up to 45 percent glass and/or mineral filler. Special reinforced grades with improved surface appearance over standard reinforced grades are also offered. Alloys with polyarylate to improve dimensional stability are under development.

Processing

Polybutylene terephthalate resins are high crystalline with sharply defined melting points in the 335° to 442°F (168°–228°C) range, depending on grade. Processing temperatures of 450° to 500°F (232°–260°C) facilitate filling of complex molds. Cycle times are relatively short (because of the high degree of crystallinity) compared with other thermoplastics. Conventional screw injection molding machines are preferred because they can operate at higher melt viscosities, hence lower and more homogeneous melt temperatures. Resins should be dried prior to molding for 2–4 hours at 250°F (121°C). A shot of 50–75 percent of rated machine capacity usually produces the best results. Parts assembly may be accomplished by most conventional methods, including solvent and adhesive bonding, and hot plate, ultrasonic, and spot welding.

Properties

Polybutylene terephthalate resin molded parts maintain their dielectric strength, even in high-humidity environments. Dielectric constant remains steady over a wide range of frequencies. Resistance to arcing and tracking is high. With 30 percent

glass fiber reinforcement, polybutylene terephthalate resins exhibit outstanding heat deflection temperatures up to 430°F (221°C) at 66 psi compared with 310°F (154°C) for unreinforced general purpose grades. However, with increased load, heat deflection for unreinforced general purpose grades drops rapidly to 130°F (54°C) at 264 psi. The drop at 264 psi with glass-reinforced grades is not nearly as dramatic, amounting to only 15°F (8°C) for some grades. Moisture absorption is low and notched impact resistance high for a thermoplastic material. Polybutylene terephthalate's tendency to warp makes it unsuitable for some end uses.

Polybutylene terephthalate resins have good room temperature resistance to:

- Water
- Aliphatic hydrocarbons
- Aromatic hydrocarbons
- Ethers
- Ketones
- Glycols
- Organic solvents, including degreasing solvents
- Flux cleaners

Polybutylene terephthalate resins are attacked by:

- Aromatics
- Acetone and ketones above ambient temperature
- Strong acids and bases
- Ethyl acetate
- Detergents
- Lubricating oils
- Hot water on prolonged exposure

Solvents include:

- Trifluoroacetic acid
- Phenol/chlorinated aliphatic hydrocarbons
- Hexafluoroisopropanol
- O-chlorophenol

Table 3-23 shows key property values for this resin.

Electrical/Electronic Uses

Unreinforced polybutylene terephthalate grades are used for bobbins, connectors, coilforms, and sensors. Reinforced grades are well suited for distributor caps and rotors, connectors, business machine parts, industrial motor controls, circuit breakers, TV components, terminal blocks, fuse holders, and housings for appliances and hand power tools.

TABLE 3-23 Key Properties of Typical Polybutylene Terephthalate Molding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.31
Dielectric strength, 125 mils, short time, V/mil*	D 149	420
Dielectric constant*	D 150	
60 Hz		3.3
10^6 Hz		3.1
Dissipation factor*	D 150	
60 Hz		0.002
10^6 Hz		0.02
Volume resistivity, Ω·cm*	D 257	4×10^{16}
Arc resistance*	D 495	184
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.08
Deflection temperature, 264 psi, °F (°C)	D 648	130 (54)
Maximum recommended service temperature °F (°C)		300 (150)
Tensile strength at break, psi*	D 638	18,200
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		1.0
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		HB
FR grade		V-0
Oxygen index, %	D 2863	
Standard grade		22
FR grade		29

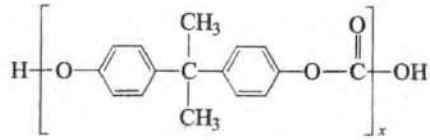
*At room temperature

Polycarbonate (PC) (Molding Resin)

Polycarbonate was discovered in the United States at General Electric and has been commercially available since 1958. It is noted for its exceptionally high impact resistance, good dielectric properties, and corona resistance. Molding resins are produced by Dow Plastics (CALIBRE™), G.E. (Lexan™), and Miles (Makrolon™). Alloys with other polymers are also available from these companies.

Chemistry

Polycarbonate, a polyester of carbonic acid, is obtained from bisphenol A and other polyhydric phenols, reacted with phosgene. It is an engineering thermoplastic with the structure:



Grades

Resins are available in low, medium, and high melt viscosities for molding and extrusion. There are special grades produced in compliance with Food Additive Regulations for food contact applications (21 CFR 177.1580 and 21 CFR 178.2010). Other special grades are UV-stabilized, and still another grade provides UL Standard 94 rating of V-0. There are glass-fiber-reinforced grades with 20–40 percent glass for improved rigidity, creep resistance, dimensional stability, and heat resistance. Military purchases are made to L-P-393, *Plastic Molding Material, Polycarbonate, Injection and Extrusion*.

Processing

All standard thermoplastic techniques may be employed in injection molding processes. Because of its hydrolytic sensitivity at processing temperatures, the resin should be dried to less than 0.02 percent moisture before processing to avoid deterioration of impact strength and formation of streaks and bubbles in the finished product. Proper design and shop practices minimize the tendency of molded parts to stress crack or craze.

Properties

Polycarbonate has noteworthy attributes: clarity, superior impact strength, dimensional stability over a wide temperature range, and self-extinguishing property.

Polycarbonate has good room temperature resistance to:

- Water
- Dilute organic and inorganic acids
- Oxidizing and reducing agents
- Neutral and acid salts
- Animal and vegetable oils and fats
- Aliphatic and cyclic hydrocarbons

Polycarbonate is attacked by:

- Alkalis
- Amines
- Ketones
- Aromatic hydrocarbons

Solvents for polycarbonate include:

- Methylene and ethylene dichloride
- Cresol
- Dioxane
- Pyridine

Table 3-24 shows key property values for this resin.

TABLE 3-24 Key Properties of Typical Polycarbonate Molding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.20
Dielectric strength, 125 mils, short time, V/mil*	D 149	380
Dielectric constant*	D 150	
60 Hz		3.2
10^6 Hz		3.0
Dissipation factor*	D 150	
60 Hz		0.0009
10^6 Hz		0.010
Volume resistivity, Ω·cm*	D 257	8.2×10^{16}
Arc resistance*	D 495	120
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.15
Deflection temperature, 264 psi, °F (°C)	D 648	265 (129)
Maximum recommended service temperature °F (°C)		240 (115)
Tensile strength at break, psi*	D 638	9,000
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		12
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		V-2
FR grade		V-0
Oxygen index, %	D 2863	
Standard grade		25
FR grade		35

*At room temperature.

Electrical/Electronic Uses

Because of its colorability and good physical, dielectric, and self-extinguishing properties, polycarbonate housings are used extensively for power tools, appliances, printers, copiers, and other business machines. Polycarbonates are successful in connectors, circuit boards, wiring blocks, and other component parts. Nonbrominated flame-retardant grades feature processing stability, UL 94V-0 rating, Oxygen Index of 35, low smoke emission and toxicity, and no corrosive gasses on decomposition.

Polyetheretherketone (PEEK) (Molding Resin)

Among the resins with the highest useful service temperature, this new aromatic, easily processed resin is produced by ICI Americas under the trademark Victrex.

Chemistry

Polyetheretherketone resin is made by condensation polymerization in an aromatic solvent. It is classed as an engineering thermoplastic.

Grades

Supplied as granules and as a powder in medium and higher viscosity unreinforced grades, and grades reinforced with 20 and 30 percent glass fiber, and 30 percent carbon fiber.

Processing

This resin is readily processed in all commonly used equipment to produce molded parts, film, sheet, wire and cable extrusions, monofilament, and composites.

Properties

The outstanding properties of this resin include:

- Continuous service temperature for electrical/electronic applications of up to 392°F (200°C).
- UL 94V-0 flammability rating with low smoke and toxic gas emission.
- Resistance to attack from up to 60 percent sulfuric acid and 40 percent sodium hydroxide solutions at elevated temperatures. The only common solvent is concentrated sulfuric acid.
- High resistance to hydrolysis—unaffected after long-term immersion in pressurized water at 480°F (250°C).
- No significant reduction in mechanical properties after absorbing 1000 Mrad of irradiation.

Electrical/Electronic Uses

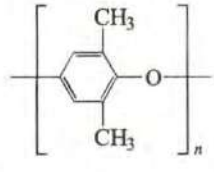
Their easy processing quality make polyetheretherketone resins suitable for a wide range of applications where their outstanding properties justify their relatively high prices.

Polyphenylene Ether, Modified (PPE) (Molding Resin)

A product of the plastics research and development program at General Electric, modified polyphenylene ether (formerly called polyphenylene oxide) with the trademark Noryl became commercially available in 1966. The resin exhibits good dielectric properties over a wide range of humidity and temperature.

Chemistry

Polyphenylene ether is formed by oxidative coupling in a reaction in which oxygen is passed through 2,6-disubstituted phenol. A copolymer (Prevex™) is formed from 2,6-disubstituted and 2,3,6-trisubstituted phenols. Polyphenylene ether has the basic structure:



Despite its high property values in its unmodified form, polyphenylene ether experienced limited acceptance because of processing difficulties. Modification with styrene polymers, with which it is highly miscible, has greatly improved its processing characteristics and lowered its cost, but at the expense of reduced maximum operating temperature.

Modified polyphenylene ether is classed as an engineering thermoplastic.

Grades

There are at least 16 grades of Noryl, including 12 injection molding grades. In addition to a general purpose grade, other grades emphasize certain properties. There are flame-retardant grades and 20 and 30 percent glass-reinforced grades. A special grade can be molded into parts with superior plating characteristics. Military purchases are made to MIL-P-46115, *Plastic Molding and Extrusion Material, Polyphenylene Oxide; Plastic Molding and Extrusion Material, Polyphenylene Oxide, Modified; Plastic Molding and Extrusion Material, Polyphenylene Oxide, Modified, Glass Fiber Reinforced.*

Processing

Reciprocating screw machines show best results because of reduced pressure through the cylinder, shorter cycle times, and lower molded-in stress. Continuous peripheral venting removes processing gases efficiently and minimizes the possibility of residue formation from the condensation of volatiles. The recommended processing temperature for general purpose grade is 425° to 600°F (218°–316°C). Predrying of the resin is not essential, but produces optimum appearance in molded parts.

Properties

Dielectric constant and dissipation factor of modified resins remain virtually unaffected over wide changes in relative humidity, temperature, and frequency. Water absorption rates are among the lowest for all engineering thermoplastics. Tensile strength and stiffness are retained under load throughout the useful temperature range. Several FR grades are available which satisfy UL 94V-0 standards. Thermally stable phosphorous-based additives improve FR characteristics.

Modified resins have good room temperature resistance to:

- Water
- Dilute inorganic acids and bases
- Saturated solutions of inorganic salts
- Alcohols
- Chlorine bleach
- Mineral oil

Modified resins are attacked by:

- 90 percent sulfuric acid
- Acetone

- Aliphatic hydrocarbons
- Ethers
- Ethyl acetate
- Vegetable oils

Solvents for modified resins include:

- Aromatic hydrocarbons
- Halogenated hydrocarbons

Table 3-25 shows key property values for the modified resin.

Electrical/Electronic Uses

Flame retardency and good mechanical properties make modified PPE resins attractive for business machine and small appliance housings. Reinforced and other grades are widely used in wall switch plates, electrical connectors, and television, telecommunication, and appliance components.

TABLE 3-25 Key Properties of Typical Modified Polyphenylene Ether Molding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.06
Dielectric strength, 125 mils, short time, V/mil*	D 149	550
Dielectric constant*	D 150	
60 Hz		2.6
10^6 Hz		2.6
Dissipation factor*	D 150	
60 Hz		0.0004
10^6 Hz		0.0009
Volume resistivity, Ω·cm*	D 257	1×10^{16}
Arc resistance*	D 495	75
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.06
Deflection temperature, 264 psi, °F (°C)	D 648	265 (129)
Maximum recommended service temperature °F (°C)		220 (105)
Tensile strength at break, psi*	D 638	9,600
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		5.0
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		HB
FR grade		V-0
Oxygen index, %	D 2863	
Standard grade		na
FR grade		30

*At room temperature.

Polyphenylene Sulfide (PPS) (Molding Resin)

Polyphenylene sulfide, developed by Phillips Chemical, became commercially available in 1972 under the trademark "Ryton." Its outstanding feature is resistance to thermal degradation, which occurs completely only at temperatures over 1300°F (704°C). In 1987, Celanese (now Hoechst Celanese) began marketing "Fortran™" and General Electric offered "Supec™" dielectric grades.

Chemistry

Polyphenylene sulfide is produced by reacting dichlorobenzene with sodium sulfide in a polar solvent:



Polyphenylene sulfide is classed as an engineering thermoplastic.

Grades

Although unfilled grades of Ryton are available, filled grades are more widely used because of greatly enhanced physical, mechanical, and thermal properties. Fillers include glass fiber and minerals. One grade containing 40 percent glass fiber has outstanding chemical resistance and electrical properties virtually unaffected by moisture. Another grade has high arc resistance and low arc tracking rate. Still another grade is essentially transparent to microwave radiation and is suitable for use at temperatures not to exceed 425°F (218°C). Colors are available. Military purchases are made to ASTM D 4067, *Specification for Reinforced and Filled Polyphenylene Sulfide Injection Molding and Extrusion Materials*.

Processing

Reciprocating screw equipment is recommended for molding polyphenylene sulfide, providing effective temperature control and short cycle capability. Molding compound should be dried for at least 6 hours at 300°F (149°C) prior to molding. Molds should be heated and insulated. Flexural strength is reduced as mold temperature is increased. Recommended melt temperatures are in the 600° to 625°F (316°–329°C) range. Parts may be annealed after molding by heat treatment at 400° to 450°F (204°–232°C) for 2–4 hours. Annealing improves dimensional stability, shear strength, and flexural modulus, but reduces gloss, tensile strength, and impact strength.

Properties

Maximum use temperatures for polyphenylene sulfide molded parts up to 400°F (204°C) are among the highest for all injection-molded thermoplastic resins. Resins are inherently flame retardant. Compounding with fillers significantly improves most mechanical and thermal properties. Hence, unfilled resins are used infrequently.

Mechanical properties for all grades drop sharply with increasing temperatures. Dielectric properties are retained even under high-humidity and high-temperature conditions.

Polyphenylene sulfide is insoluble in any known chemical below 400°F (204°C), and has good resistance to virtually all chemicals with the exception of oxidizing acids such as concentrated hypochlorous, perchloric, nitric, and sulfuric acids.

Table 3-26 shows key property values for this resin.

Electrical/Electronic Uses

Polyphenylene sulfide compounds are used for a wide range of electrical/electronic applications, and are especially suitable for parts exposed to high temperatures. Suggested applications include microwave ovenwear, bobbins, coil forms, connectors, sockets, switch components, and brush holders. The high arc resistance and low arc tracking rate of some polyphenylene sulfide compounds make them attractive for high voltage use and for structural components requiring a UL sole support rating. Polyphenylene sulfide is suitable for encapsulating integrated circuits and printed circuit components.

TABLE 3-26 Key Properties of Typical Polyphenylene Sulfide Molding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.34
Dielectric strength, 125 mils, short time, V/mil*	D 149	380
Dielectric constant*	D 150	
60 Hz		3.1
10^6 Hz		3.2
Dissipation factor*	D 150	
60 Hz		0.0003
10^6 Hz		0.0007
Volume resistivity, Ω·cm*	D 257	1×10^{16}
Arc resistance*	D 495	34
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.02
Deflection temperature, 264 psi, °F (°C)	D 648	275 (135)
Maximum recommended service temperature °F (°C)		400 (204)
Tensile strength at break, psi*	D 638	9,500
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		0.3
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		V-0
FR grade		none needed
Oxygen index, %	D 2863	
Standard grade		46
FR grade		none needed

*At room temperature.

Polypropylene (PP) (Molding Resin)

Polypropylene is a highly versatile resin suitable for processing into molded insulation parts, extruded wire and cable insulation, and dielectric films, all covered separately in this handbook. This section covers polypropylene molding resins, produced by over a dozen large suppliers. Formerly made by Hercules, grades specifically designed for dielectric applications are now produced by Himont U.S.A. with the trademark "Pro-fax."

Chemistry

This subject is covered in "Propylene Polymers" (p. 160) of Chapter 5, *Extrusion Compounds*.

Grades

There are few grades designed specifically for molded dielectric applications. A wide range of properties can be obtained, depending on whether a grade is composed of homopolymer, copolymers, or terpolymers. Only grades with the highest degree of purity are suitable for electrical/electronic uses. Homopolymers generally have the best dielectric properties. Copolymer and terpolymer grades have better thermal and impact properties. Grades with 20–30 percent glass fiber reinforcement show significantly improved tensile strength, impact strength, and deflection temperature. Military purchases are made to L-P-394, *Plastic Molding Material (Propylene Plastics, Injection & Extrusion)* and ASTM D 4101, *Specification for Propylene Plastic Injection and Extrusion Materials*.

Processing

Polypropylene may be processed with all conventional injection molding methods. Melt temperatures generally range from 400° to 450°F (205°–230°C), with mold temperatures between 50° and 105°F (10° and 40°C). Because of its low moisture absorption, it is not necessary to dry polypropylene compounds before molding.

Properties

Polypropylene, the most rigid polyolefin, is one of the lightest plastics, with specific gravity of 0.90, making it more economical to mold than most other resins. Dielectric properties and moisture resistance are among the best for all plastics. Polypropylene is a good gas barrier. It is insoluble in solvents at room temperatures, but will dissolve in aromatic and chlorinated solvents above 175°F (80°C). Polypropylene is attacked by chlorine, fuming nitric acid, and other strong oxidizing agents. However, it is highly resistant to environmental stress cracking, even when it comes into contact with solvents and polar materials. Polypropylene is heat sealable and nontoxic. Without modification, it burns readily and is degraded by heat and light. It has poor impact strength below 16°F (–9°C).

Table 3-27 shows key property values for this resin.

TABLE 3-27 Key Properties of Typical Heat-Resistant Polypropylene Homopolymer Molding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	0.90
Dielectric strength, 125 mils, short time, V/mil*	D 149	600
Dielectric constant*	D 150	
60 Hz		2.2
10^6 Hz		2.2
Dissipation factor*	D 150	
60 Hz		<0.0005
10^6 Hz		<0.0005
Volume resistivity, ohm·cm*	D 257	$>10^{16}$
Arc resistance*	D 495	150
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		<0.01
Deflection temperature, 264 psi, °F (°C)	D 648	140 (60)
Maximum recommended service temperature °F (°C)		250 (120)
Tensile strength at break, psi*	D 638	5,400
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		0.5
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		HB
FR grade		V-0
Oxygen index, %	D 2863	
Standard grade		18
FR grade		27

*At room temperature.

Electrical/Electronic Uses

Polypropylene is used extensively for motor vehicle connectors, fuse blocks, and other electrical components. Automotive battery cases are virtually all made from impact grade polypropylene, which is also used for appliance, tool, and equipment housings.

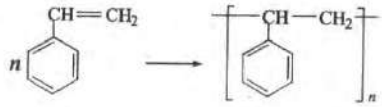
Styrenics: Polystyrene (PS) (Molding Resin)

The first general purpose polystyrene resins were marketed in the U.S. in 1939 by Dow Chemical, still the largest producer, using the trademark "Styron." Other producers of homopolymer grades include Amoco Performance Products, ARCO Chemical (Dylite™), Eastman Performance Plastics (Tenite™), Fina Oil & Chemical, Huntsman Chemical, Novacor Chemicals, and Phillips (Marlex™).

Chemistry

General purpose polystyrene is produced by polymerizing styrene monomer, obtained by dehydrogenation of ethyl benzene, into polymers of 100–20,000

monomer units. The reaction is initiated by organic peroxides, such as benzoyl peroxide, or thermally.



styrene monomer polystyrene

Grades

There are many commercially available grades of polystyrene with a wide range of molecular weights and specialized additives. Properties affected include melt flow rate, softening point, deflection temperature, tensile strength, and flammability. Military purchases are to ASTM D 4549, *Specification for Polystyrene Molding and Extrusion Materials*.

Processing

Polystyrene injection molding grades exhibit exceptionally low moisture absorption, and hence usually do not require drying before molding. Conventional injection molding machines are used to process polystyrene. Both molding temperature and molding cycle affect the quality of the molded piece. If the processing temperature is too low, pieces are likely to have a high degree of internal stress. Processing temperatures that are too high will degrade the polymer and its properties. Injection-molding temperatures typically range from 350° to 500°F (177°–260°C), depending on grade, part size, and molding equipment. Oven annealing is advised at 5° to 10°F (2.8°–5.6°C) below the heat distortion temperature.

Properties

General purpose polystyrene resins are noteworthy for their clarity, low moisture absorption, and low cost. Electrical properties are good. Unmodified grades, however, burn readily, have low impact strength, and are attacked by many organic chemicals. Polystyrene has a tendency to stress crack when exposed to certain chemicals while under stress. High temperatures hasten stress cracking. Reagents which cause severe stress cracking include:

- Butter
- Coconut oil
- Dimethyl-dichloro-vinyl phosphate
- Gasoline
- *n*-heptane
- Kerosene
- Turpentine

Polystyrene is resistant to attack by:

- Inorganic acids, except strong oxidizing acids
- Weak organic acids
- Alcohols
- Aliphatic amines
- Bases

Polystyrene is attacked by

- Aldehydes
- Aromatic amines
- Esters
- Chlorinated hydrocarbons
- Insecticides
- Ketones
- Essential oils

Solvents for polystyrene include aliphatic and aromatic hydrocarbons.

Table 3-28 shows key property values for polystyrene, polystyrene-butadiene, styrene acrylonitrile, and acrylonitrile-butadiene-styrene resins.

Electrical/Electronic Uses

The flammability, low impact strength, tendency to craze, and susceptibility to attack by hydrocarbons limit electrical/electronic applications. End uses include computer tape and video-cassette reels, and compact battery cases.

Styrenics: Styrene-Butadiene (Molding Resin)

The impact resistance of polystyrene may be significantly improved by polymerizing it with butadiene, forming a block copolymer. Producers include Dow Plastics and Phillips 66 (K-Resin™).

Chemistry

The major constituent, styrene, is polymerized with 1,3-butadiene in a solution process with an organolithium initiator.

Grades

Commercially available injection molding grades include: general purpose, high heat, easy flow, and flame-retardant modified. Military purchases are to L-P-398, *Plastic Molding Material, Styrene-butadiene.*

Processing

Impact polystyrene may be molded in conventional injection molding equipment without drying, except under high-humidity conditions. Material temperature should not

TABLE 3-28 Key Properties of Typical Polystyrene, Styrene-Butadiene, Styrene-Acrylonitrile, and Acrylonitrile-Butadiene-Styrene Molding Resins

	ASTM TEST METHOD	POLY-STYRENE VALUE	STYRENE-BUTADIENE VALUE	STYRENE-ACRYLO-NITRILE VALUE	ACRYLONITRILE-BUTADIENE-STYRENE VALUE
Specific gravity*	D 792	1.04	1.03	1.07	1.03
Dielectric strength, 125 mils, short time, V/mil*	D 149	500	400	425	425
Dielectric constant*	D 150				
60 Hz		2.5	2.5	2.6	2.6
10^6 Hz		2.4	2.4	2.6	2.6
Dissipation factor*	D 150				
60 Hz		0.0001	0.002	0.007	0.004
10^6 Hz		0.0001	0.002	0.007	0.004
Volume resistivity, Ω·cm*	D 257	$<1 \times 10^{16}$	$<1 \times 10^{16}$	$<1 \times 10^{16}$	2×10^{16}
Arc resistance*	D 495	65	50	115	100
Water absorption, 1/8 in thick specimen, %	D 570				
24 h @ 73°F (23°C)		0.02	0.06	0.20	0.22
Deflection temperature, 264 psi, °F (°C)	D 648	200 (93)	200 (93)	200 (93)	210** (99**)
Maximum recommended service temperature °F (°C)		160 (70)	150 (65)	180 (80)	200 (95)
Tensile strength at break, psi*	D 638	6,000	4,000	9,500	7,000
Izod impact strength	D 256				
Foot pounds per inch notched 1/8 in specimen*		0.4	2.5	0.40	6.0
Flammability ratings					
UL Standard 94, 1/16 in specimen					
Standard grade		HB	HB	HB	HB
FR grade		V-0	V-0	V-0	V-0/5V
Oxygen index, %	D 2863				
Standard grade		18	18	na	19
FR grade		na	28	na	na

*At room temperature.

**Annealed.

exceed 475°F (246°C), at which point toxic and corrosive gases can be given off, requiring operator protection and other safety precautions. Oven annealing is advised at 5° to 10°F (2.8°–5.6°C) below the heat distortion temperature.

Properties

Significant improvement in impact strength over crystal polystyrene is achieved in impact grades at the expense, however, of lower tensile values. Impact polystyrene will stress crack with certain reagents similar to crystal polystyrene.

Impact polystyrene is resistant to attack by:

- Organic acids
- Aliphatic amines
- Bases
- Salts

Impact polystyrene is attacked by:

- Aldehydes
- Aromatic amines
- Esters
- Aliphatic, aromatic, and chlorinated hydrocarbons

Table 3-28 shows key property values for polystyrene, polystyrene-butadiene, styrene acrylonitrile, and acrylonitrile-butadiene-styrene resins.

Electrical/Electronic Uses

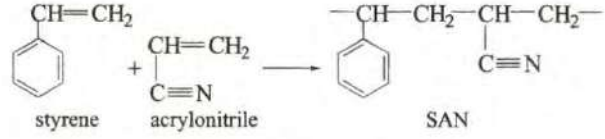
The improved impact resistance of impact polystyrene qualifies it for appliance parts, tape cartridges, cassette covers, and housings. Parts, however, have limited chemical resistance and, except for specialty grades, are flammable.

Styrenics: Styrene-Acrylonitrile (SAN) (Molding Resin)

While retaining excellent clarity, styrene-acrylonitrile has improved toughness, tensile strength, heat distortion, and chemical resistance over crystal polystyrene. Producers include BASF (Luran™), Dow Plastics (Tyril™), and Monsanto (Lustran™).

Chemistry

Styrene-acrylonitrile is produced by emulsion, suspension, or continuous mass copolymerization of styrene and acrylonitrile monomers. With increased molecular weight or acrylonitrile content, physical properties are improved, but processing ease is reduced and polymer color is increased:



styrene acrylonitrile SAN

Grades

Commercially available styrene-acrylonitrile grades include general purpose, easy flow, light stabilized, superior chemical resistance, 30 percent glass fiber reinforced, and flame retardant. Military purchases are to L-P-399, *Plastic Molding & Extrusion Material, Styrene Acrylonitrile Copolymers.*

Processing

All conventional injection molding equipment can produce satisfactory styrene-acrylonitrile parts. Resins should be dried prior to molding at 160° to 180°F (71°–82°C) for a period of 2 hours. Oven annealing is advised at 5° to 10°F (2.8°–5.6°C) below the heat distortion temperature.

Properties

Styrene-acrylonitrile resins have excellent transparency and colorability. Parts have hard, scratch-resistant surfaces. Water absorption is higher than crystal styrene or styrene-butadiene. General purpose grades are flammable. Styrene-acrylonitrile resins are compatible with other thermoplastics, and are used to modify and improve flow characteristics of acrylonitrile-butadiene-styrene, polyvinyl chloride, and other resins.

Styrene-acrylonitrile is resistant to attack by:

- Aliphatic hydrocarbons
- Nonoxidizing acids
- Bases
- Formaldehyde
- Gasoline
- Mineral oil
- Vegetable oils
- Most detergents

Styrene-acrylonitrile is attacked by:

- Glacial acetic acid
- Aromatic hydrocarbons
- Chlorinated hydrocarbons
- Esters
- Ketones
- Concentrated sulfuric acid

Solvents for styrene-acrylonitrile include methyl-ethyl-ketone and methylene chloride.

Table 3-28 shows key property values for polystyrene, polystyrene-butadiene, styrene-acrylonitrile, and acrylonitrile-butadiene-styrene resins.

Electrical/Electronic Uses

Applications include transmitter caps, battery cases, instrument covers, and meter lenses.

Styrenics: Acrylonitrile-Butadiene-Styrene (ABS) (Molding Resin)

By varying the proportions of acrylonitrile, butadiene, and styrene, a wide range of properties is obtainable, permitting resins to be tailored to specific end uses with empha-

sis on toughness. The major U.S. producers of acrylonitrile-butadiene-styrene resins are Dow Chemical (Magnum™), General Electric (Cycolac™), and Monsanto (Lustran™).

Chemistry

Acrylonitrile-butadiene-styrene resins may be made by emulsion, suspension, or mass polymerization methods. The most common process is graft polymerization in which styrene-acrylonitrile copolymer (SAN) is grafted on butadiene polymer. The continuous phase is styrene-acrylonitrile. Monomer components contribute the following properties:

- Acrylonitrile—heat stability, chemical resistance, aging resistance
- Butadiene—low temperature property retention, toughness, impact strength
- Styrene—processing ease, rigidity, gloss, low cost.

Flame retardancy is achieved by incorporating halogen additives or by alloying with polyvinyl chloride.

Acrylonitrile-butadiene-styrene is classed as an engineering thermoplastic.

Grades

Injection-molding grades include easy flow, medium impact, high impact, heat resistant, flame retardant, glass fiber reinforced, and plating. Military purchases are to ASTM D 4673, *Specification for Acrylonitrile Butadiene Styrene (ABS) Molding and Extrusion Materials*.

Processing

Conventional injection molding techniques can be used to process acrylonitrile-butadiene-styrene polymers. Resins should be dried at 180°F (82°C) for 2–4 hours just prior to molding. Melt temperatures should be 450° to 525°F (232°–274°C). Oven annealing is advised at 5° to 10°F (2.8°–5.6°C) below the heat distortion temperature.

Properties

As noted above, a wide range of properties is obtainable by varying the proportions of acrylonitrile, butadiene, and styrene polymers. Physical properties of acrylonitrile-butadiene-styrene resins are high. Resistance to ultraviolet light is poor.

Acrylonitrile-butadiene-styrene is resistant to attack by:

- Inorganic acids except strong oxidizing acids
- Organic acids
- Aliphatic amines
- Bases
- Polyglycols
- Salts

Acrylonitrile-butadiene-styrene is attacked by:

- Aldehydes
- Aromatic amines

- Polyglycol ethers
- Aliphatic, aromatic, and chlorinated hydrocarbons
- Ketones
- Essential oils

Solvents for acrylonitrile-butadiene-styrene include ketones, esters, and some chlorinated hydrocarbons.

Table 3-28 shows key property values for polystyrene, polystyrene-butadiene, styrene-acrylonitrile, and acrylonitrile-butadiene-styrene resins.

Electrical/Electronic Uses

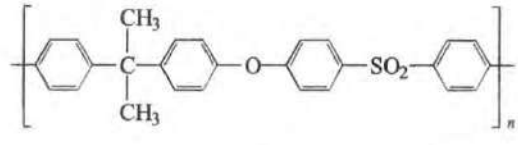
Most applications for acrylonitrile-butadiene-styrene take advantage of its strong mechanical properties. Electrical/electronic uses include business machine housings and components, telephones, conduit, and, when electroplated or vacuum metallized, shielding for electronic equipment.

Sulfone Polymers: Polysulfone (Molding Resin)

Polysulfone resins were introduced in 1965 by Union Carbide. They are now produced by Amoco Performance Products (Udel™) and by BASF (Ultrason S.™). These resins feature excellent heat- and water-resistant properties.

Chemistry

Polysulfone is made by reacting the sodium salt of bisphenol A with 4,4′-dichlorophenyl sulfone in dimethyl sulfoxide or similar polar solvent. The resulting polymer has the following structure:



Polysulfone is classed as an engineering thermoplastic.

Grades

Udel is available in transparent and opaque grades, and in UL 94V-0 natural or light beige translucent grades. Reinforced and filled grades containing glass fibers and spheres, carbon fibers, and polytetrafluoroethylene are available. Military purchases are to MIL-P-46120, *Plastic Molding and Extrusion Material, Polysulfone*.

Processing

Reciprocating screw injection molding equipment is preferred, although ram machines may also be used with the shot size between 30 and 50 percent of rated capacity. Stock

temperatures are usually in the 650° to 750°F (345°–400°C) range with cylinder temperatures 50° to 100°F (10°–40°C) lower in screw machines. Mold temperatures range from 200°F (95°C) for simple designs to 320°F (160°C) for complex parts. Polysulfone resins should be dried below 0.05 percent moisture content before molding. Drying for $3^1/_2$ hours at 275°F (135°C) is recommended.

Properties

Polysulfone resins exhibit high continuous use temperatures of up to 300°F (149°C), and are hydrolytically stable with long-term resistance to creep. Dielectric properties are maintained over a wide temperature and frequency range, and resistance to radiation is the highest for all polymers. Compared with polyether-sulfone, polysulfone has superior dielectric values and lower water absorption, but has lower thermal, mechanical, and flammability values.

Polysulfone resins are resistant to:

- Mineral acids (except concentrated strong acids)
- Alkalies in solution
- Salt solutions
- Aliphatic oils

Polysulfone resins are attacked by:

- Esters
- Ketones
- Aromatic and chlorinated hydrocarbons

Polysulfone resins are dissolved by halogenated hydrocarbons. Table 3-29 shows key property values for both polysulfone and polyethersulfone resins.

Electrical/Electronic Uses

Polysulfone resins are preferred for applications requiring high-temperature resistance and hydrolytic stability beyond the capability of most other thermoplastics. Because of stress cracking, they are not suitable for parts exposed to aromatic or halogenated hydrocarbons.

Examples of electrical/electronic applications include printed circuit boards, integrated circuit carriers, coil bobbins, connectors, bushings, terminal blocks, brush holders, alkaline battery cases and cells, TV and stereo components, and business machine parts.

Sulfone Polymers: Polyethersulfone (PES) (Molding Resin)

Polyethersulfone resins were introduced first in the United Kingdom and then in the United States in 1972–1973. They are produced by BASF with the trademark "Ultrason E" and are also marketed by ICI Americas with the trademark "Vitrex." Continuous use temperature index rating for unfilled resin by Underwriters Laboratories is 355°F (180°C), among the highest for any rated thermoplastic.

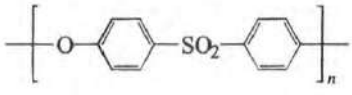
TABLE 3-29 Key Properties of Typical Polysulfone and Polyether-Sulfone Molding Resins

	ASTM TEST METHOD	POLY-SULFONE VALUE	POLYETHER-SULFONE VALUE
Specific gravity*	D 792	1.25	1.37
Dielectric strength, 125 mils, short time, V/mil*	D 149	425	400
Dielectric constant*	D 150		
60 Hz		3.1	3.5
10^6 Hz		3.0	3.5
Dissipation factor*	D 150		
60 Hz		0.0008	0.001
10^6 Hz		0.0034	0.004
Volume resistivity, Ω·cm*	D 257	1×10^{16}	$>1 \times 10^{17}$
Arc resistance*	D 495	122	70
Water absorption, 1/8 in thick specimen, %	D 570		
24 h @ 73°F (23°C)		0.3	0.43
Deflection temperature, 264 psi °F (°C)	D 648	345 (174)	397 (203)
Maximum recommended service temperature °F (°C)		300 (150)	355 (180)
Tensile strength at break, psi*	D 638	10,200	12,200
Izod impact strength	D 256		
Foot pounds per inch notched 1/8 in specimen*		1.3	1.2
Flammability ratings			
UL Standard 94, 1/16 in specimen			
Standard grade		V-2	V-0
FR grade		V-0	none needed
Oxygen index, %	D 2863		
Standard grade		30	38
FR grade		32	none needed

*At room temperature.

Chemistry

Polyethersulfone is made by Friedel Crafts reaction from diphenyletherchlorosulfone and has the following structure:



Polyethersulfone is classed as an engineering thermoplastic.

Grades

Injection molding grades of Victrex include the following:

- General purpose amber/transparent grade
- Higher viscosity grade with improved chemical and creep resistance, and slightly lower melt flow properties

- Filled grades with 20–30 percent glass fibers
- Easy-flow grades with 20–30 percent glass fibers

Military purchases are to MIL-P-46185, *Plastic Molding and Extrusion Materials, Polyethersulfone.*

Processing

A reciprocating screw injection molding machine is recommended. Barrel temperatures should be in the range of 644° to 680°F (340°–360°C) for general purpose grade and 680° to 734°F (360°–390°C) for glass-filled grades. Recommended mold temperature range is 248° to –320°F (120°–160°C). Resins should be dried at 300°F (149°C) for 3 hours before molding.

Properties

The outstanding property of polyethersulfone is its high use temperature. Electrical insulating properties are largely retained up to 355°F (180°C). Long-term load-bearing values, toughness, inherent low flammability, and mechanical strength are other noteworthy characteristics. Resistance to radiation is good, but resistance to UV light is poor. Compared with polysulfone, polyethersulfone has superior thermal, mechanical, and flammability values, but has poorer dielectric values and higher water absorption.

Polyethersulfone has good resistance to:

- Mineral acids
- Alkalis in solution
- Alcohols
- Most inorganic aqueous solutions
- Most oils and greases
- Gasolines

Polyethersulfone is attacked by:

- Esters
- Ketones
- Diester and phosphate based oils
- Chloroform
- Polar aromatic chemicals

Polyethersulfone dissolves in:

- N-methylpyrollidone
- Methylene chloride
- 1,1,2-trichloroethane
- Dimethylformamide

Table 3-29 shows key property values for both polyethersulfone and polysulfone resins.

Electrical/Electronic Uses

Polyethersulfone resins are suitable for demanding applications such as terminal blocks for aircraft, printed circuit boards, coil bobbins, switching and control components, and appliance housings subject to possible high temperatures under fault conditions.

4

Thermosetting Molding Compounds

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INTRODUCTION

The thermosetting plastics industry got its start in the first decade of the twentieth century as a result of the development work of Dr. Leo Bakeland, the inventor of phenolics, in Germany. As a tribute to him, these early thermosets were referred to as *bakelites*. Until the 1930s, thermoplastics were virtually unknown, so phenolics and succeeding thermosets had no competition until then for molded parts, especially electrical parts. It is unlikely that the electrical industry could have undergone its astonishing early growth without the availability of thermosets to make essential equipment such as switchgear, electrical controls, and wiring devices. The budding automotive industry also became dependent on thermosets for essential components of electrical systems, including magnetos, distributors, and batteries.

This chapter covers the basic thermosets used in forming parts by compression, transfer, and injection molding techniques. Thermosets used in embedding processes are covered in Chapter 16.

As used in this handbook, *thermoset* refers to an organic material capable of undergoing, or that has undergone, a polymerization or polycondensation reaction to form a rigid, infusible substance.

THERMOSETTING PLASTICS CONSUMED IN ELECTRICAL/ELECTRONIC APPLICATIONS

Table 4-1 shows 1993 U.S. consumption of principal thermosetting plastics in dielectric applications.

TABLE 4-1 1993 U.S. Consumption of Principal Thermosetting Plastics in the U.S.

MATERIAL	MILLION POUNDS
Epoxys (electrical laminates)	53
Phenolics	94
Polyesters, reinforced	55
Ureas	54
Total	256

Source: Modern Plastics Magazine.

POLYMERIZATION AND POLYCONDENSATION

Unlike thermoplastics, thermosets, when fully cured, lose their plasticity. Curing rate is controlled by heat and pressure, and may be aided by catalysts, which are unique for each polymer. Except for phenolics and aminos, which cure by polycondensation, other thermosets covered in this chapter cure by addition polymerization and crosslinking,

without emission of gaseous byproducts. Where gases are generated, provision for their venting must be incorporated in mold design. See "Polymerization" (p. 41) in Chapter 2, *Thermoplastic Molding Compounds*.

REINFORCEMENTS AND FILLERS, ANTIOXIDANTS, ULTRAVIOLET STABILIZERS

Thermosetting resins, by themselves, are brittle and of little practical value, but are made useful by compounding with reinforcements and fillers, which may constitute 50 percent or more of compound weight. Glass fibers and mineral fillers are most often used in electrical grade recipes. See "Reinforcements and Fillers" (p. 44) in Chapter 3, *Thermoplastic Molding Compounds*. Antioxidants and ultraviolet stabilizers are also covered in that chapter.

COMPRESSION MOLDING

The earliest production method for thermosetting compounds, compression molding, consists of placing a measured charge of material in a mold cavity, closing the mold, and applying heat and pressure to react the resin irreversibly, forming a rigid, infusible part. This process, however, has significant limitations and its use is specialized and mostly for low-volume production. Material charges must be handled individually, often for numerous, small cavities. Curing is slower than in the transfer molding method, especially for parts with thick walls. Pins and inserts in the cavity may be damaged by closing of the press on unheated compound. Compression molding is not well suited for intricate shapes where easy flow is required to fill the mold.

For certain applications, however, compression molding has noteworthy attributes. Tooling and capital equipment costs are lower than for transfer molding, and there is no wastage with sprues and runners. Fillers receive minimal damage in the molding process, and thus mechanical properties of molded parts are optimal. Clamping pressures are lower than for other methods, permitting more cavities per press of given tonnage. Finishing costs are minimal since there are no gate marks to remove.

Compression molding machines are hydraulically operated. Heat is applied by steam, hot oil, high-pressure water, gas flames, or, now most popular, by electrical heating coils, strips, or cartridges which permit higher temperatures and faster cycles.

TRANSFER MOLDING

The process most commonly employed for making parts from thermosetting compounds is transfer molding. A measured charge of suitably preheated material is placed in a chamber, or pot, from which it is forced (transferred) by a plunger through channels (sprues and runners) and past a gate into a closed cavity. Throughout this process, a temperature adequate for rapid curing is maintained. At the end of the curing cycle,

the part is ejected attached to the gates, sprues, and runners, which are then trimmed from the part.

Preheating of compound is usually done in dielectric heaters, although heat lamps and ovens are also used. Grades most suitable for transfer molding are of softer plasticity than materials for compression molding.

See the preceding section on "Compression Molding" for a discussion of relative merits of compression and transfer molding methods.

INJECTION MOLDING

The principal difference between injection molding thermoplastics and thermosets is that the former are heated to a fluid state and injected into the mold cavity where the part is shaped and cooled, while thermosets, after being heated to fluid state and injected into the mold cavity, undergo final curing at the specified elected temperature and for the required time period.

For thermosets, the temperature of material in the injection barrel is raised to a level just below the point where precure would occur by hot water or hot oil circulating through a jacket in the barrel and also by the shear friction action of the rotary screw. The last step in injection occurs as the screw rotation is stopped and the mechanism acts as a high-pressure plunger, driving the heated plasticated material through the barrel nozzle, the sprues and runners, and into the cavity. The controlled material flow rate in this stage is very rapid, generating considerable frictional heat which completes curing. The ejection of parts is similar to that of thermoplastic injection machines. See also "Injection Molding" (p. 46) in Chapter 3, *Thermoplastic Molding Compounds*.

STANDARD TESTS

Standard tests for thermosets are the same as for thermoplastics, described in Chapter 3, *Thermoplastic Molding Compounds*. This section covers ranking of thermosets by selected characteristics as shown in the table of key properties for each thermoset. It is important to note that properties listed are for commercially available grades and may vary from producer to producer for the same grade. (See Tables 4-2 through 4-13.)

TABLE 4-2 Specific Gravity of Thermosetting Compounds (23/23°C) (ASTM D 792)

COMPOUND	VALUE
Glass-filled allyl MIL-M-14G Type GDI-30	1.70
Glass-filled phenolic MIL-M-14G Type GPI-100	1.74
Glass-filled melamine MIL-M-14G Type MMI-30	1.92
Glass-filled epoxy electrical grade	1.92
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	2.07

TABLE 4-3 Dielectric Strength of Thermosetting Compounds (Short Time, 125 mils, volts/mil) (ASTM D 149)

COMPOUND	VALUE
Glass-filled allyl MIL-M-14G Type GDI-30	400
Glass-filled epoxy electrical grade	390
Glass-filled phenolic MIL-M-14G Type GPI-100	380
Glass-filled alkyd-polyester MIL-M-14G Type MAI-60	375
Glass-filled melamine MIL-M-14G Type MMI-30	340

TABLE 4-4 Dielectric Constant of Thermosetting Compounds (ASTM D 150)

COMPOUND	60 Hz	10^6 Hz
Glass-filled allyl MIL-M-14G Type GDI-30	4.2	3.5
Glass-filled epoxy electrical grade	5.0	4.6
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	5.3	4.6
Glass-filled phenolic MIL-M-14G Type GPI-100	6.0	5.0
Glass-filled melamine MIL-M-14G Type MMI-30	8.0	6.2

TABLE 4-5 Dissipation Factor of Thermosetting Compounds (ASTM D 150)

COMPOUND	10^6 Hz
Glass-filled epoxy electrical grade	0.01
Glass-filled allyl MIL-M-14G Type GDI-30	0.01
Glass-filled phenolic MIL-M-140G Type GPI-100	0.02
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	0.02
Glass-filled melamine MIL-M-14G Type MMI-30	0.02

TABLE 4-6 Volume Resistivity of Thermosetting Compounds (ASTM D 257)

COMPOUND	Ω·cm
Glass-filled epoxy electrical grade	1×10^{13}
Glass-filled allyl MIL-M-14G Type GDI-30	1×10^{13}
Glass-filled phenolic MIL-M-14G Type GPI-100	1×10^{13}
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	1×10^{13}
Glass-filled melamine MIL-M-14G Type MMI-30	2×10^{11}

TABLE 4-7 Arc Resistance of Thermosetting Compounds (ASTM D 495)

COMPOUND	SECONDS
Glass-filled epoxy electrical grade	187
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	180+
Glass-filled melamine MIL-M-14G Type MMI-30	180+
Glass-filled phenolic MIL-M-14G Type GPI-100	180
Glass-filled allyl MIL-M-14G Type GDI-30	140

TABLE 4-8 Water Absorption of Thermosetting Compounds (1/8 in Thick Specimen) (ASTM D 570)

COMPOUND	% GAIN IN WEIGHT AFTER 24 h @ 73°F (23°C)
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	0.07
Glass-filled phenolic MIL-M-14G Type GPI-100	0.15
Glass-filled epoxy electrical grade	0.20
Glass-filled allyl MIL-M-14G Type GDI-30	0.20
Glass-filled melamine MIL-M-14G Type MMI-30	0.40

TABLE 4-9 Deflection Temperature of Thermosetting Compounds (ASTM D 648)

	FLEXURAL LOAD 264 psi	
COMPOUND	°F	°C
Glass-filled allyl MIL-M-14G Type GDI-30	540	282
Glass-filled phenolic MIL-M-GPI-100	500+	260+
Glass-filled epoxy electrical grade	450	232
Glass-filled melamine MIL-M-14G Type MMI-30	440	227
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	400+	204+

TABLE 4-10 Maximum Recommended Service Temperature of Thermosetting Compounds

COMPOUND	°F	°C
Glass-filled allyl MIL-M-14G Type GDI-30	500	260
Glass-filled phenolic MIL-M-14G GPI-100	450	232
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	400	204
Glass-filled epoxy electrical grade	400	204
Glass-filled melamine MIL-M-14G Type MMI-30	400	204

TABLE 4-11 Tensile Strength of Thermosetting Compounds (ASTM D 638)

COMPOUND	PSI AT BREAK
Glass-filled epoxy electrical grade	10,500
Glass-filled allyl MIL-M-14G Type GDI-30	10,000
Glass-filled melamine MIL-M-14G Type MMI-30	8,000
Glass-filled phenolic MIL-M-GPI-100	7,500
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	6,000

TABLE 4-12 Izod Impact Strength of Thermosetting Compounds (Foot pounds per inch notched 1/8 in specimen) (ASTM D 256)

COMPOUND	VALUE
Glass-filled phenolic MIL-M-14G Type GPI-100	12
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	9.5
Glass-filled melamine MIL-M-14G Type MMI-30	5.5
Glass-filled allyl MIL-M-14G Type GDI-30	5.0
Glass-filled epoxy electrical grade	0.45

TABLE 4-13 Flammability Ratings of Thermosetting Compounds (UL Standard 94, 1/16 in specimen) (Standard Grades)

COMPOUND	RATING
Glass-filled epoxy electrical grade	V-0
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	V-0
Glass-filled phenolic MIL-M-14G Type GPI-100	V-0
Glass-filled melamine MIL-M-14G Type MMI-30	V-0
Glass-filled allyl MIL-M-14G Type GDI-30	HB

RELATIVE COSTS OF THERMOSETTING COMPOUNDS

The difference in specific volumes of two compounds considered equally suitable for an application is an indication of the higher price per pound the compound with lower specific gravity may carry while retaining the same part cost as the lower priced but heavier compound. See discussion of this subject in Chapter 3, *Thermoplastic Molding Compounds*, p. 63.

Table 4-14 shows cubic inches per pound for selected thermosetting compounds, from which are calculated price advantages of lighter compounds. For example, if the price of allyl compound were 21 percent higher than alkyd/polyester, part cost would be equal due to the higher specific volume of allyl (16.3 versus 13.4).

TABLE 4-14 Specific Volume and Cost Factor of Thermosetting Compounds

COMPOUND	CUBIC INCHES/lb*	% PRICE/lb DIFFERENCE FOR EQUAL PART COST
Glass-filled allyl MIL-M-14G Type GDI-30	16.3	21
Glass-filled phenolic MIL-M-14G Type GPI-100	15.9	19
Glass-filled melamine MIL-M-14G Type MMI-30	14.4	7
Glass-filled epoxy electrical grade	14.4	7
Glass-filled alkyd/polyester MIL-M-14G Type MAI-60	13.4	—

*Specific volume.

DEVELOPMENT PROGRAMS

The need for faster production methods for molding thermosetting compounds has resulted in new molding technologies. American Cyanamid has developed *cold sprue molding* especially well suited for molding small parts of alkyd/polyester compounds. Essentially, this method is a version of injection molding with a minimum of material loss. The sprue does not cure with the part and is injected into the cavity in the next cycle. However, there is a small runner which does cure with the part and must be trimmed after ejection. It is claimed that up to 500 cycles/hour can be achieved. Mold design is critical and must be tailored for this method.

Another technology (patented), designed to conserve material, is the *runnerless injection process (RIC)*. In this method, the mold is held open as in compression molding while the material is injected. After filling, the mold is closed, compression occurs, and curing takes place. It is claimed that material savings with this method averages about 30 percent.

MARKET TRENDS

Thermosetting compounds have been used successfully for many years in molding parts for all types of electrical equipment. It is expected that this usage will continue, following the primary trends in the electrical industry, but probably gradually losing market share to high-temperature thermoplastic compounds.

RANKING OF THERMOSETTING COMPOUNDS BY KEY PROPERTIES

Table 4-15 ranks thermosetting compounds according to characteristics listed in the table of key properties for each compound. Rankings range from 1, most favorable from an electrical insulation viewpoint, to 5, least favorable. Note that no compound ranks either highest or lowest in all properties. This table is intended as an aid to design engineers desiring to investigate compounds potentially suitable to meet critical criteria. However, consideration should be given to the fact that properties of each thermosetting type may vary significantly from listed values, depending on characteristics and amount of filler and also on certain additives.

TABLE 4-15 Ranking of Thermosetting Compounds by Key Property Values

	SPECIFIC GRAVITY	DIELECTRIC STRENGTH	DIELECTRIC CONSTANT	DISSIPATION FACTOR	VOLUME RESISTIVITY	ARC RESISTANCE	WATER ABSORPTION	DEFLECTION TEMPERATURE	MAXIMUM SERVICE TEMPERATURE	TENSILE STRENGTH	IZOD IMPACT STRENGTH	UL 94 FLAMMABILITY[a]
Alkyd/polyester	5	4	3	3	1	2	1	5	3	5	2	1
Allyl	1	1	1	1	1	5	3	1	1	2	4	5
Melamine	3	5	5	3	5	3	5	4	3	3	3	1
Epoxy (Novolac)	3	2	2	1	1	1	3	3	3	1	5	1
Phenolic	2	3	4	3	1	4	2	2	2	4	1	1

[a]Number 1 = V-0
5 = HB

FEDERAL SPECIFICATION MIL-M-14

The title of this specification is *Molding Plastics and Molded Plastic Parts*. This specification is approved for use by all departments and agencies of the Department of Defense, and it covers the basic properties of molding compounds and the methods suited to their satisfactory determination. The appendix covers requirements for parts molded from such compounds, together with procedures for inspection of such parts. The types of compounds for each thermosetting resin are listed in the section for that resin in this chapter.

PRINCIPAL THERMOSETTING COMPOUNDS FOR ELECTRICAL/ELECTRONIC USES

The chemistry, grades, processing, properties, and electrical/electronic uses of principal thermosetting compounds are described in the sections which follow. The values

shown in tables are for electrical grades, where possible those defined by MIL-M-14G Specification.

The following resins are covered:

- Alkyds/polyesters
- Allyls
- Aminos
- Epoxies
- Phenolics

Alkyds/Polyesters (Molding Resins)

Alkyds, also called thermosetting polyesters, are complex resins, many of which are used extensively in electrical/electronic applications. Producers include American Cyanamid, Glastic, Hasite, Premix, Quantum Composites, and Plastics Engineering.

Chemistry

Alkyds are formulated from unsaturated polyesters combined with free-radical-producing peroxide catalysts and unsaturated monomers, for example, diallyl phthalate or vinyl toluene. Polyesters are the condensation reaction products of polyfunctional alcohols and dibasic organic acids. The crosslinking between polyester and monomer is initiated by heat and the catalyst. This is an addition reaction giving off no volatile products. A multitude of complex resins may thus be formulated from numerous suitable and readily available alcohols, acids, and monomers. The terms *alkyd* and *polyester* are often used interchangeably in connection with molding resins. When referring to varnish resins, the term *alkyd* applies to polyesters modified with drying oils.

Grades

MIL-M-14G lists the following grades for alkyd/polyester compounds:

- *Type MAG.* A mineral-filled compound for use where good dielectric properties and arc resistance are required.
- *Type MAI-60.* A glass-fiber-filled compound for use where high-impact strength, *good dielectric properties*, and arc resistance are required.
- *Type MAT-30.* A heat-resistant, track-resistant, flame-resistant, high-impact, mineral-filled glass-reinforced compound. Impact strength is about 3.0 foot pounds per inch notch.
- *Type MAI-30.* A mineral-filled, glass-fiber reinforced compound having excellent handling and molding characteristics. It is an arc-resistant, flame-resistant, heat-resistant, high-impact compound having good mechanical and excellent electrical characteristics.

Processing

Alkyd compounds may be successfully molded by compression, transfer, injection, and runnerless injection equipment. Compounds go through a low-viscosity phase of short duration, enabling the mold to be filled at lower pressures than are required for other thermosetting compounds. The reaction is exothermic and curing is rapid. Molding temperatures depend somewhat on the catalyst employed, and range from 270° to 380°F (132°–193°C). Preheating, while not necessary, improves flow characteristics and curing rate. Preheating may be done in an air circulating oven or in an electronic preheater. Temperature should not exceed 140°F (60°C).

Polymerization reaction of unfilled reactants is highly exothermic, making them unsuitable for molding accurate parts because of excessive shrinkage on cooling. Thus, mineral fillers and glass fiber reinforcements are required to moderate the reaction and control shrinkage.

Properties

Over a wide temperature range, alkyds exhibit excellent electrical properties, mechanical strength, and dimensional stability. Arc resistance is high. As with all thermoset-

TABLE 4-16 Key Properties of Glass-filled Alkyd/Polyester Molding Resin (MIL-M-14G Type MAI-60)

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	2.07
Dielectric strength, 125 mils, short time, V/mil*	D 149	375
Dielectric constant*	D 150	
60 Hz		5.6
10^6 Hz		4.6
Dissipation factor*	D 150	
60 Hz		0.10
10^6 Hz		0.02
Volume resistivity, Ω·cm*	D 257	1×10^{13}
Arc resistance, seconds*	D 495	180+
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.07
Deflection temperature, 264 psi, °F (°C)	D 648	400+ (204+)
Maximum recommended service temperature °F (°C)		400 (204)
Tensile strength at break, psi*	D 638	6,000
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		9.5
Flammability ratings		
UL standard 94, 1/16 in specimen		
Standard grades		V-0
Oxygen index %	D 2863	
Standard grades		63

*At room temperature.

ting compounds, properties vary significantly with types and amounts of fillers and other ingredients, and also with molding method. For outdoor exposure, recipes should include an ultraviolet light absorber, such as 2-hydrobenzophenone.

The resistance to attack by most chemicals varies from poor to good, depending on compound formulation. All grades are attacked by oxidizing acids, aromatic and halogenated hydrocarbons, esters, and ketones.

Table 4-16 shows key property values for electrical grade alkyd compounds.

Electrical/Electronic Uses

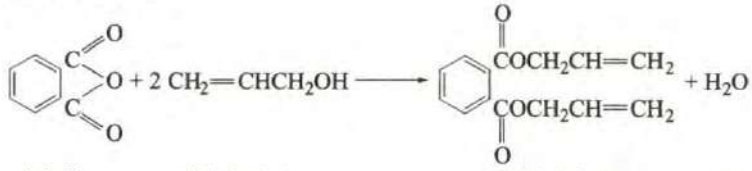
Alkyds are used extensively in electrical/electronic products, including brush holders, distributor caps, circuit breakers, relays, switches, connectors, terminal boards, and housings.

Allyls (Molding Resins)

Allyl molding compounds are usually sold under military specifications for critical electrical and electronic applications where superior dielectric and thermal properties are required. Principal suppliers include Occidental (Durez™), Rogers, and Quantum Composites.

Chemistry

The two most commonly encountered allyls are diallyl phthalate (DAP) and diallyl isophthalate (DIAP), prepared by esterification of phthalic anhydrides with allyl alcohol in an acid medium:



phthalic anhydride — allyl alcohol — diallyl phthalate — water

Polymerization is by addition with crosslinking, aided by a peroxide catalyst.

The major difference in properties between diallyl phthalate and diallyl isophthalate is that diallyl isophthalate will withstand significantly higher operating temperatures up to 500°F (260°C) versus 400°F (204°C) for diallyl phthalate. This advantage is obtained at considerable increase in resin price.

Grades

MIL-M-14G lists the following grades for allyl compounds:

- *Type GDI-30.* A glass-fiber-filled diallyl phthalate resin of low loss, high dielectric strength, low shrinkage, excellent moisture resistance, and relatively high impact strength.

- *Type GDI-30F.* A resin for applications where flame retardancy is at a maximum.
- *Type MDG.* A mineral-filled compound for use where good dielectric properties and low shrinkage are required.
- *Type SDG.* A glass-filled compound of low loss, high dielectric strength, low shrinkage, and good moisture resistance. Impact strength is relatively low.
- *Type SDG-F.* A glass-filled compound of low loss, high dielectric strength, low shrinkage, flame resistance, and good moisture resistance. Impact strength is relatively low.
- *Type SDI-5.* An acrylic polymer fiber-filled compound of low loss, high dielectric strength, low shrinkage, excellent moisture resistance, and moderate impact strength.
- *Type SDI-30.* A polyethylene terephthalate fiber-filled compound of low loss, high dielectric strength, low shrinkage, very good moisture resistance, and high impact strength.

A full range of colors is available in most compounds.

Processing

Allyl resins may be processed easily by all techniques suitable for thermosetting compounds. The curing reaction is a chemical crosslinking polymerization (not a polycondensation), without formation of volatiles which occurs with phenolics.

Strength of transfer molded parts is usually somewhat lower and shrinkage is somewhat higher than that of parts molded by compression. Recommended range of mold temperatures is 290° to 320°F (143°–160°C). In molding large parts, intricate parts, or parts with inserts, preheating of compounds is necessary for optimum appearance, minimum cycle time, and low scrap loss. Post-curing is recommended, starting at 275°F (135°C) and rising to at least the maximum temperature encountered in service.

Properties

Allyls have outstanding dielectric properties and selected grades have good arc resistance. They retain these properties at elevated temperatures, and are virtually unaffected by high-humidity conditions. Dimensional stability throughout a wide temperature range is excellent, and post-molding shrinkage is negligible for most parts. Resistance to attack by most chemicals is good. Exceptions are strong inorganic acids and bases, toluene, and some paint removers.

Table 4-17 shows key property values for electrical grade allyl compounds.

Electrical/Electronic Uses

Allyls are used extensively for high reliability connectors, switches, and terminal boards. Other applications include tuner strips, brush holders, motor starter blocks, cases and housings, and parts for aerospace vehicles and missiles.

TABLE 4-17 Key Properties of Glass-Filled Allyl Molding Resin (MIL-M-14G Type GDI-30)

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.70
Dielectric strength, 125 mils, short time, V/mil*	D 149	400
Dielectric constant*	D 150	
60 Hz		4.2
10^6 Hz		3.5
Dissipation factor*	D 150	
60 Hz		0.004
10^6 Hz		0.01
Volume resistivity, Ω·cm*	D 257	1×10^{13}
Arc resistance, seconds*	D 495	140
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		<0.20
Deflection temperature, 264 psi, °F (°C)	D 648	540 (282)
Maximum recommended service temperature °F (°C)		500 (260)
Tensile strength at break, psi*	D 638	10,000
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		5.0
Flammability ratings		
UL standard 94, 1/16 in specimen		
Standard grades		HB
FR grades		V-0
Oxygen index %	D 2863	
Standard grades		26–32
FR grades		36

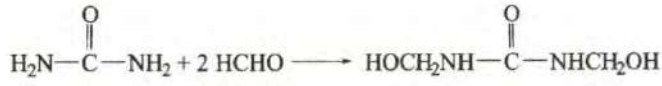
*At room temperature.

Aminos (Molding Resins)

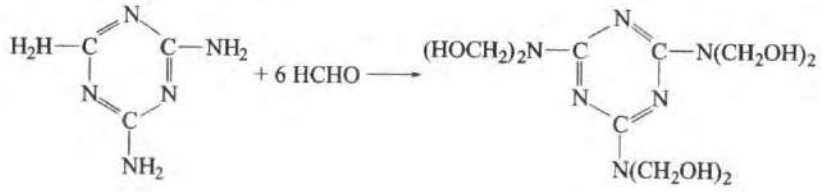
The most widely used amino resins are urea formaldehyde (urea) and melamine formaldehyde (melamine). Principal producers of electrical grade compounds include BTL Specialty Resins, ICI Fiberite, Neste Resins, and Plastics Engineering (Plenco™).

Chemistry

One mole of urea combines with two moles of formaldehyde under neutral or mildly alkaline conditions to form dimethylolurea:



Likewise, one mole of melamine combines with up to six moles of formaldehyde to form hexamethylol melamine:



melamine formaldehyde hexamethylol melamine

These addition products condense in the presence of an acid catalyst to form highly crosslinked urea and melamine resins with water as a byproduct.

Grades

Melamine compounds are generally superior to urea compounds in resistance to acids, alkalis, heat, and boiling water. Parts made of urea shrink on aging and tend to crack, especially around inserts and sharp corners. Melamine exhibits these characteristics to a lesser extent, and is usually preferred for critical electrical applications. MIL-M-14G does not list urea grades, but lists the following grades for melamine compounds:

- *Type CMG.* A cellulose-filled, general purpose compound with good dielectric and mechanical properties, for use where good arc resistance is required.
- *Type CMI-5.* A cellulose-filled, moderate impact compound with good all-around mechanical properties for use where resistance to arcing and moderate impact are required.
- *Type CMI-10.* A cellulose-filled, moderate impact phenol modified compound with good all-around mechanical properties suitable for tableware and similar applications. It is not intended for electrical use.
- *Type MME.* A mineral-filled compound for use where good dielectric properties and arc and flame resistance are required. Of the melamine compounds, this is the most dimensionally stable.
- *Type MMI-5.* A glass-fiber-filled compound of lower impact strength and higher dielectric constant and dissipation factor at 1 megacycle than Type MMI-30. It has superior moldability than Type MMI-30. Impact strength is approximately 0.5 foot-pounds per inch notch.
- *Type MMI-30.* A glass-fiber-filled compound of high impact strength for use where heat resistance, arc resistance, and flame resistance are required.

A full range of colors in most compounds is available.

Processing

Amino compounds are suitable for use with compression and transfer molding equipment. Molding temperatures from 260° to 340°F (127°–171°C) are used for ureas with

slightly higher temperatures for melamines. Melamine compounds may be effectively preheated to 200° to 250°F (93°–121°C) by high-frequency heaters. Urea compounds are usually not preheated.

Properties

Alpha cellulose-filled amino resins are among the hardest, most rigid, abrasion-resistant plastics available, and in the case of melamines, these properties are relatively unaffected between –70° and 210°F (–57°–99°C). Ureas are not recommended for use above 170°F (77°C). Melamines, but not ureas, may be used in outdoor environments. Both urea and melamine resins are classed as self-extinguishing. Shrinkage of parts during and after molding, especially for ureas, may present problems with dimensional stability and lead to development of cracks on aging or cycling between dry and wet condition or hot and cold temperatures.

Amino resins are attacked by strong mineral acids and bases, and by sodium hypochlorite solutions. Otherwise, resistance to chemicals is high.

Table 4-18 shows key property values for electrical grade melamine compounds.

TABLE 4-18 Key Properties of Glass-Filled Melamine Molding Resin (MIL-M-14G Type MMI-30)

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.92
Dielectric strength, 125 mils, short time, V/mil*	D 149	300
Dielectric constant*	D 150	
60 Hz		8.0
10^6 Hz		6.2
Dissipation factor*	D 150	
60 Hz		na
10^6 Hz		0.02
Volume resistivity, Ω·cm*	D 257	2×10^{11}
Arc resistance, seconds*	D 495	180+
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.40
Deflection temperature, 264 psi, °F (°C)	D 648	440 (227)
Maximum recommended service temperature °F (°C)		400 (204)
Tensile strength at break, psi*	D 638	8,000
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		5.5
Flammability ratings		
UL standard 94, 1/16 in specimen		
Standard grades		V-0
Oxygen index %	D 2863	
Standard grades		na

*At room temperature.

na = not available.

Electrical/Electronic Uses

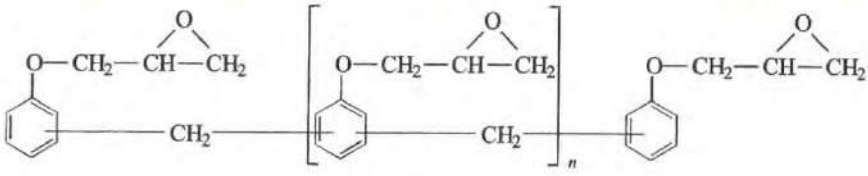
Applications for amino resins include switchgear, wiring devices, appliance housings and knobs, engine ignition parts, terminal strips, and sockets.

Epoxies (Molding Resins)

Epoxies in many forms are among the most widely used dielectrics. This section covers electrical grade solid epoxy molding compounds. Producers of resins for these compounds include Ciba-Geigy, and Dow Plastics. Electrical grade epoxy compounders include, in addition to the above, ICI, Fiberite, and Rogers. For information on epoxies in embedding compounds, coatings and impregnants, and clad and unclad structures, see appropriate chapters.

Chemistry

The epoxide group, $-CH\overset{O}{\diagdown\diagup}CH_2$, serves as a terminal linear polymerization point in all epoxy resins. Crosslinking of epoxide molecules occurs at the epoxide group and also at hydroxyl groups that may be present in the molecule. The epoxy resins generally used to make solid molding compounds are epoxy novolacs. Novolacs, formed by reaction of phenol or ortho-cresol with formaldehyde under acidic conditions (see discussion in the next section on "Phenolics"), are reacted with epichlorohydrin to form epoxy novolacs:



average value for *n*, 1.6
epoxy functionality, 3.6

epoxy phenol novolac

For a discussion of hardeners necessary for curing epoxies, see "Epoxies" (p. 183) of Chapter 6, *Embedding Compounds*.

Grades

Both phenol and ortho-cresol epoxy novolacs are available with glass fiber or mineral reinforcements. Military purchases are made to MIL-P-46892, *Plastic Molding Material, Epoxy, Glass Fiber*.

Processing

Conventional preheating, automatic preforming, compression and transfer molding methods are suitable for molding epoxy compounds. Recommended molding temperature range is 290° to 350°F (143°–177°C). Compounds do not require special handling.

Properties

Parts molded from electrical grade epoxy compounds exhibit outstanding dimensional stability and retention of electrical properties with virtually no outgassing at temperatures up to 500°F (260°C).

Epoxies are resistant to attack by most chemicals. Exceptions include phenols, ketones, ethers, and concentrated organic and inorganic acids.

Table 4-19 shows key property values for electrical grade epoxy compounds.

TABLE 4-19 Key Properties of Glass-Filled Epoxy Molding Resin Electrical Grade

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.92
Dielectric strength, 125 mils, short time, V/mil*	D 149	390
Dielectric constant*	D 150	
60 Hz		5.0
10^6 Hz		4.6
Dissipation factor*	D 150	
60 Hz		0.01
10^6 Hz		0.01
Volume resistivity, Ω·cm*	D 257	1×10^{13}
Arc resistance, seconds*	D 495	187
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		<0.20
Deflection temperature, 264 psi, °F (°C)	D 648	450 (232)
Maximum recommended service temperature °F (°C)		400 (204)
Tensile strength at break, psi*	D 638	10,500
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		0.45
Flammability ratings		
UL standard 94, 1/16 in specimen		
Standard grades		V-0
Oxygen index %	D 2863	
Standard grades		35

*At room temperature.

Electrical/Electronic Uses

Important applications of epoxy molding compounds include bobbins, connectors, and a variety of electrical and electronic components.

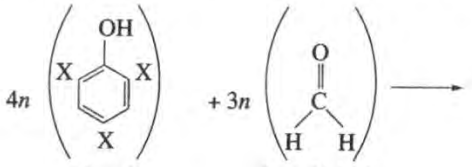
Phenolics/Furfurals (Molding Resins)

Phenolics, developed in Belgium by Leo Baekeland, were the first commercially available plastics and continue to be used in a wide variety of heavy duty electrical appli-

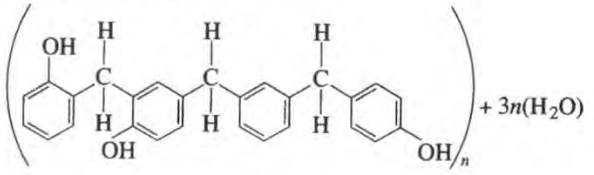
cations. Major producers include ICI Fiberite, Occidental Chemical (Durez™), Plastics Engineering (Plenco™), Resinoid Engineering, Rogers, and Valite.

Chemistry and Processing

Pure phenolic resin is the condensation reaction product of phenol and formaldehyde:



phenol (active points at X) formaldehyde



typical (intermediate) condensation product

The molecular ratio of formaldehyde-to-phenol in a typical intermediate is less than one-to-one, for example, three-to-four as in the above illustration. Crosslinking occurs as molecular size increases, tending to make the material hard and infusible.

The problem in making phenolic resins is to control the formaldehyde-to-phenol ratio so that the material is moldable when it goes into the mold, yet is hard, infusible, and serviceable after curing and removal from the mold. The usual method is by a two-step process, which utilizes an acid catalyst. The reaction, once started, is exothermic. The water formed is removed by vacuum distillation. The resulting resin is an amber-colored, brittle, "A-stage" resin, or *novolac* (also *novolak*) which is fusible, thermoplastic, soluble in alcohol and ketones, and can be used as a key ingredient of high-quality synthetic varnishes as well as to make molding resins.

The novolac resin is converted into a molding compound by grinding into a fine powder and then mixing with a filler, a pigment, or a dye; a mold lubricant such as aluminum stearate; and hexamethylenetetramine (hexa). During molding, the hot mold decomposes the hexa into formaldehyde and ammonia. The ammonia acts as a catalyst for crosslink formation, and the formaldehyde begins to react, forming complex three-dimensional networks. The resulting material has the desired characteristics attributed to phenolics. Steam formed in the condensation reaction will cause bubbles, voids, and porosity unless sufficient counterpressure is used. Typical molding conditions are 325°F (163°C) and 1500 pounds per square inch pressure for 2 minutes.

There is also a one-step process in which alkali is used as a catalyst and about 1.2 moles of formaldehyde is introduced per mole of phenol. Condensation reaction proceeds more slowly than with acid catalyst, and is controlled by temperature. To produce a molding resin, the reaction is stopped in the early B-stage by cooling. The

resin is then ground and mixed with a filler, a pigment, or a dye, and a lubricant, but not with hexa. The reaction is completed in the mold as in the two-step process. It is claimed by some advocates of this process that it is lower in cost and its resins contain less residual phenol and catalyst, thereby imparting less odor, taste, and tarnish on inserts.

Molding may be carried out in any one of several ways:

- Compression molding with cold powder or radio frequency heated preforms, including use of automatic rotary presses
- Transfer molding with radio frequency heated pills
- Automatic injection molding of parts without inserts, offering advantages in cycle time, material utilization, and other manufacturing costs
- Runnerless injection compression process, a patented method in which the mold is held open while the compound is injected with little or no pressure, after which the mold is closed and compression occurs

Furfural resins are based on furfuraldehyde (C_4H_4O–CHO) rather than formaldehyde, and have the unique molding property of having their cure going almost directly from the A-stage to the C-stage without the intermediate B, or gel stage. Thus, they flow and fill a mold readily, then congeal rapidly on reaching cure temperature. This is an important advantage in molding complex objects with metal inserts which must not be deformed or disturbed, as in the molding of large radio cabinets.

Grades

By itself, pure phenolic resin is too brittle, or friable, for practical use. When compounded approximately 50 percent with fibrous fillers, however, utility is enhanced dramatically. The following phenolic compounds are classified by Military Specification MIL-M-14G:

- *Type CFG.* A general purpose, wood-flour-filled compound intended for applications requiring good dielectric properties with mechanical properties better than acceptable minimum. Preheating the molding compound is advisable and improves the electrical properties. Moldability of this material is excellent.
- *Type CFI-15.* A moderate-impact, cotton- or paper-filled compound intended for use where good all-around mechanical properties are required. Impact strength is approximately 0.5 foot-pounds per inch notch.
- *Type CFI-10.* A medium-impact, cotton rag-filled compound providing good finish. Impact strength is approximately 1.0 foot-pounds per inch notch.
- *Type CFI-20.* A high-impact, rag- or cotton-filled compound providing good finish. Impact strength is approximately 2.0 foot-pounds per inch notch.
- *Type CFI-30.* A high-impact, cotton-filled compound, providing good finish. Impact strength is approximately 3.0 foot-pounds per inch notch.
- *Type CFI-40.* The highest impact grade of cotton-filled compound. Impact strength is approximately 4.0 foot-pounds per inch notch.

• *Type MFA-30.* A heat-resistant, arc-resistant, flame-resistant, high-impact, asbestos-filled compound. Impact strength is approximately 3.0 foot-pounds per inch notch.

• *Type MFE.* A low-loss, high-dielectric-strength, low-water absorption, mineral-filled compound intended for applications requiring the best dielectric properties for a phenolic material. To secure optimum dielectric properties, this compound should be preheated immediately before molding. Care should be taken, however, to prevent precuring.

• *Type MFG.* A general purpose, asbestos-filled compound intended for applications requiring good mechanical and heat-resistant properties.

• *Type MFH.* A mineral-filled compound intended for applications requiring highest heat resistance. Mechanical properties are relatively low.

• *Type MFI-10.* A heat-resistant, medium-impact, asbestos-filled compound. Impact strength is approximately 1.0 foot-pounds per inch notch.

• *Type MFI-20.* A heat-resistant, high-impact, asbestos-filled compound. Impact strength is approximately 2.0 foot-pounds per inch notch.

TABLE 4-20 Key Properties of Glass-Filled Phenolic Molding Resin (MIL-M-14G Type GPI-100)

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.74
Dielectric strength, 125 mils, short time, V/mil*	D 149	380
Dielectric constant*	D 150	
60 Hz		6.0
10^6 Hz		5.0
Dissipation factor*	D 150	
60 Hz		na
10^6 Hz		0.02
Volume resistivity, Ω·cm*	D 257	1×10^{13}
Arc resistance, seconds*	D 495	180
Water absorption, $^1/_8$ in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.15
Deflection temperature, 264 psi, °F (°C)	D 648	500+ (260+)
Maximum recommended service temperature °F (°C)		450 (232)
Tensile strength at break, psi*	D 638	7,500
Izod impact strength	D 256	
Foot pounds per inch notched $^1/_8$ in specimen*		12
Flammability ratings		
UL Standard 94, $^1/_{16}$ in specimen		
Standard grades		V-0
Oxygen index %	D 2863	
Standard grades		45–60

*At room temperature.

• *Type GPI-100.* A glass-fiber-filled compound with high impact strength and good dielectric properties. Impact strength is approximately 10.0 foot-pounds per inch notch.

Military purchases are also made to MIL-P-82650, *Plastic Molding Material, Glass Phenolic*, ASTM D 4617, *Specification for Phenolic Compounds (PF)* includes sections on classification, requirements, and testing.

Properties

As may be noted from the above description of grades, a material specialist has many options in selecting a phenolic resin for a specific end use. In general, phenolics are among the lowest priced resins. Processing costs are also relatively low. Resistance to deformation under load is high, and service temperatures as high as 550°F (288°C) are possible for special grades and certain applications. Dielectric properties are well suited to heavy duty electrical apparatus. Resistance to weathering is excellent. Compounds are inherently flame-retardant. Disadvantages of phenolics include volatiles released during molding and limited color choices in dark shades.

Phenolics are resistant to attack by most chemicals, but have poor resistance to bases and oxidizing acids.

Table 4-20 shows key property values for electrical grade phenolic compounds.

Electrical/Electronic Uses

Long the workhorse for heavy-duty electrical apparatus insulation, such as in switchgear and electrical controls, phenolics are widely used for cases, connectors, wiring devices, panels, bases, and hermetically sealed electrical equipment.

5

Extrusion Compounds

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INTRODUCTION

Since World War II, extruded plastics have become the principal dielectrics in the manufacture of wires, cords, and cables. It is convenient to classify these materials into three groups:

- High-temperature insulations, including fluoropolymers and silicone rubber
- Low-temperature insulations, including polyolefins and polyvinyl chloride
- Elastomers, used primarily as jackets but also as insulation on low-voltage cords and cables.

This chapter contains tables comparing key properties of materials within each group. The text also discusses fluoropolymers and elastomers as separate groups. Although there is close likeness in chemical structure of polyethylenes and polypropylene, individual members of this family are discussed separately and at length to highlight differences as well as similarities in characteristics and end uses. Polyvinyl chloride and silicone rubber are also discussed separately with emphasis on the compounding of polyvinyl chloride and because of the unique chemical structure of silicone rubber.

CONDUCTORS

Wires, cords, and cables provide the means for transmitting electrical power from the point of its generation to the point where it energizes electrical and electronic equipment essential to virtually every aspect of modern life.

Copper, electrolytically refined to 99.9 percent purity, has traditionally been the principal conductor metal. In the refining process, traces of copper oxide are removed to produce oxygen-free high-conductivity copper (OFHC). Cast copper bars at temperatures up to 1,700°F (927°C) are rolled into rods, which are then drawn through successively smaller dies to the desired wire gauge. Finally, the wire is annealed to the required ductility. The American Society for Testing and Materials (ASTM) has developed specifications for the wire-making process.

Conductors with greater strength than copper alone are made by fabricating wire with a steel core and copper skin by molten welding of copper to steel, by electroplating copper over steel, or by metallurgically bonding the two metals. Copper-clad wire may be annealed for greater flexibility or hard drawn for greater strength. At high frequencies, conductivity is the same as for copper alone, since high-frequency currents travel along the outer skin of a conductor. At power frequencies, conductivity is 30 to 40 percent of equal gauge copper wire.

At higher cost, copper alloys, with 80 to 85 percent the conductivity of copper, may be used for special applications where weight, strength, and space are critical. Most commonly used are alloys with cadmium, cadmium–chromium, chromium, and zirconium. Cadmium–chromium copper is noted for high conductivity combined with high tensile strength.

Aluminum is also widely used as a conductor metal where weight is the principal consideration. It is 30 percent the weight of an equal volume of copper, but has only 61.8 percent the conductivity of copper. To obtain equivalent current-carrying capacity,

the diameters of aluminum conductors must be increased more than 50 percent over copper conductors. The susceptibility to corrosion discourages the use of aluminum in communication, instrumentation, and control cables. Copper conductors are the norm for power plant circuits.

Tensile strength of annealed copper is about 36,000 psi and of annealed aluminum 10,000 psi. Tensile strengths up to 58,000 psi are obtainable from copper-clad steel and copper alloys. Because of the cost of energy to anneal drawn conductors, three-quarters to full hard copper and aluminum are furnished in power cable. Their tensile strengths are correspondingly higher.

Wire sizes are designated by the American Wire Gauge System (AWG), designed by J. R. Brown of Brown & Sharp in 1857. In this system, the higher the AWG number, the smaller the diameter of the wire. Numbers typically range from AWG 44 (0.0019 inch) to AWG 4/0 (0.4554 inch). See also the tables in "Magnet Wire Data" (p. 210) of Chapter 7, *Magnet Wire Enamels*. The convenient part of the system is that successive sizes represent approximately one reduction in die size in the wire drawing operation. Another convenient part is that an increase of two conductor sizes is required when substituting aluminum for copper for comparable conductivities. Note also that an increase (or decrease) of three sizes, halves (or doubles) the cross section in circular mils, and doubles (or halves) the resistance. A circular mil is the area of a circle 1 mil in diameter and is equal to 0.784 mil^2. The area of a solid conductor in circular mils is the square of its diameter in mils.

TEMPERATURE COEFFICIENT OF RESISTANCE

Temperature has a significant effect on the resistance of a conductor, with dc resistance increasing with temperature according to the formula:

$$R_t = R_o[1 + \alpha(t - t_o)]$$

where

R_t = Resistance as measured at temperature t
R_o = Resistance at reference temperature t_o
α = Temperature coefficient of resistance at t_o
t = Temperature at which measurement is made
t_o = Reference temperature

At 20°C (68°F) with copper having 100 percent conductivity, α = 0.00393/°C (0.00218/°F).

AMPACITY

Current-carrying capacity, or ampacity, measures the current an insulated conductor can safely carry without exceeding its insulation and jacket temperature limitations. This property is unique for each wire, cord, or cable construction, and is influenced by

conductor material and cross-sectional area, ambient temperature, thermal conductivity and thickness of insulation, ability of construction to dissipate heat after installation, and the number of conductors in the construction. From a practical point of view, this property is a paramount factor in design of insulated conductors and is of greater significance than conductivity values.

INSULATED CONDUCTOR DESIGN

The design of insulated conductors is often complex and involves several elements:

- *Selection of conductor metal.* The choice is usually between copper and aluminum, and is greatly influenced by cost of the completed construction, and not just metal prices. Aluminum, with 61.8 percent the conductivity of copper, requires larger wire sizes for equal current-carrying capacity, with resultant significant increase in overall diameter and usage of other materials. However, aluminum is only 30 percent the weight of copper, requires no plating (copper does at temperatures over 200°C), and may be anodized, adding dielectric properties and mechanical protection.
- *Choice of solid or stranded conductor.* Stranded wires, used for all but small conductor sizes, provide greater flexibility and flex life and are much easier to install. There are several types of stranded conductors. The true concentric and equilay constructions provide the most circular cross section and are preferred for thin wall extruded insulations. These constructions have alternate layers of wires applied helically in opposite directions over a core wire. In the true concentric construction, each successive layer has an increased length of lay, whereas in equilay stranding, the length of lay is the same in all layers. In unidirectional concentric stranding, all the layers of wire have the same direction of lay and an increased length of lay for each successive layer. Unilay stranding employs more than one layer of helically laid wires with the same direction and length of lay for each layer. This provides the smallest diameter, and therefore the lowest weight of all helical types. Rope stranding consists of a stranded central core with one or more layers of helically laid groups of bunched or concentric stranded wires. The lowest cost construction is bunch stranding, which consists of twisting wire strands in the same direction with the same lay. This type is the most difficult to extrusion coat with thin wall insulations. The effect of stranding is to increase the length of the path through which current travels in a conductor. Thus, for a given circular mils cross-sectional area, stranded construction imparts higher dc resistance than solid wire, and because of the spaces between wires in stranding, solid wire would contain more circular mils than stranded wire of the same AWG.
- *Determination of insulation and jacketing materials.* Important considerations, in addition to dielectric requirements, include resistance to moisture, chemicals, and temperatures to be encountered in operation, as well as specific gravity, mechanical properties, flame resistance and combustion products, and cost. The jacket holds all components together as the outer barrier.
- *Selection of shielding.* Shields are designed to protect against dc magnetic fields and ac frequencies and are required for many constructions:

—To filter out stray signals and low-frequency interference from nearby sources, including power lines,
—To contain conductor signals, preventing their radiation to other nearby conductors,
—To serve as a return wire in coaxial cables,
—To act as a second conductor in matched or tuned lines,
—To level out surge impedance in the conductor,
—To physically protect wires and cables from damage by insects, animals, and other natural and man-made hazards.

There are several types of shields and methods of applications. High-permeability metals, such as permalloy and steel, are most effective against dc and low-frequency (60 Hz) fields. Here, the effectiveness of the shield is directly proportional to its thickness, since the objective is to minimize reluctance or resistance to carrying flux. For higher frequencies, copper and aluminum shields are used, since it is desirable to have high conductivity so that voltages, induced by magnetic flux, generate eddy currents which oppose the action of the flux, restricting its penetration through the shield. Bronze tapes are used in underground telephone cables to protect against damage by termites or rodents. Underground power cable shields are usually copper, while aluminum is used for suspended installations because of its weight advantage. Bimetallic shields are toughest of all and provide the best protection from external damage. Shields may be braided or spiral wrapped wire, tapes, or solid metal, including corrugated, providing 100 percent coverage. Semiconductive textile, paper, and plastic shields are used for low-frequency applications where extreme flexibility or light weight are required. Coverage of 75 to 80 percent is usually adequate for low frequencies. At higher frequencies, coverage should be over 85 percent.

FLOODING AND FILLING COMPOUNDS

To prevent the ingress and movement of water in filled telephone cables, including cables with cellular insulation, a waterproofing gel is injected to fill the interstices between insulated conductors. The filling material normally used by independent companies is a polyethylene/petroleum compound usually referred to as PE/PJ. Bell companies use an extruded thermoplastic rubber called FlexGel, a trademark of AT&T. The related ASTM specifications are:

- D 4730, *Specification for Flooding Compounds for Telecommunications Wire and Cable*
- D 4731, *Specification for Hot-Application Filling Compounds for Telecommunications Wire and Cable*
- D 4732, *Specifications for Cool-Application Filling Compounds for Telecommunications Wire and Cable*

Some aircore cable designs are kept dry by pressurizing the core of the cable with dry air or nitrogen.

FIRE HAZARDS

Conductor insulations which burn or decompose in fires may produce lethal volatile products or smoke capable of causing fatalities in certain locations, such as aircraft, telephone exchanges, power stations, and subways. Federal specifications, industry standards, and building codes are under continuing review to prevent or restrict use of all materials which are hazardous in fire environments. An example is FAA Standard 25.1359, which covers electrical system fire and smoke protection in aircraft. Insulation on electrical cable and wire installed in any area of the fuselage must be self-extinguishing when tested at an angle of 60 degrees; the average burn length may not exceed 3 inches for the same size wire or cable used in the aircraft; and the average flame time after removal of the flame source may not exceed 30 seconds. Drippings from the test specimen may not continue to flame for more than an average of 3 seconds after falling.

Improved grades of most plastics are being marketed by most producers and compounders. Even where not required by code or specification, careful consideration should be given to possible exposure to intense heat or fire in the design of insulated conductors. UL 94, *Flammability Test* and ASTM D 2863, *Oxygen Index Test* are described in Chapter 3, *Thermoplastic Molding Compounds*.

TREEING

The complex phenomenon known as treeing occurs in all solid dielectrics under appropriate conditions of electrical stress, and is stimulated by contaminants and voids within the dielectric itself. Treeing is a breakdown of a dielectric along paths which appear to branch out from a central trunk, similar to limbs on a tree. Trees tend to grow in the direction of electrical stress, radiating from minute contaminants or voids toward or away from the cable conductor. Trees may be either nonvented or vented. In nonvented trees, the branches are contained entirely within the insulation. Vented trees, by far the more troublesome, grow from the outer or inner surfaces of the insulation, allowing gases formed by decomposition of the dielectric to escape. This opens paths for penetration of air, moisture, and other undesirable substances which increase conductivity and encourage tree growth. High ac stresses cause the greater damage.

The two stages of tree growth are *initiation* and *propagation*. Factors which stimulate initiation do not necessarily encourage propagation, and vice versa. *Water trees* result from the presence of water and a voltage stress. *Electrical trees* are formed usually by higher voltage stress, but without the presence of water. The subjects of tree initiation and propagation are being studied intensively by, among others, scientists at Union Carbide, Electric Power Research Institute (EPRI), and the Institut de resherche d'Hydro-Quèbec (IREQ).

Although the incidence of electrical failures directly attributable to treeing is low, there is concern that treeing failures may become more common as buried cable installations continue to increase and age. Most of the studies on treeing have involved polyethylene and crosslinked polyethylene, since trees in these materials are visible and they are the most widely used insulations for buried power cables. Treeing may also occur in

filled versions of these materials as well as in other insulations. Treeing becomes a more serious problem as voltages increase. It occurs in ac cables over 600 volts.

PRODUCTION PROCESSES FOR POLYMERS

Fluoropolymers are prepared by suspension and emulsion techniques. Polyolefins are produced by gas-phase or liquid-phase processes. Polyvinyl chloride is made by several methods, including suspension, solution, and mass polymerization processes. Elastomers, often copolymers, are made by all of the above processes.

For further discussion of this subject, see individual and group polymer sections of this chapter and the section "Polymerization" (p. 140) in Chapter 3, *Thermoplastic Molding Compounds*.

EXTRUSION PROCESS

Wires, cords, and cables are most frequently insulated and jacketed by the extrusion process, in which a plastic melt is forced under pressure by a screw through a shaping die in equipment similar to that shown in Fig. 5-1.

The screw compresses and imparts shear energy into the plastic, causing it to flow and mix on its way to the die orifice. Screw design differs from one plastic to another.

Extrusion of corrosive compounds, such as fluoroplastics, requires barrels to be lined with a corrosion-resistant liner.

The manufacture of wires, cords, and cables often includes in-line equipment for curing or sintering (in the case of polytetrafluoroethylene) compounds.

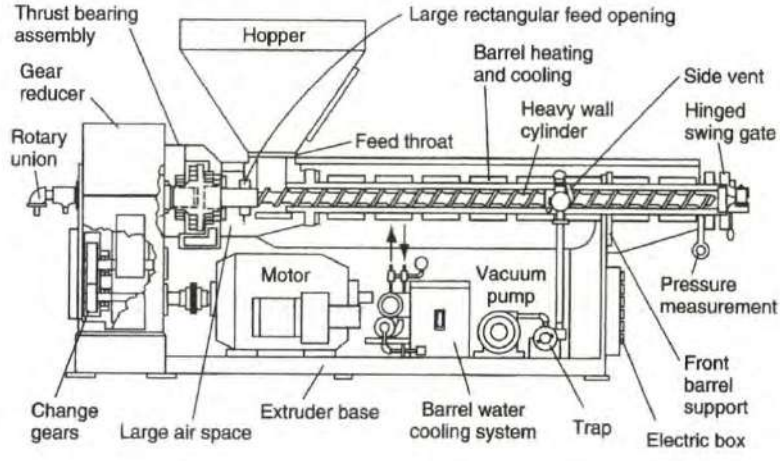


Fig. 5-1 Water-cooled extruder. (*Courtesy HPM Corporation.*)

For further discussion of this subject, see individual and group polymer sections of this chapter.

STANDARD TESTS

Standard tests for extrusion compounds are the same as for thermoplastics, described in Chapter 3, *Thermoplastic Molding Compounds*.

Spark Tester

Extrusion lines for insulated conductors typically include a spark tester. This device applies a voltage to the surface of the insulation to break down and reveal any weak spots, pin holes, or dirt specks. Both ac and dc spark tests are used on 0 to 2,000 volt cables. Spark test voltages vary with insulation wall thickness. For polyethylene insulated cables, the test voltages range from 10,500 volts dc for 45 mils to 42,000 volts ac for 120 mils. For polyvinyl chloride insulated cables, the test voltages range from 7,500 volts dc for 45 mils to 21,000 volts ac for 125 mils. The applicable document is National Electrical Manufacturers (NEMA) Standard WC 5, *Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy*.

In most spark testers, the insulated conductor is run between two wet sponges, the conductor being grounded back at the extruder. If a defect exists in the insulation, the voltage on the sponges causes an arc through to the conductor, and a fault registers on the tester. Metal brushes or fine-bead metal chains are often used in place of sponges on testers.

UL STANDARDS FOR WIRE AND CABLE

Underwriters Laboratories has approved the following standards for wire and cable:

- UL 83, *Thermoplastic-Insulated Wires and Cables*
- UL 493, *Thermoplastic-Insulated Underground Feeder and Branch-Circuit Cables*
- UL 543, *Impregnated-Fiber Electrical Conduit*
- UL 854, *Service-Entrance Cables*
- UL 1063, *Machine-Tool Wires and Cables*
- UL 1072, *Medium-Voltage Power Cables*

COMPARATIVE PROPERTIES OF EXTRUDED INSULATIONS

Tables 5-1 through 5-3 show comparative properties for high-temperature insulations, low-temperature insulations, and elastomer insulations.

TABLE 5-1 Comparative Properties of High-Temperature Insulations

PROPERTY	HALON FLUON TEFLON PTFE	TEFLON PFA	TEFLON FEP	HOSTAFLON TEFZEL ETFE	KYNAR PVDF	HALAR ECTFE	KEL-F PCTFE	SILICONE RUBBER[b]
Specific gravity ASTM D 792	2.13–2.20	2.12–2.17	2.14–2.17	1.70	1.76	1.68	2.13	1.15–1.55
Tensile, psi ASTM D 638	4,000	4,300	3,000	7,500	6,000	7,000	5,700	700 (I) 1,800 (J)
Elongation, % ASTM D 638	350	300	300	150	250	200	150	200 (I) 800 (J)
Abrasion resistance[a]	F	P	P	G	G	E	G	F
Cut-thru resistance[a]	F	F	F	E	E	E	na	P
Water resistance[a]	E	E	E	E	G	E	E	G
Max. oper. temp., °C	260	260	205	150	135	165	200	200
Low-temp. embrittlement, °C ASTM D 746	–267	–267	–73	–101	–62	–76	–253	–65
Flame resistance[a]	E	E	E	G	G	E	E	P
Solder iron resistance[a]	E	F	F	G	G	E	na	na
Dielectric constant @ 1 MHz ASTM D 1531	2.1	2.1	2.1	2.6	6.1	2.5	2.5	3.0–3.6 (I)
Dissipation factor @ 1 MHz ASTM D 1531	0.0003	0.0003	0.0007	0.005	0.159	0.009	0.006	na
Volume resistivity, Ω·cm ASTM D 257	$>10^{18}$	$>10^{18}$	$>10^{18}$	$>10^{16}$	2×10^{14}	10^{15}	$>10^{18}$	10^{15} (I)
Dielectric strength, V/mil. 125 mils ASTM D 149	500	550	500	400	260	490	500	na
Relative price per cubic inch[c]	3	5	4	5	2	4	6	1

[a]E—excellent G—Good F—Fair P—Poor

[b](I)—Insulation Grade (J)—Jacketing Grade

[c]1—Lowest 6—Highest

na—not available

TABLE 5-2 Comparative Properties of Low-Temperature Insulations

PROPERTY	POLYVINYL CHLORIDE			POLYETHYLENE				POLYPROPYLENE/ POLYETHYLENE COPOLYMER
	Flexible	Semi-Rigid	Irra-diated	Low Density	High Density	Flame Retard.	Cross-Linked	
Specific gravity ASTM D 792	1.37	1.31	1.34	0.92	0.95	1.30	0.92	0.902
Tensile, psi (min) ASTM D 638	2,200	3,150	4,500	2,200	3,000	1,800	2,200	3,400
Elongation, % (min) ASTM D 638	300	300	150–200	600	400	250	500	400
Abrasion resistance[a]	F-G	G	E	G	G	G	F	G
Cut-thru resistance[a]	G	G	E	G	G	G	F	G
Water resistance[a]	G	G	G	E	E	E	E	E
Max. oper. temp. °C	60–105	80	105	80	90	80	125	90
Brittleness temp. °C (% nonfailure) ASTM D 746	–35 (8/10)	–10 (8/10)	na	–76 (8/10)	–76 (8/10)	–65 (5/10)	–65 (5/10)	–15 (8/10)
Flame resistance[a]	G	G	G	P	P	G	P–G	P
Solder iron resis.[a]	P	P	E	P	P	F	G	P
Dielectric constant @ 1 MHz ASTM D 1531	6.2 max	4.3	2.7	2.28	2.34	2.50	2.30	2.24
Dissipation factor @ 1 MHz ASTM D 1531	na	0.10 max	na	0.0005	0.0007	0.0015	0.0003	0.0003
Volume resistivity Ω·cm ASTM D 257	5×10^{13}	2×10^{14}	2×10^{12}	10^{16}	10^{16}	10^{16}	10^{16}	4×10^{15}
Dielectric strength V/mil ASTM D 149	na	na	na	550	500	na	550	600

[a]E—Excellent G—Good F—Fair P—Poor

na—not available

TABLE 5-3 Comparative Properties of Elastomer Insulations

PROPERTY	NATURAL RUBBER	BUTYL RUBBER	SBR	NEOPRENE	HYPALON	EPDM	TPR
Specific gravity ASTM D 792	0.93	0.90	0.94	1.25	1.18	0.85	0.88
Tensile, psi[a]	1,500 (I) 3,000 (J)	na 2,500 (J)	700 (I) 2,000 (J)	1,250 (I) 3,000 (J)	1,250 (I) 3,000 (J)	700 (I) 2,400 (J)	800 (I) 1,500 (J)
Elongation, %[a] ASTM D 412	350 (I) 800 (J)	na 500 (J)	300 (I) 500 (J)	350 (I) 600 (J)	350 (I) 600 (J)	200 (I) 550 (J)	350 (I) 580 (J)
Abrasion resistance[b]	E	G	G–E	E	E	G	E
Water resistance[b]	F	E	E	F–E	G	G–E	G
Max. oper. temp., °C	82	149	82	116	163	177	125
Min. oper. temp., °C	–51	–46	–51	–40	–40	–51	–70
Flame resistance[b,c]	P	P	P	G	G	P	P
Oil resistance[b]	P	P	P	G	G	P	F
Heat aging[b]	P	F	P	F	G	G+	G+
Resistance to ozone[b]	P	E	P	G+	E	E	E
Dielectric constant @ 60 Hz ASTM D 1531	2.3–3.0	2.1–2.4	3.0–3.5	6–8	6–8	2.5–3.5	2.2
Dissipation factor @ 1 kHz ASTM D 1531	0.0025	0.003	0.003	0.030	0.03–0.07	0.007	na
Volume resistivity Ω·cm ASTM D 257	10^{16}	10^{17}	10^{15}	10^{11}	10^{14}	10^{16}	na
Dielectric strength V/mil 125 mils ASTM D 149	600–800	600	600–800	400–700	400–700	500–800	650
Relative price	Moderate	Moderate	Low	Moderate	Moderate	Low	Low

[a](I)—Insulation Grade (J)—Jacketing Grade

[b]E—Excellent G—Good F—Fair P—Poor

[c]Ratings are for standard electrical grades. Flame-retardant grades are usually available

na—not available

DEVELOPMENT PROGRAMS

Efforts continue to reduce contaminants in extrusion compounds. As an example, Union Carbide is now offering a crosslinkable polyethylene for wire and cable use that is claimed to be at least 75 percent freer from contamination than the firm's existing "clean" grades of polyethylene insulation compounds. The new material, run on modern extrusion lines, is expected to add years of useful life to wire and cable insulated with it.

The compound is made in a facility at Seadrift, TX, which provides enclosed systems and hospital-room cleanliness, a completely integrated process, new equipment and operating procedures, and new contaminant detectors such as the continuous detection Electrical Power Research Institute's pellet inspector which detects contaminants of size less than 0.005 inch.

Intensive development work continues to improve flame-retardant properties of electrical wires and cables. The goal is an insulation with lower rate of fire propagation and with less smoke and toxic gas generation than is currently available.

MARKET TRENDS

Transition is being made from coaxial cable to fiber optic cable for voice and data transmission. The first transoceanic fiber optic cable, TAT-8, has the capacity to carry 40,000 simultaneous voice conversations on two pairs of optic fibers compared with a potential maximum of 9,000 for coaxial cables.

Fiber optic cable thus forestalls the demise of undersea cable predicted with the advent of communications satellites. These satellites, controlled by Communications Satellite Corporation, are a quantum leap forward from coaxial cable. However, because they require an orbit 23,000 miles above the earth, a signal takes a quarter of a second to go from earth to satellite and back to earth, and a response would take as long. Thus, a pause of half a second would occur between "hello" and a reply. This delay becomes significant for data transmission. Fiber optic cable is a much faster method with lower capital cost. Satellites are best suited to transmitting a signal to many widely scattered stations. Fiber optic cable is designed to give the lowest cost and fastest service between two centers with intensive information traffic flow.

Optic fibers are filaments of a high-purity silica glass of 125 μm (about the diameter of a human hair) made by pulling through a die a thin filament drawn from one end of a glass rod heated to its melting point. In one process, the fiber is subsequently coated with polymethyl methacrylate (PMMA) resin and jacketed with a fluoroplastic polymer. In an early process, the primary coating was thermosetting silicone resin and the secondary coating was Nylon 12. Still another, newer, process utilizes in-line technology where a filament is drawn, coated with an ultraviolet (UV) light-curing polymer, the coating cured, and the filament wound on a drum. The coating must have sufficient mechanical strength to withstand high-speed processing, have stable transmission characteristics, and be easily strippable when it is necessary to splice and to test the cable.

In operation, the laser, a high-energy beam of monochromatic light is developed in a cylinder of crystalline material, such as a ruby, or in a tube of gas, for example, car-

bon dioxide. A high-intensity light source feeds energy into the crystal cylinder or gas tube, where photons are formed. The ends of the device are mirrored to reflect the excited photons, which are finally emitted through a small hole at the "muzzle" end of the device in a single, precise frequency, monochromatic beam. An optical-integrated circuit turns the laser beam on and off thousands of times per second, with pulses formed by a digital code into which a caller's voice or facsimile signal is translated. At the receiving end, a photodetector converts the pulses into electrical signals, which are then separated into two digital codes—one for voice and one for facsimile. Commercial lasers pulse at up to 400 million times a second, enough to transmit 6,000 calls over a single glass fiber. The applicable ASTM guide is D 4967, *Guide for Selecting Materials to be Used for Insulation Jacketing, and Strength Components in Fiber Optic Cables.*

The growing trend toward housing developments, industrial parks, and shopping malls ensures increased underground cable installations at the expense of aerial cables. Underwriters Laboratories has approved the following standards for optical-fiber cables:

- UL 910, *Test Method for Fire and Smoke Characteristics of Electrical and Optical-Fiber Cables Use in Air-Handling Spaces*
- UL 1666, *Flame Propagation Height of Electrical and Optical-Fiber Cables Installed Vertically in Shafts*

PRINCIPAL EXTRUSION POLYMERS FOR ELECTRICAL/ELECTRONIC USES

The chemistry, grades, processing, properties, and electrical/electronic uses of principal extrusion polymers are described in the sections which follow. The values shown in tables are for general purpose grades except as noted.

Polymers are presented in this order:

- Fluoropolymers
- Ethylene Polymers (PE)
- Propylene Polymers (PP)
- Polyurethane Polymers (PUR)
- Polyvinyl Chloride (PVC)
- Silicone Rubber
- Organic Elastomers

Fluoropolymers (Extrusion Resins)

The first fluorocarbon, polytetrafluoroethylene (PTFE) was discovered at Du Pont in 1938, but because early production was devoted to military products in World War II, it was not commercially available until 1947. Since that time, the family of fluoro-

polymers has grown to include several materials which are discussed in this section. These materials all have in common the widest operating temperature ranges of all plastics, outstanding resistance to attack by chemicals, excellent dielectric properties, and virtually no tendency to absorb water. These characteristics are attributable to the carbon-fluorine bond, among the strongest known in organic chemistry, and much stronger, for example, than the carbon-chlorine bond.

These plastics are soft, tough materials with room temperature mechanical properties similar to medium density polyethylene. With the exception of polytetrafluoroethylene, fluoroplastics can be processed by conventional thermoplastic molding and extrusion techniques, although processing temperatures are relatively high and equipment must be corrosion resistant. Polytetrafluoroethylene must be processed by sintering at 370°C (700°F) following ram or paste extrusion.

A distinction is sometimes made among the terms *fluoropolymers*, *fluorocarbons*, and *fluoroplastics*. *Fluoropolymers* is the generic term and includes fluorocarbons and fluoroplastics. *Fluorocarbons* consist of polymers with only carbon-fluorine bonds. *Fluoroplastics* may have, in addition to carbon-fluorine bonds, carbon-hydrogen and carbon-chlorine bonds.

In general, fluoroplastics that are not fully fluorinated have a narrower useful temperature range, lower dielectric properties, and less resistance to attack by some chemicals. However, on the plus side, fluoroplastics, within their useful temperature range, are stiffer and have better resistance to cut-through, deformation under load, and creep.

Table 5-4 lists the principal fluoropolymers in common use. Comparative properties are shown in Table 5-1 (p. 142) in this chapter.

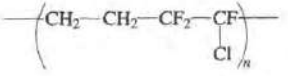
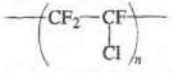
ASTM Standards for Fluoropolymer Extrusion Compounds

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

- D 1430, *Specification for Polychlorotrifluoroethylene (PCTFE) Plastics*
- D 1457, *Specification for PTFE Molding and Extrusion Materials*
- D 2116, *Specification for FEP-Fluorocarbon Molding and Extrusion Materials*
- D 3159, *Specification for Modified ETFE-Fluoropolymer Molding and Extrusion Materials*
- D 3222, *Specification for Unmodified Poly(Vinylidene) Fluoride (PVDF) Molding, Extrusion, and Coating Materials*
- D 3275, *Specification for E-CTFE-Fluoroplastic Molding, Extrusion, and Coating Materials*
- D 3307, *Specification for PFA-Fluorocarbon Molding and Extrusion Compounds*
- D 4745, *Specification for Filled Compounds of Polytetrafluoroethylene (PTFE) Molding and Extrusion Materials*
- D 4894, *Specification for Polytetrafluoroethylene (PTFE) Granular Molding and Ram Extrusion Materials*

TABLE 5-4 Summary of Characteristics of Fluoropolymers

FLUOROPOLYMER	SUPPLIERS	CHEMISTRY	ADVANTAGES	LIMITATIONS
Polytetrafluoro-ethylene (PTFE)	Ausimont Daikan Du Pont Hoechst-Celanese ICI	Tetrafluoroethylene (TFE) made by pyrolysis of chlorodifluoro-methane is polymerized to PTFE in aqueous medium by agitation (for molding uses) or by dispersion (for paste extrusion) using an emulsifying agent. PTFE is 76% fluorine, 24% carbon. $2\,CHClF_2 \rightarrow CF_2{=}CF_2 + 2\,HCl$ $nCF_2{=}CF_2 \rightarrow -(CF_2{-}CF_2)_n-$	Excellent dielectric properties. Widest useful temperature range of all plastics. Unaffected by virtually all chemicals. Low coefficient of friction. Oxygen index over 95%. Excellent solder iron resistance.	Cannot be processed by melt techniques. Must be processed by sintering at 370°C following ram or paste extrusion, or coating on glass fabric or metal. Poor resistance to corona and radiation.
Perfluoroalkoxy (PFA)	Du Pont	The PFA molecular structure is, like PTFE, a straight chain, but with a perfluoroalkane group with an oxygen linkage to the chain. $-\left[(CF_2{-}CF_2)_n CF_2{-}CF(O{-}C_nF_{2n+1})\right]_m-$	Dielectric, mechanical, and chemical properties equal to PTFE. Can be processed by conventional molding and extrusion techniques. Better mechanical properties than FEP above 150°C (302°F).	Higher in price than PTFE.
Fluorinated ethylene-propylene copolymer (FEP)	Du Pont	FEP is a copolymer of hexafluoropropylene and tetrafluoroethylene, prepared by several methods including aqueous and nonaqueous dispersion polymerizations similar to those used to make PTFE. $-\left[(CF_2{-}CF_2)_n CF_2{-}CF(CF_3)\right]_m-$	Dielectric, mechanical, chemical properties equal to PTFE and PFA except narrower useful temperature range. Can be processed by conventional molding and extrusion techniques. Oxygen index of 95%.	Narrower useful temperature range than PTFE or PFA. Not as tough as PTFE.

Ethylene-tetrafluoroethylene (ETFE)	Ausimont Du Pont	ETFE is a modified copolymer of ethylene and TFE. $-(CH_2-CH_2-CF_2-CF_2)_n-$	Mechanical properties better than other fluoroplastics except PCTFE. Lower maximum operating temperature than PTFE, PFA, FEP, and ECTFE. Can be processed by conventional molding and extrusion techniques.	Dielectric properties not quite as good as PTFE, PFA, and FEP. Oxygen index much lower (28–32%).
Polyvinylidene fluoride (PVDF)	Ausimont Elf Autochem Solvey Polymer	PVDF is made by free radical chain polymerization of vinylidene fluoride using both emulsion and suspension polymerization techniques. $-(CH_2-CF_2)_n-$	PVDF can be solvated by organic esters and ketones as well as processed by conventional molding and extrusion techniques. High abrasion resistance and resistance to UV and nuclear radiation. Oxygen index 44%. Low price.	Chemical resistance, dielectric properties not as high as other fluoroplastics, with narrowest useful temperature range.
Ethylene-chlorotrifluoro ethylene copolymer (ECTFE)	Ausimont	ECTFE is a copolymer of ethylene and chlorotrifluoroethylene in a 1:1 alternating structure. 	Highest tensile strength and abrasion resistance of all fluoroplastics. Good dielectric properties. Can be processed by conventional molding and extrusion techniques. Oxygen index of 60. Lowest specific gravity of all fluoroplastics.	Attacked by hot amines (otherwise good chemical resistance).
Polychlorotrifluoroethylene (PCTFE)	3M Elf Autochem	PCTFE is produced by suspension or emulsion polymerization of chlorotrifluoroethylene. The monomer is prepared by dechlorination of trichlorotrifluoroethane in liquid phase in the presence of a metallic zinc slurry in methanol, or in a hydrogen gas phase reaction with nickel catalyst at elevated temperature. 	Excellent resistance to oxygen, ozone, sunlight, and fuming oxidizing acids. Good abrasion resistance. Excellent gas and liquid barrier. Can be processed by conventional molding and 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 fluoroplastics.

Federal Specifications for Fluoropolymer Extrusion Compounds

The following Federal specification has been developed for fluoropolymer extrusion compounds:

- MIL-P-46122, *Plastic Molding Material and Plastic Extrusion Material, Polyvinylidene Fluoride Polymer and Copolymer*

Federal Specifications for Fluoropolymer Insulated Wire

The following Federal specifications have been developed for fluoropolymer insulated wire:

Polytetrafluoroethylene (PTFE)

- MIL-W-16878
  - /4B Wire, Electrical PTFE Insulated, 200 Deg C, 600 Volts, Extruded Insulation
  - /23 Wire, Electrical, PTFE Insulated, 260 Deg C, 250 Volts, Extruded Insulation
  - /25 Wire, Electrical, PTFE Insulated, 260 Deg C, 600 Volts, Extruded Insulation
  - /27 Wire, Electrical, PTFE Insulated, 260 Deg C, 1000 Volts, Extruded Insulation
- MIL-W-22759
  - /1E Wire, Electric, Fluoropolymer-insulated, TFE and TFE-coated-glass, Silver-coated Copper Conductor, 600 Volts
  - /2E Wire, Electric, Fluoropolymer-insulated, TFE and TFE-coated-glass, Nickel-coated Copper Conductor, 600 Volts
  - /3D Wire, Electric, Fluoropolymer-insulated, TFE-glass-TFE, Medium Weight, Nickel-coated Copper Conductor, 600 Volts
  - /4B Wire, Electric, Fluoropolymer-insulated, TFE-glass-FEP, Silver-coated Copper Conductor, 600 Volts
  - /5B Wire, Electric, Fluoropolymer-insulated, Abrasion Resistant, Extruded TFE, Silver-coated Copper Conductor, 600 Volts
  - /6B Wire, Electric, Fluoropolymer-insulated, Abrasion Resistant, Extruded TFE, Nickel-coated Copper Conductor, 600 Volts
  - /7B Wire, Electric, Fluoropolymer-insulated, Abrasion Resistant, Extruded TFE, Medium Weight, Silver-coated Copper Conductor, 600 Volts
  - /8B Wire, Electric, Fluoropolymer-insulated, Abrasion Resistant, Extruded TFE, Medium Weight, Nickel-coated Copper Conductor, 600 Volts
  - /9B Wire, Electric, Fluoropolymer-insulated Extruded TFE, Silver-coated Copper Conductor, 1000 Volts
  - /10B Wire, Electric, Fluoropolymer-insulated Extruded TFE, Nickel-coated Copper Conductor, 1000 Volts
  - /11F Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Silver-coated Copper Conductor, 600 Volts

/12F Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Nickel-coated Copper Conductor, 600 Volts

/20 Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Silver-coated High Strength Copper Alloy Conductor, 1000 Volts

/21 Wire, Electric, Fluoropolymer-insulated Extruded TFE, Nickel-coated High Strength Copper Alloy Conductor, 1000 Volts

/22 Wire, Electric, Fluoropolymer-insulated Extruded TFE, Silver-coated High Strength Copper Alloy Conductor, 600 Volts

/23 Wire, Electric, Fluoropolymer-insulated Extruded TFE, Nickel-coated High Strength Copper Alloy Conductor, 600 Volts

/24 Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Polyimide-coated, Silver-coated Copper Conductor, 600 Volts

/29 Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Polyimide-coated, Nickel-coated Copper Conductor, 600 Volts

/30 Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Polyimide-coated, Silver-coated High Strength Copper Alloy Conductor, 600 Volts

/31 Wire, Electric, Fluoropolymer-insulated, Extruded TFE, Polyimide-coated, Nickel-coated High Strength Copper Alloy Conductor, 600 Volts

Fluorinated Ethylene-Propylene Copolymer (FEP)

- MIL-W-22759

/13D Wire, Electric, Fluoropolymer-insulated, FEP-PVF2, Medium Weight, Tin-coated Copper Conductor, 600 Volts

/14B Wire, Electric, Fluoropolymer-insulated, FEP-PVF2, Lightweight, Tin-coated Copper Conductor, 600 Volts

/15B Wire, Electric, Fluoropolymer-insulated, FEP-PVF2, Lightweight, Silver-Plated High Strength Copper Alloy, 600 Volts

Ethylene-Tetrafluoroethylene (ETFE)

- MIL-W-22759

/17A Wire, Electric, Fluoropolymer-insulated, Extruded ETFE, Medium Weight, Silver-coated High Strength Copper Alloy Conductor, 600 Volts, 150 Deg C

/19A Wire, Electric, Fluoropolymer-insulated, Extruded ETFE, Lightweight, Silver-coated High Strength Copper Alloy Conductor, 600 Volts, 150 Deg C

/32A Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Lightweight, Tin-coated Copper Conductor, 150 Deg C, 600 Volts

/33A Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Lightweight, Silver-coated Copper Conductor, 150 Deg C, 600 Volts

/34B Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Normal Weight, Tin-coated Copper Conductor, 150 Deg C, 600 Volts

/35B Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Normal Weight, Silver-coated High Strength Copper Alloy Conductor, 200 Deg C, 600 Volts

/41A Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Normal Weight, Nickel-coated Copper Conductor, 200 Deg C, 600 Volts

/42 Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Normal Weight, Nickel-coated High Strength Copper Alloy, 200 Deg C, 600 Volts

/43A Wire, Electric, Fluoropolymer-insulated, Crosslinked Modified ETFE, Normal Weight, Silver-coated Copper Conductor, 200 Deg C, 600 Volts

NEMA Standards for Fluoropolymer Insulated Wire

The following NEMA standards have been developed for fluoropolymer insulated wire:

- HP 100, *High Temperature Instrumentation and Control Cables*
- HP 100.1, *High Temperature Instrumentation and Control Cables Insulated with FEP Fluorocarbons*
- HP 100.2, *High Temperature Instrumentation and Control Cables Insulated and Jacketed with ETFE Fluoropolymers*
- HP 100.3, *High Temperature Instrumentation and Control Cables Insulated and Jacketed with Cross-Linked (Thermoset) Polyolefin (XLPO)*
- HP 100.4, *High Temperature Instrumentation and Control Cables Insulated and Jacketed with ECTFE Fluoropolymers*
- HP 3, *Electrical and Electronic PTFE (Polytetrafluoroethylene) Insulated High Temperature Hook-Up Wire; Types (600 Volt), EE (1000 Volt), and ET (250 Volt)*
- HP 4, *Electrical and Electronic FEP Insulated High Temperature Hook-Up Wire, Types K, KK, and KT*

Grades

- Polytetrafluoroethylene is supplied as granular resins, both filled and unfilled, for ram extrusion and compression molding, as aqueous dispersions for coating substrates, and as fine powders for paste extrusion. Suppliers are Ausimont, USA (Halon™, Algoflon™), Daikan (Polyfluon™), Du Pont (Teflon™ TFE), Hoechst Celanese (Hostaflon™), and ICI Americas (Fluon™).
- Perfluoroalkoxy is available as pellets for molding and extrusion, and as powders for coatings. Supplier is Du Pont (Teflon™ FPA).
- Fluorinated ethylene-propylene copolymer is furnished as pellets, as aqueous dispersions, and as powders. Supplier is Du Pont (Teflon™ FEP).
- Ethylene-tetrafluoroethylene is sold as pellets, with and without glass fiber reinforcement, and as powders. Suppliers are Ausimont, USA (Halon ET™), and Du Pont (Tefzel™).
- Polyvinylidene fluoride may be purchased as pellets, both filled and unfilled, as dispersions, and as powders. Suppliers are Autochem (Foraflon™) and Pennwalt (Kynar™).

• Ethylene-chlorotrifluoroethylene copolymer comes as pellets, as powders for rotomolding and coatings, and as a foamable grade. Supplier is Ausimont, USA (Halar™).

• Polychlorotrifluoroethylene is offered as pellets, with and without glass fiber reinforcement. Supplier is 3M Company (Kel-F™).

Processing

Methods used to process fluoropolymers include the following:

• Conventional injection molding and extrusion techniques may be successfully employed with due provision made for higher processing temperatures than are required for other plastics and for the highly corrosive nature of fluoropolymers. Not used for polytetrafluoroethylene.

• Paste extrusion is the process used to convert polytetrafluoroethylene fine powder into thin wire insulation. Particles about 0.2 micron in diameter are blended with naphtha or similar lubricant. In coating wire, the wire is held in a hollow mandrel and fed through the ram of the extruder and not through a crosshead as in the case of melt extrusion. The wire meets the lubricated polymer at the entrance to the die, making it essential that the rate of travel of the wire is the same as the rate of extrusion. The coated wire then passes through an oven in line where the polytetrafluoroethylene is sintered to a homogeneous film with thickness in the range of 0.005 to 0.010 inch. Another method involves extruding a thin film which may be slit into tape and served on wire with subsequent sintering. Sintering temperatures exceed 620°F (326°C).

• Billets, or cylinders, of polytetrafluorethylene weighing up to 1500 pounds may be sintered in ovens at 698°F (370°C) from preforms of granules. These billets may then be precisely skived to films as thin as 0.001 inch or to sheets as thick as 0.1 inch.

• Fluorocarbons, normally not cementable, may be made cementable by special treatment with molten caustic.

Electrical/Electronic Uses

The principal electrical/electronic use for fluoropolymers is for wire and cable insulation where no other materials suffice. Examples include:

• Low-smoke, low-flame-spread communication wire and cable in plenum areas (PTFE), (FEP), (ECTFE)

• Fire alarm cable (PTFE), (FEP)

• Oil well logging cable (FEP)

• Back panel wiring in computers (FEP), (ETFE), (PVDF)

• Hookup wire for aerospace and mass transit applications (ETFE), (ECTFE), (FEP), (PVDF)

• Wiring in nuclear power plants (ETFE), (ECTFE)

• Coaxial cable (ECTFE), (PTFE), (FEP)

• Appliance wire (ECTFE)

- Motor lead wire (ECTFE)
- Down hole cables (FEP)
- Cathodic protection lead wire (ECTFE)

In addition, there are many other demanding applications, if not high volume, for both molded and extruded fluoropolymers.

Ethylene Polymers (PE) (Extrusion Resins)

From pilot plant production in the early 1930s, polyethylene has become by far the most versatile wire and cable insulation. Polyethylene for this end use is largely the domain of Union Carbide, with Dow Chemical the only supplier of chlorinated polyethylene (Dow also supplies other types). Other suppliers of dielectric grade polyethylene include Du Pont (Alathon™) and Quantum Composites (Petrothene™).

Chemistry

Low-density polyethylene (LDPE), the first polyethylene resin, is produced by polymerizing ethylene gas ($CH_2=CH_2$) into long polymer chains in an autoclave or tubular reactor. Polymerization is initiated by a small amount of oxygen or other free radical source. The conventional process requires pressures in the 15,000 to 45,000 psi range. A newer process involves gas-phase fluidized-bed reactors or liquid-phase solution process reactors. The material produced by these methods is designated linear low density polyethylene (LLDPE).

High-density polyethylene (HDPE) is a later development, dating from the early 1950s. A catalyzed gas-phase system with pressures under 1,500 psi is one production method. High-density polyethylene may also be produced in solution processes or as dispersions in hydrocarbon diluents. High-density polyethylene resins are characterized by a linear structure and exhibit a high degree of crystallinity.

Medium-density polyethylene (MDPE) may be made by any of the above processes or by blending low-density polyethylene and high-density polyethylene. ASTM has developed definitions for four types of polyethylene (ASTM D 1248, *Specification for Polyethylene Molding and Extrusion Materials*):

TYPE	NOMINAL DENSITY (G/CM^3)
I	0.910–0.925
II	0.926–0.940
III	0.941–0.959
IV	0.960 and higher

Polyethylenes are classified not only by density, but also by molecular weight. High-density polyethylene resins with molecular weights averaging in the 300,000–500,000 range are designated high-molecular-weight high-density polyethylene (HMW-HDPE). This version may be made in a gas-phase fluidized-bed reactor or in a gas-

phase system using catalysts such as aluminum trialkyl/titanium tetrachloride, or chromium oxide on a silica support. Solution polymerization is not a practical method because when the polymer approaches the high-molecular-weight range, it precipitates. High-molecular-weight high-density polyethylene polymers are predominantly linear. Although the average molecular weight is 300,000–500,000, molecular weight distribution is broad, with a significant proportion of lower molecular weight molecules to facilitate processing.

A high-density polyethylene with molecular weight in the range of 3–6 million is called ultrahigh-molecular-weight polyethylene (UHMWPE). This polymer is produced by a system similar to that used for high-density polyethylene. Ultrahigh-molecular-weight polyethylene, because of its extremely high molecular weight, cannot be processed by conventional techniques.

Thus, a wide range of properties may be obtained by different manufacturing methods, by varying the type and amount of modifier and catalyst, and by controlling process temperature and pressure. A highly crystalline molecular structure, as in high-density polyethylene, results from minimum side chain branching. Branching is controlled by varying process conditions, and also by adding comonomers such as propylene, butene, and hexene. Higher crystallinity increases tensile strength, rigidity, chemical resistance, and opacity, but reduces permeability to liquids and gases.

Polyethylene properties may be modified by additives and fillers, usually mixed with resins during the extrusion process. Antioxidants are important to prevent degradation of polymer properties during manufacture and in service. These include amines, hindered phenols, and phosphites. Compounds for wire and cable insulation may include metal deactivators. Degradation by ultraviolet light is inhibited to a remarkable degree by including in formulations less than 3 percent of carbon black, which in larger amounts (up to 30 percent) can be incorporated to reduce cost. Special carbon blacks provide semiconductive properties for shielding power cables. Inherent flammability of polyethylene is significantly reduced, at the expense of physical properties and processing ease, by additives such as antimony oxide, aluminum trihydrate, and halogenated compounds. Other additives act as slip, antiblock, and antistatic agents.

Polyethylene may be crosslinked (XLPE), or vulcanized, to a thermoset material by addition of $1\frac{1}{2}$ to 2 percent dicumyl peroxide to formulations, or by electron beam radiation, both of which are continuous in-line processes following extrusion of polyethylene on conductors.

Ethylene vinylsilane copolymers are the latest crosslinkable materials designed for wire and cable insulations. The silane is usually a vinylsilane with three functional groups: $H_2C{=}CHSi(OR)_3$, where the R group can be one of several functional methyl, ethyl, or acetyl groups. The double bond of the vinyl group enables the silane to be attached to or incorporated into the copolymer. The copolymer may be formed either by grafting with a peroxide initiator or by copolymerization directly in a reactor used to produce low density polyethylene. Both graft and copolymerized materials crosslink upon exposure to moisture and a catalyst, such as methyl carboxylate. After extrusion, crosslinking is accomplished in a steam room (requiring a few hours), hot water (16–24 hours at 90°C), or by humidity during storage (which takes up to a few weeks).

High-density polyethylene may be chlorinated in a slurry to a polymer containing 25 to 48 percent chlorine. Chlorinated polyethylene (CPE), in concentrations of 3 to 8 percent, is often blended with polyvinyl chloride to improve impact properties. With over 42 percent chlorine, chlorinated polyethylene is fire retardant.

Ethylene is frequently copolymerized with vinyl acetate. Copolymers are referred to as polyethylene or modified polyethylene when vinyl acetate content is less than 5 percent. With 5 to 50 percent vinyl acetate content, the copolymer is called ethylene-vinyl acetate (EVA). Above fifty percent concentration, the resins are considered vinyl acetate-ethylene compolymers (VAE). Low-density polyethylene jacketing compounds for telephone cable typically contain 2 percent vinyl acetate. As vinyl acetate content increases, density increases and crystallinity decreases. Higher density results in lower stiffness, greater toughness, lower melting point, and higher permeability.

Another technique for changing polyethylene properties is injecting nitrogen into molten polymer or compounding with a blowing agent. The result with either process is lightweight cellular insulation with reduced dielectric constant. This material is used in some filled "exchange" communications cables installed between control offices of the telephone companies. Filled cables are discussed in the section of this chapter entitled "Flooding and Filling Compounds." A potential problem using these compounds with cellular insulation is to prevent the migration of the compound into the insulation where it adversely affects the dielectric and physical properties of the insulation.

ASTM Standards for Extruded Polyethylene Compounds

The American Society for Testing and Materials has developed the following standards for extruded polyethylene and chlorinated polyethylene compounds:

For polyethylene:

- D 1248, *Polyethylene Plastics Molding and Extrusion Materials*
- D 1351, *Polyethylene Insulated Wire and Cable*
- D 2308, *Polyethylene Jacket for Electrical Insulated Wire and Cable*
- D 2647, *Crosslinkable Ethylene Plastics*
- D 2655, *Crosslinked Polyethylene Insulation for Wire and Cable Rated 0 to 2000 V*
- D 2656, *Crosslinked Polyethylene Insulation for Wire and Cable Rated 2001 to 35,000 V*
- D 3485, *Smooth-Wall Coilable Polyethylene (PE) Conduit (Duct) for Preassembled Wire and Cable*
- D 3554, *Track-Resistant Black Thermoplastic High-Density Polyethylene Insulation for Wire and Cable*
- D 3555, *Track-Resistant Black Crosslinked Polyethylene Insulation for Wire and Cable*
- D 4020, *Ultra-High-Molecular-Weight Polyethylene Molding and Extrusion Compounds*
- D 4976, *Polyethylene Plastics Molding and Extrusion Materials*

And for chlorinated polyethylene:

- D 4313, *General-Purpose Heavy-Duty and Extra-Heavy-Duty Crosslinked Chlorinated Polyethylene Jackets for Wire and Cable*
- D 4314, *General-Purpose Heavy-Duty and Extra-Heavy-Duty Crosslinked Chlorosulfonated Polyethylene Jackets for Wire and Cable*

Military Specifications for Polyethylene Insulated Wire

The following Military specifications have been developed for polyethylene insulated wire:

- MIL-W-16878
  - /10C Wire, Electrical, Polyethylene-Insulated, 75 Deg C, 600 Volts
  - /14 Wire, Electrical, Modified Polyethylene (XLPE) Insulated, 125 Deg C, 600 Volts
  - /15 Wire, Electrical, Modified Polyethylene (XLPE) Insulated, 125 Deg C, 1000 Volts
  - /16 Wire, Electrical, Modified Polyethylene (XLPE) Insulated, 125 Deg C, 3000 Volts
  - /33 Wire, Electrical, Polyethylene-Insulated, 75 Deg C, 600 Volts, Polyamide Covering, Abrasion Resistant
- MIL-W-81044
  - /6B Wire, Electric, Crosslinked Polyalkene-insulated, Tin-coated Copper Conductor, Normal Weight, 150 Deg C
  - /7B Wire, Electrical, Crosslinked Polyalkene-insulated, Silicone-coated, High Strength Copper Alloy Conductor, Normal Weight, 600 Volts, 150 Deg C
  - /9B Wire, Electric, Crosslinked Polyalkene-insulated, Tin-coated, Medium Weight, 600 Volts, 150 Deg C
  - /10B Wire, Electric, Crosslinked Polyalkene-insulated, Silicone-coated, High Strength Copper Alloy Conductor, Medium Weight, 600 Volts, 150 Deg C
  - /12B Wire, Electric, Crosslinked Polyalkene-insulated, Tin-coated Copper Conductor, Light Weight, 600 Volts, 150 Deg C
  - /13B Wire, Electric, Crosslinked Polyalkene-insulated, Silicone-coated, Light Weight, 600 Volts, 150 Deg C.

Federal, ICEA/NEMA, AEIC, ANSI, and UL Standards and Listings

Governmental and industry organizations (in addition to ASTM and the Military) have developed the following specifications and listings for polyethylene insulated wire and cable:

- Federal Specification

  L-P-390C: covers PE and copolymers molding and extrusion compounds for use as a dielectric.

- Insulated Cable Engineers Association (ICEA) National Electrical Manufacturers Association (NEMA)

  S-61-402/WC 5 covers thermoplastic-insulated wire and cable products

  S-66-524/WC 7 covers crosslinked-thermosetting-polyethylene-insulated wire and cable products

  S-68/WC 8 covers ethylene-propylene insulated wire and cable products

- Association of Edison Illuminating Companies (AEIC)

  CS5-82: covers thermoplastic and crosslinked PE insulated shielded power cables rated 5,000 to 69,000 volts.

- American National Standards Institute (ANSI)

  C8.35-1975: covers weather-resistant wire and cable—PE type.

- Underwriters Laboratories (UL)

  UL 83: covers thermoplastic-insulated wires and cables.

Grades

As may be inferred from the above discussion, countless grades of polyethylene with its many types, processes, additives, and comonomers are available. A commonly used indicator of average molecular weight in grade descriptions is melt index (MI), which measures the amount in grams of compound that can be forced through an 0.0825 inch orifice when subjected to a 2,160 gram force in 10 minutes at 374°F (190°C), ASTM D 1238. Thus, there is an inverse relationship between MI and molecular weight—a compound with low MI value has high average molecular weight. Density is another indicator included in grade descriptions (see discussion under "Chemistry" (p. 154) in this section).

Grades are available to meet the requirements for wire and cable insulations covered by industry and government specifications listed above.

Halogen-free grades are available which minimize flame propagation, smoke generation, and release of toxic gases. These grades are processed at a relatively low temperature of approximately 347°F (175°C) to avoid degradation of the alumina trihydrate usually blended in at levels of about 65 percent by weight.

Processing

The basic process of extrusion coating polyethylene on a conductor consists of pulling the preheated conductor through an annular die which forms molten compound around the conductor with a coating of 0.005 inch to over 1.0 inch. For good results, it is essential that the coating be of uniform thickness to provide a high degree of concentricity for the conductor. It is also essential that the manufacturing environment be scrupulously clean and free from contaminants.

Linear low-density polyethylene processes more stiffly than does comparable melt index low-density polyethylene. In screw design for linear low-density polyethylene, a longer transition section and shorter metering section are recommended than for low-density polyethylene.

In the extrusion of high-density polyethylene, critical control of melt temperatures is required to produce high-quality insulated conductors. In extruding high-

molecular-weight high-density polyethylene, melt viscosities make process controls even more critical. Ultrahigh-molecular-weight polyethylene cannot be extruded or injection molded and must be compression molded.

Following extrusion, the coated conductor passes through a water-cooling trough where the temperature, based on experience, is closely controlled to optimize properties of the finished insulated conductor.

In the manufacture of cable insulated with crosslinkable (vulcanizable) polyethylene, the hot compound must be extruded around the conductor below the rapid reaction temperature in the 230° to 270°F (110°–132°C) range. The conductor coated with the uncured compound and frequently also with an extruded shield is then processed by one of several methods to cure the insulation, including the following:

- The cable is passed into a steam tube with pressure at 200 to 300 psi to bring the insulation to reaction temperature of 350° to 450°F (176°–232°C). All variables must be carefully controlled at this stage for good results. To prevent formation of voids from decomposition of the peroxide crosslinking agent, the cable is finally passed through a chamber where it is cooled under high-pressure water.
- A hot salt bath is used to cure the compound.
- Radiant heat is used in nitrogen atmosphere.
- Electron beam radiation is used for 600 volt cables. High-voltage cables have not been cured by irradiation because of thick walls and treeing inception from trapped electrons.

Properties

Important factors affecting the properties of polyethylene are degree of crystallinity, molecular weight, and molecular weight distribution. In general, polyethylene exhibits excellent dielectric properties which are independent of frequency or temperature. Water vapor permeability is low, but permeability to air and other gases is high. Toughness is retained at low temperatures. However, flammability is high except for special formulations, heat distortion temperatures are quite low, and load-bearing characteristics are poor. Resistance to weathering is low, although this can be improved significantly by addition to recipes of ultraviolet inhibitors and 2.6 percent carbon black.

Chemical resistance is generally good and increases with polymer density. Polyethylene is attacked by organic solvents, halogenated hydrocarbons, and concentrated oxidizing acids.

Crosslinking renders polyethylene infusible and suitable for service temperatures up to 125°C (257°F), compared with 75°C (167°F) for noncrosslinked polyethylene insulation, thus permitting cables to carry higher current densities. Resistance to cold flow and abrasion are superior to conventional polyethylene, while dielectric properties are comparable. Another advantage of crosslinking is that it makes possible higher filler loading without significant loss of physical properties.

Cellular polyethylene may have varying degrees of foaming, with higher gas volumes tending to reduce the dielectric constant toward that of air ($K = 1$). At a gas volume of 50 percent, the dielectric constant becomes about 1.5, significantly lower than

even the best solid dielectric, Teflon™ TFE with $K = 2.1$. With cellular polyethylene, care must be taken to prevent cell filling with moisture or cable filler compound.

Comparative properties with other low temperature insulations are shown in Table 5-2 (p. 143) in this chapter.

Electrical/Electronic Uses

By far the principal electrical use for polyethylene is as jacket material and primary insulation for wire and cable. High-molecular-weight low-density polyethylene and increasingly linear low-density polyethylene with carbon black are used extensively for cable jackets. Aging characteristics are excellent. High-molecular-weight polymers and closely controlled molecular weight distribution and chain branching contribute to high stress crack resistance. These compounds meet REA Specification PE-200 for cable jacketing material. High-molecular-weight low-density polyethylene is also used for primary insulation, including crosslinkable and foamable grades.

High-molecular-weight high-density polyethylene is used principally as primary insulation, where it competes with polypropylene. High-molecular-weight high-density polyethylene may be formulated to exhibit excellent oxidative stability, toughness, and abrasion resistance. Resistance to environmental degradation and thermal stress cracking is high, and superior dielectric properties are maintained. Foamable grades are available.

Propylene Polymers (PP) (Extrusion Resins)

Polypropylene, closely related to polyethylene both chemically and in end uses, was a later development, becoming commercially available in the mid-1950s. The principal supplier of electrical grades of polypropylene, formerly Hercules, is now Himont U.S.A.

Chemistry

Polypropylene is formed by polymerizing propylene ($CH_3CH{=}CH_2$). The reaction is carried out commercially in several ways. The newest process, introduced by Rexene in mid-1980, is based on high-efficiency catalysts which reduce process energy consumption. This gas-phase process increases yield of isotactic (crystalline) polymer per pound of catalyst with low enough formation of atactic (amorphous) polymer so that its removal is not required. Other steps necessary in other processes are eliminated, including deashing, drying, and solvent recovery.

Diluent and slurry processes are also in general use. In both processes, polymerization, aided by a Ziegler-type catalyst such as aluminum alkyl, is carried out in a reactor vessel and the polymer separates out as an insoluble powder containing about 10 percent of atactic polymer which must be reduced by solvent extraction to less than 7 percent.

Polypropylene homopolymer has a relatively high brittleness temperature. By copolymerizing with 2 to 20 percent ethylene, a resin is formed with significantly more useful properties. For telephone cable, the ratio is 82 to 84 percent propylene, 16 to 18

percent ethylene. This block copolymer has brittleness temperature of –15°C (5°F), over 20°C (36°F) lower than polypropylene homopolymer, and a maximum continuous use temperature of 90°C (195°F). REA accepts this copolymer as an alternative for high-density polyethylene.

Molecular weight is controlled by process variables. High-molecular-weight resins are softer but tougher, and more flexible. Low-molecular-weight resins are harder, more brittle, and stiffer. To protect the polymer from oxidative degradation during fabrication and use, most compounds contain a hindered phenol antioxidant and a hydroperoxide decomposer. Since copper catalyzes oxidative degradation, an inhibitor for this action should be added to recipes for wire coating compounds. Stability to ultraviolet light is achieved by adding UV inhibitors.

As with high-density polyethylene, a cellular insulation with reduced dielectric constant may be produced by injecting nitrogen into molten polymer or compounding with a blowing agent.

Polypropylene Versus High-Density Polyethylene

Since REA and cable manufacturers recognize polypropylene and high-density polyethylene as alternatives for each other, price is a principal factor in determining usage. At equal price, polypropylene has the advantage of lower specific gravity (0.90 versus 0.95) and slightly better dielectric properties, theoretically permitting material savings of about 5 percent.

This is not to say that substitution can be made without problems or adjustments. For example, slightly greater wall thicknesses of high-density polyethylene are needed to compensate for its somewhat higher dielectric constant ($K = 2.32$ versus $K = 2.24$). This requires tighter packing of wires to keep the outer diameter of the high-density polyethylene cable the same as the polypropylene cable. Polypropylene can undergo severe draw downs during line start-up while maintaining a uniform and continuous coating on wire. High-density polyethylene does not act as satisfactorily. High-density polyethylene dielectric properties are affected to a greater extent by changes in other process conditions such as preheat temperature, melt temperature, water trough temperature, and length of water trough. Thus, it is claimed by proponents that polypropylene has significant manufacturing advantages. High-density polyethylene, however, has much lower brittleness temperature (–76°C (–105°F) versus –15°C (5°F)).

Grades

Homopolymer grades are not in general use for electrical end uses because of their high brittleness temperature. Copolymer grades are available for electrical applications and meet the following industry and government specifications:

- Atomic Energy Commission Specification AEC-1C8–10. Specification AEC-NV-RF-1 through -3.
- Western Electric Specification MS 59056 Issue 2 Modified/T.I.M. 434140.
- ASTM Specification D 4101, *Specification for Propylene Plastic Injection and Extrusion Materials*.

• ICEA Standard S-61-402/NEMA Standard WC 5: *Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy.*

Processing

Wire preheating at a constant temperature in the 200° to 300°F (93°–149°C) range is necessary to obtain optimum elongation and to control shrinkback. A cooling trough is required. Recommended stock temperature range is 440° to 500°F (227°–260°C) with barrel temperature in the range of 450° to 475°F (232°–240°C).

Properties

For a wide variety of applications, polypropylene possesses an excellent balance of properties, including the lowest specific gravity of all commonly used plastics, high stiffness, good chemical resistance, and superior dielectric properties. Weaknesses of polypropylene homopolymer include high brittleness temperature and low impact resistance below 40°F (4°C). Additives to recipes are required to prevent attack and degradation by free radicals and ultraviolet light. See also preceding discussion of "Polypropylene Versus High Density Polyethylene."

Polypropylene, while having excellent resistance to most chemicals, is attacked by halogenated hydrocarbons and concentrated oxidizing acids.

Comparative properties with other low-temperature insulations are shown in Table 5-2 (p. 143) in this chapter.

Electrical/Electronic Uses

The principal electrical uses of polypropylene/polyethylene copolymer are for extruded primary insulation on wire and cable and for service at under 5,000 volts. It is also used extensively for injection-molded battery cases.

Polyurethane Polymers (PUR) (Extrusion Resins)

A relatively new thermoplastic polyurethane (Esthane™) suitable for extrusion as halogen-free cable jacketing has been developed by Geon. This compound is reported to feature excellent flame retardancy, low smoke generation, low toxic gas emissions, and to have a V-0 rating in the UL 94 vertical burn flammability test with an oxygen index of 40 percent.

Polyvinyl Chloride (PVC) (Extrusion Resins)

Polyvinyl chloride was first used as wire and cable insulation and jacketing in the late 1930s. During World War II, its use spread as a replacement for rubber, then in short supply. Polyvinyl chloride is now one of the most widely used materials in extrusion applications, as producers and fabricators have successfully complied with

EPA standards, which in 1974 and 1975 appeared to threaten the survival of the industry.[1] Major producers of insulation grades of polyvinyl chloride include Geon (formerly B. F. Goodrich), Occidental Chemical, and Pantasote Polymers (Kohinor™).

Chemistry

Vinyl chloride, $CH_2=CHCl$, is a gas at room temperature. There are several commercial polymerization processes, all carried out in pressure vessels.

In the predominating *suspension process*, vinyl chloride droplets are suspended in water by rapid agitation and protective colloids such as polyvinyl alcohol, gelatin, or methyl cellulose. Polymerization is activated by a peroxide initiator, soluble in the monomer, which decomposes with heat to form free radicals. The reaction is exothermic and must be controlled by cooling. At a predetermined point in the process, unreacted monomer is removed by vacuum. Water is extracted by centrifuge from the slurry, which is then dried. Average particle size is in the range of 100 to 160 microns, although process variables may be controlled to produce particles of 1 to 3 microns. A similar process utilizes more emulsifier and less rapid agitation. The resulting particle size is about 0.5 micron, suitable for latexes, plastisols, and organisols.

The *mass polymerization process* is carried out in two stages. Partial polymerization to a viscous liquid occurs in the first stage without the presence of water or other medium. Polymerization is completed to a dry state in a second vessel. Unreacted monomer is stripped by vacuum. Particles range in size from 100 to 160 microns.

In the *solution process*, vinyl chloride monomer is dissolved in a solvent and polymerized with controlled temperature and pressure. With selected solvents, the resin remains in solution or is recovered as a powder by stripping the solvent. With other monomer solvents, the polymer is insoluble and precipitates. Dry resin remains after the solvent is removed.

A wide range of resin properties may be obtained by controlling molecular weight, particle size, and particle configuration. High-molecular-weight resins are more difficult to process, but exhibit superior strength and greater resistance to heat and chemicals. Particle configuration determines the degree of porosity and ability to absorb or not to absorb plasticizers.

PVC typically contains 56.8 percent chlorine, but this ratio may be increased to as much as 67 percent. At this level, there is a significant extension of the upper service temperature limit.

Vinyl chloride may be copolymerized with vinyl acetate to produce resins with improved flow at lower processing temperatures, greater solubility, and better pigment binding. Graft polymers with ethylene/vinyl acetate (EVA) or ethylene/propylene/diene polymer (EPDM) have improved resistance to impact.

Properties of polyvinyl chloride compounds may also be changed by irradiation. This is accomplished by introducing into recipes multifunctional organic chemical additives, or sensitizers, such as tetraethylene glycol dimethacrylate. When this compound is exposed to high-energy electrons, free radicals are created on polyvinyl

[1]There are, however, continuing worldwide efforts by Greenpeace, among others, alleging that PVC products are highly toxic and should be phased out of usage.

chloride molecules, which then react with sensitizers to form a network of crosslinked polymer chains. This process imparts higher values for mechanical strength, abrasion and cut-through resistance, and temperature resistance, raising the maximum operating temperature rating of polyvinyl chloride insulated wire to 105°C (221°F).

Plasticizers

Polyvinyl chloride resins alone are inherently hard and brittle at temperatures up to 180°F (82°C). To be made useful, they must be compounded with plasticizers and other additives. A typical electrical grade formulation would contain about 50 percent polyvinyl chloride resin, 25 to 35 percent plasticizer, and the rest other additives. Phthalates have long been the most commonly used plasticizers for all PVC grades, including electrical grades. Trimellitates, with low volatility, are favored for high-temperature wire and cable applications up to 105°C. Adipate, azelate, and sebacate esters improve low-temperature flexibility, a characteristic weakness of polyvinyl chloride compounds. Phosphate plasticizers impart added flame resistance for inside wiring. Epoxidized esters of unsaturated fatty acids give heat and light stability, but tend to impart stiffness at low temperatures.

To achieve the desired balance of properties, two or more plasticizers are usually required. Important considerations in selection of a plasticizer are its compatibility, volatility, tendency to migrate to other materials, toxicity, odor, burning characteristics, dielectric properties, weatherability, and efficiency (concentration required).

Other Additives

There are several other essential ingredients usually added to polyvinyl chloride compounds:

- *Heat stabilizers*, frequently organometallic compounds, retard thermal degradation, prolonging useful life.
- *Lubricants*, such as fatty esters, waxes, and metallic soaps, improve processing characteristics and reduce adhesion to metal parts of process equipment.
- *Impact modifiers* improve impact resistance. Materials include chlorinated polyethylene (CEP), acrylonitrile-butadiene-styrene (ABS), methyl methacrylate-butadiene-styrene, and ethylene/vinyl acetate (EVA) polymers.
- *Processing aids* include styrene-acrylonitrile (SAN), methyl methacrylate copolymers, and alpha methyl styrene. These materials act to produce uniform melts.
- *Fillers*, such as calcium carbonate, reduce compound cost and raise heat deflection temperature. Calcined clay improves dielectric properties.
- *Pigments* impart color and opacity, and improve weatherability.
- *Flame retardants*, such as antimony oxide, significantly increase the oxygen index (OI) of polyvinyl chloride compounds.

ASTM Standards for Extruded Polyvinyl Chloride Compounds

The American Society for Testing and Materials has developed the following standards for extruded polyvinyl chloride compounds:

- D 1047, *Poly(Vinyl Chloride) Jacket for Wire and Cable*
- D 2219, *Poly(Vinyl Chloride) Insulation for Wire and Cable, 60°C Operation*
- D 2220, *Poly(Vinyl Chloride) Insulation for Wire and Cable, 75°C Operation*

Federal Specifications for Polyvinyl Chloride Insulated Wire and Cable

The following Federal specifications have been developed for polyvinyl chloride insulated wire and cable:

- MIL-W-76, *Wire and Cable, Hookup, Electrical, Insulated*
- MIL-W-5086 (1), *Wire, Electric, PVC Insulated, Copper or Copper Alloy*

  /1B Wire, Electric, PVC Insulated, Nylon Jacket, Tin-coated Copper Conductor, 600 Volts, 105 Deg C

  /2C Wire, Electric, PVC Insulated, PVC-Glass-Nylon, Tin-coated Copper Conductor, 600 Volts, 105 Deg C

  /3B Wire, Electric, PVC Insulated, PVC-Glass-PVC Nylon, Tin-coated Copper Conductor, 600 Volts, 105 Deg C

  /4B Wire, Electric, PVC Insulated, Nylon Jacket, Tin-coated Copper Conductor, 3000 Volts, 105 Deg C

  /6C Wire, Electrical, PVC Insulated, Polyvinylidene Fluoride Jacket, Silver-coated Copper Alloy Conductor, 600 Volts, 110 Deg C

  /7B Wire, Electrical, PVC Insulated, Nylon Jacket, Tin-coated Copper Conductor, Medium Weight, 600 Volts, 105 Deg C

- MIL-W-16878

  /2A Wire, Electrical, PVC Insulated, 105 Deg C, 1000 Volts

  /17 Wire, Electrical, PVC Insulated, 105 Deg C, 600 Volts, Polyamide Jacket

  /18 Wire, Electrical, PVC Insulated, 105 Deg C, 1000 Volts, Polyamide Jacket

  /19 Wire, Electrical, PVC Insulated, 105 Deg C, 3000 Volts, Polyamide Covering

NEMA and UL Standards and Listings

Industry organizations (in addition to ASTM and the Military) have developed the following specifications and listings for polyvinyl chloride insulated wire and cable:

- NEMA Standard WC 5: covers thermoplastic-insulated wire and cable products.
- UL National Electrical Code designations covering building wire:
  T—General Wire
  TW—Wet Locations 60°C Rating

THW—Hot, Wet Locations 75°C Rating
THHN—Hot, Wet Locations, Nylon Jacket 75°C Rating
AWM—80°C, 90°C, 105°C Ratings
NM and UF

Grades

There is a virtually unlimited number of polyvinyl chloride custom and specification grade compounds available, including grades to meet the requirements for wire and cable insulations covered by standards groups and the government.

Processing

In extrusion of polyvinyl chloride compounds on wire, the feed section temperature should be maintained in the 100° to 125°F (38°–52°C) range. Overheating initiates preplasticizing, causing the feed throat to plug or bridge. The outer diameter of the insulated wire is controlled by die size and by regulating the speed of the capstan which pulls the wire through the extruder crosshead.

Properties

Polyvinyl chloride may be compounded to produce low-cost wire and cable insulation and jacketing with thermal ratings up to 105°C. Polyvinyl chloride has outstanding tensile and impact strengths and adequate dielectric properties. Low-temperature characteristics are generally poor, and flexibility varies greatly over its useful temperature range. Without careful formulation, plasticizers may volatilize or migrate to other cable materials. Flame resistance is inherently high.

Polyvinyl chloride has good resistance to:

- Aliphatic hydrocarbons
- Oils, fats, and waxes
- Alcohols
- Concentrated inorganic acids and bases
- Dilute organic acids
- Salts
- Most solvents
- Weathering

Polyvinyl chloride is attacked by:

- Aromatic hydrocarbons
- Halogenated hydrocarbons
- Phenols
- Ketones
- Esters
- Ethers
- Concentrated organic acids

Comparative properties with other low temperature insulations are shown in Table 5-2 (p. 143) of this chapter.

Electrical/Electronic Uses

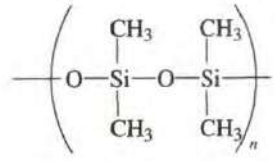
Because of its low cost and low flammability, which can be made lower with flame-retardant additives, polyvinyl chloride is used extensively for inside telephone wire, electronic low-temperature wire, building wire, apparatus wire, and low-tension automotive wire. Polyvinyl chloride is used as jacket material on telephone, power, and apparatus cables.

Silicone Rubber (Elastomer)

Silicone rubber is a high-temperature insulation applied to specialty types of wire and cable. Dow Corning and General Electric are the principal producers.

Chemistry

The basic polymer for heat-vulcanizable silicone rubber is linear polysiloxane, formed by hydrolysis of dichlorosilane and polycondensation of resulting silanediols. This gum has the following structure:



For wire and cable insulation, some methyl groups are replaced with phenyl and/or vinyl groups to increase tensile strength, impart tear resistance, extend the useful temperature range, and improve resistance to gamma radiation. The extruded gum is crosslinked, or vulcanized, by the action of heat and a vulcanizing agent, such as 2,4 dichlorobenzoyl peroxide.

Physical properties are enhanced by compounding with fillers such as small particle size silica and diatomaceous earths.

Federal Specifications for Silicone Rubber

The following Federal specifications have been developed for silicone rubber:

- MIL-C-915, *Silicone Rubber Insulated Navy Nuclear Plant Cable*
- MIL-W-8777C, *Type MS-25471 (Dacron Jacket) and Type MS-27110 (FEP Jacket) Interconnection Wire, Silicone Rubber Insulated, 600 Volts, –55° To 200°C*
- MIL-W-16878

  /7A Wire, Electrical, Silicone Rubber Insulated, 200 Deg C, 600 Volts

  /29 Wire, Electrical, Silicone Rubber Insulated, 150 Deg C, 600 Volts

  /30 Wire, Electrical, Silicone Rubber Insulated, 150 Deg C, 1000 Volts

/31 Wire, Electrical, Silicone Rubber Insulated, 150 Deg C, 1000 Volts, Glass Braid Covering, Abrasion Resistant

/32 Wire, Electrical, Silicone Rubber Insulated, 200 Deg C, 1000 Volts, Glass Braid Covering, Abrasion Resistant

Grades

As with other elastomers, large wire and cable manufacturers usually compound their own silicone rubber formulations. Grades are available to meet all Military specifications.

Processing

Extruders should have a screw especially designed for silicone rubber. The gum should not be allowed to reach a temperature of 130°F (54°C) during extrusion, since higher temperatures may produce scorching and loss of vulcanizing agent. Extrusions are usually vulcanized in continuous-process equipment, most commonly in a vertical hot air oven with temperature in the range of 482° to 800°F (250°–427°C), through which the coated wire is pulled.

Properties

Extruded silicone rubber wire and cable coatings provide long-life insulation at temperatures from –55° to 200°C. When exposed to gamma radiation, silicone rubber will increase hardiness and decrease in elongation. Dielectric properties do not undergo significant change. Methyl-vinyl silicone polymers are satisfactory for use in the range of 5×10^7 to 1×10^8 rads. Incorporation of phenyl groups increases radiation tolerances, as shown in Table 5-5.

Heat-curable silicone rubber has good resistance to ozone, corona, and weathering. It is inherently flame retardant, and when burned, forms a nonconductive silica dioxide ash which maintains circuit integrity. Mechanical properties are relatively low in comparison with those of organic rubbers at room temperature.

Silicone rubbers have good resistance to:

- Alcohols
- Dilute acids and alkalies

TABLE 5-5 Radiation Resistance—Silicone Rubber

	METHYL-VINYL		METHYL-PHENYL-VINYL	
DOSAGE (Rads)	Elongation %	Tensile Strength (psi)	Elongation %	Tensile Strength (psi)
None	200	1,200	600	1,200
5×10^6	130	1,000	450	1,100
5×10^7	50	900	225	900
1×10^8	20	600	75	850

- Salts
- Oils, fats, and waxes

Silicone rubbers are attacked by:

- Halogenated hydrocarbons
- Aromatic solvents
- Phenol
- Concentrated acids
- Steam

Key property values for heat curable silicone rubber are shown in Table 5-1 (p. 142) in this chapter.

Electrical/Electronic Uses

Because of its relatively high cost, extruded heat-curable silicone rubber insulation is used only when less costly insulation is inadequate. Applications include appliance and fixture wire, shipboard power, control, and hookup cables, aircraft high-tension ignition and control cables, automotive ignition system wiring, nuclear power cable, and flexible multiconductor flat cable.

Organic Elastomers

As used in this handbook, elastomers are polymeric materials which exhibit elastic properties similar to rubber, the original elastomer. When properly processed and within their elastic limits, they tend to return to their original shape after being stretched, compressed, or otherwise deformed. Like natural rubber, some elastomers require vulcanization with sulfur, sulfur compounds, or other polymerizing agents or methods. Other elastomers can be processed directly into finished products. The compounding and processing of all elastomers is an intricate combination of art, technology, and experience, all of which significantly affect the properties of any elastomer.

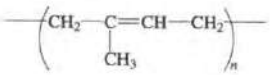
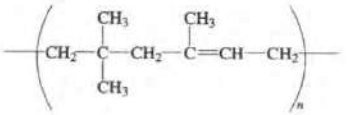
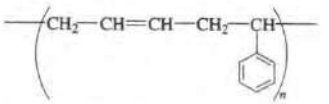
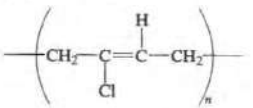
Table 5-6 lists the principal elastomers used as insulation and jacketing on wires and cables. Comparative properties are shown in Table 5-3 (p. 144) in this chapter.

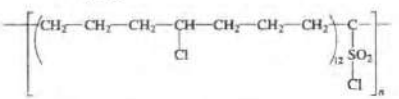
ASTM Standards for Extruded Organic Elastomer Compounds

The American Society for Testing and Materials has developed the following standards for extruded organic elastomer compounds:

- D 353, *Natural Rubber Insulation for Wire and Cable, 60°C Operation*
- D 469, *Natural Rubber Heat-Resisting Insulation for Wire and Cable, 75°C Operation*
- D 532, *Natural Rubber Jacket for Wire and Cable*
- D 866, *Styrene-Butadiene (SBR) Synthetic Rubber Jacket for Wire and Cable*

TABLE 5-6 Summary of Characteristics of Selected Elastomers

ELASTOMER	SUPPLIERS	CHEMISTRY	ADVANTAGES	LIMITATIONS
Polyisoprene (IR)	Goodyear Chemical Goodrich Chemical Shell Chemical	Synthetic equivalent to natural rubber. Vulcanize cure. 	Controlled molecular weights. Good dielectric and mechanical properties at room temperature.	Poor aging properties. Low ozone resistance. Attacked by halogenated, aliphatic, and aromatic hydrocarbons, mineral and vegetable oils, oxidizing chemicals. Poor flame resistance.
Butyl Rubber (IIR)	Exxon Chemical	Copolymer of isobutylene with 2 to 3% isoprene. Vulcanize cure. 	Dielectric properties about the same as IR. Better resistance to aging and oxidation. Resistant to mineral and vegetable oils. Low gas permeability.	Low resilience at room temperature. Attacked by halogenated, aliphatic, and aromatic hydrocarbons, and concentrated acids. Poor flame resistance.
Styrene Butadiene Rubber (SBR) (GR-S)	Goodyear Chemical Goodrich Chemical Phillips Chemical	Copolymer of butadiene (75%) and styrene (25%). Vulcanize cure. 	Low cost. Dielectric properties about the same as IR. Also mechanical properties.	Lower tensile strength, resilience, and heat resistance than IR. Attacked by halogenated, aliphatic, and aromatic hydrocarbons, mineral and vegetable oils, oxidizing chemicals, and sunlight. Poor flame resistance.
Chloroprene Rubber (CR) (Neoprene™)	Du Pont	Polymerized 2-chlorobutadiene-1,3. Vulcanize cure. 	Better resilience than IR to high temperatures, weathering, oxidation, aliphatic hydrocarbons, bases, oils. Good mechanical properties and flame resistance.	Lower dielectric properties than IR. Attacked by halogenated and aromatic hydrocarbons, esters, and concentrated oxidizing acids and agents.

Chlorosulfonated Polyethylene (CSM) (Hypalon™)	Du Pont	Made by reacting PE with sulfur dioxide and chlorine. Vulcanize cure. 	Excellent resistance to abrasion, moisture, high humidity, ozone, oils, weathering, underground environments. Superior flexibility. Good flame resistance.	Lower dielectric properties than IR. Attacked by halogenated, aliphatic, and aromatic hydrocarbons, gasoline, aldehydes, and ketones.
Ethylene Propylene Rubber (EPR), (EPM) and Ethylene Propylene Diene Rubber (EPDM)	Du Pont Uniroyal Exxon Chemical Goodrich Chemical	Copolymer of ethylene and propylene. Terpolymer of ethylene, propylene, and 1,4 hexadiene or ethylidene norbornene. Vulcanize cure.	Low specific gravity. Superior resistance to ozone, corona cutting, weathering, heat, hot water, steam, acids, bases, alcohols, esters, ketones.	Poor flame resistance. Attacked by halogenated, aliphatic, and aromatic hydrocarbons, turpentine, and oils.
Chlorinated Polyethylene (CPE)	Dow Chemical	Made by randomly chlorinating HDPE to resin containing 25–48% chlorine. Vulcanize cure.	Excellent resistance to ozone, weathering, heat aging, oils, bases, most acids, alcohols. Low cost. Blends well with other polymers.	Lower dielectric and mechanical properties than most other elastomers. Forms toxic fumes on burning. Attacked by halogenated and aromatic hydrocarbons.
Thermoplastic Rubber (TPR)	Reichhold Advanced Elastomer Systems	Physical blend of EPDM (5 parts) and polyolefins (3 parts). Reichhold's TPR is partially prevulcanized. Santoprene™ (Advanced Elastomer Systems) is fully prevulcanized. Both are thermoplastic.	Low specific gravity. Excellent dielectric properties. Good resistance to heat aging, ozone, UV radiation, organic acids and bases. Low temperature flexibility. Thermoplastic processing.	Relatively low physical properties. Attacked by halogenated and aromatic hydrocarbons.

- D 1352, *Ozone-Resisting Butyl Rubber Insulation for Wire and Cable*
- D 1523, *Synthetic Rubber Insulation for Wire and Cable, 90°C Operation*
- D 1679, *Synthetic Rubber Heat- and Moisture-Resisting Insulation for Wire and Cable, 75°C Operation*
- D 2768, *General-Purpose Ethylene-Propylene Rubber Jacket for Wire and Cable*
- D 2770, *Ozone-Resisting Ethylene-Propylene Rubber Integral Insulation and Jacket for Wire and Cable*
- D 2802, *Ozone-Resistant Ethylene-Propylene Rubber Insulation for Wire and Cable*
- D 4203, *Styrene-Acrylonitrile (SAN) Injection and Extrusion Materials*
- D 4244, *General-Purpose, Heavy-Duty, and Extra-Heavy-Duty Acrylonitrile-Butadiene/Polyvinyl Chloride (NBR/PVC) Jackets for Wire and Cable*
- D 4245, *Ozone-Resistant Thermoplastic Elastomer Insulation for Wire and Cable, 90°C Dry/75°C Wet Operation*
- D 4246, *Ozone-Resistant Thermoplastic Elastomer Insulation for Wire and Cable, 90°C Operation*
- D 4247, *General-Purpose Black Heavy-Duty and Black Extra-Heavy-Duty Polychloroprene Jackets for Wire and Cable*

ICEA/NEMA Standard for Rubber Insulated Wire and Cable

The Insulated Cable Engineers Association (ICEA) and the National Electrical Manufacturers Association (NEMA) have jointly approved the following standard for Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy:

- NEMA WC 3/ICEA S-19

UL Standard for Insulated Wires and Cables

Underwriters Laboratories (UL) has approved the following standard:

- UL 44, *Rubber-Insulated Wires and Cables*

Grades

Electrical grades are available from several, but by no means all, suppliers of elastomers and elastomer compounds. Compounding is generally done at the fabricator's plant with due consideration given to recommendations by suppliers, based on intended application and type of process equipment to be used.

Processing

The compounding of elastomers and blends of elastomers is very complex, often involving recipes with 10–15 or more ingredients. Depending on the elastomer(s) and curing system, ingredients may include:

- The elastomer(s), up to 50 percent by weight
- Sulfur or sulfur compounds as crosslinking agents, 2 percent or less.
- A peroxide curing agent, such as dicumyl peroxide, 3 percent or less.
- A rubber accelerator, such as dipentamethylene thiuram hexasulfide (Du Pont's Tetrone A™ or 2-mercaptobenzothiazole), 2 percent or less.
- A curing promoter to improve scorch and insulation resistance, such as N,N′-*m*-phenylenediamaleide (Du Pont's HAV-2™), 1 percent or less.
- A metal oxide acid acceptor and vulcanizing agent, such as sublimed letharge (PbO) or dibasic lead phthalate, up to 5 percent.
- A hydrogenated wood rosin to activate compounds containing litharge, such as Stabelite Resin™ (Hercules), 1 percent or less.
- A stabilizer to improve heat resistance, such as nickel dibutyldithiocarbamate (Du Pont's NBC™), 2 percent or less.
- Carbon black to improve weathering properties, up to 25 percent.
- A lubricant, such as paraffin or petrolatum, up to 12 percent.
- A hindered phenol antioxidant, 3 percent or less.
- A filler, such as calcined clay or kaolin, up to 50 percent.
- A plasticizer, such as phthalate ester, chlorinated paraffin, or alkyl substituted trimellitate.

There are three basic curing systems in general use for elastomers:

- *Conventional curing* using vulcanizing agents such as:
  —Sulfur or sulfur-containing compounds, often with metal/organic activators.
  —Organic peroxides, which usually produce better dielectric properties and water resistance with no tendency to form metal sulfides.
- *Lead sheath curing*, which prevents sponging as compound is vulcanized.
- *Radiation curing*, with less tendency to scorch, faster extrusion rates, and reduced heat build-up during cure.

The first of these uses continuous vulcanization processing in equipment 100–350 feet in length (30–108 meters), incorporating pay-off reel, extruder, pressurized steam tube, pressurized water cooling chamber, capstan, cooling trough, and take-up reel. The system may be arranged so the cable travels horizontally, vertically, or with the pay-off reel and extruder on a level above the water-cooling chamber, permitting the cable to hang loose in the slanted steam tube (the catenary system). Production rate depends on cable size, thickness of extrudate, steam pressure, length of curing tube, and cure rate of compound.

Lead sheath curing involves formation by lead presses of a tight lead covering over the insulated or jacketed cable. Processing may be continuous or batch operation, although storing cable at least 24 hours before applying the lead sheath improves quality. After leading and reeling, cable ends are sealed and the cable is cured in steam vulcanizer at from $1\frac{1}{2}$ to $4\frac{1}{2}$ hours at 235°–265°F (113°–130°C). After curing, the cable is rapidly cooled with water to reduce internal pressure and the possibility of rupture

of the lead sheath. Finally, the lead is stripped from the cable, cut into chips, and reused.

Radiation, or electron beam curing, covered by U.S. Patent 3.990.479 assigned to Samuel Moore Company, utilizes high-energy radiation to crosslink polymers through formation of free radicals. Radiation dosage controls the density of crosslinking. However, required dosage levels are unique with each polymer. Choice of compound is very selective with this method. Highly unsaturated or highly aromatic plasticizers should be avoided.

While electrical applications for elastomers are mostly for cable jackets, there is also some usage as primary insulation on low-voltage conductors. Here, and also in the lead-press curing method where compound comes in direct contact with metal, vulcanizing with sulfur and sulfur-containing compounds may result in the formation of undesirable metal sulfides.

Electrical/Electronic Uses

Elastomers are used extensively as jackets on wires and cables, and to a lesser extent as primary insulation in certain applications:

- Welding cable jackets (EPDM), (CR), (TPR)
- Motor lead wire insulations in corrosive environments (CSM)
- X-ray cables (CSM)
- 600 volt power cable insulation/jacket
- Semiconducting shield (CPE)
- Jackets for mine excavator trailing cables (CR)
- Building wire and cable (CR), (EPDM), (SBR)
- Control cable jackets (CR), (CSM), (EPDM), (SBR)
- Trailer cable (TPR)
- Apparatus and portable cords (EPDM), (SBR), (CR), (CSM)
- Appliance cord (CSM), (TPR), (EPDM)
- Roadway heating cables (CSM)
- Primary wiring for trucks (CSM), (TPR), (EPDM)

In addition, there are electrical applications for molded elastomers:

- Connectors (CR), (TPR)
- Direct-burial telephone cable termination enclosures (CR)
- Encasements for underground transformers (CR)

6

Embedding Compounds

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INTRODUCTION

As used in this handbook, the term *embedding* includes encapsulating, potting, casting, and dipping processes employing a compound that may be cured either at room or elevated temperature. Coatings and impregnants are covered in Chapter 8.

All embedding processes involve encasing electrical/electronic parts in plastic with or without the use of molds. The parts are thus protected dielectrically and physically, ensuring greater reliability and longer life than otherwise would be the case.

This chapter covers the major embedding resins, namely, epoxies, polyesters, polyurethanes, and silicones. Other resins are also used to embed electronic parts employing injection molding and low-pressure transfer molding processes. For information on these resins, see Chapters 3 and 4, *Thermoplastic Molding Compounds* and *Thermosetting Molding Compounds*.

CRITICAL PROPERTIES

To perform the processing, protective, and dielectric functions of a good encapsulant, critical properties include:

- A high degree of purity ensuring the absence of ionic and other contaminants
- Long pot life
- Low toxicity
- Ease of application and clean up
- Initial low viscosity to facilitate flow and penetration into the interstices of the part being encapsulated
- Ability to cure with low exotherm and without formation of water, corrosive, or volatile reaction products
- Low shrinkage on curing
- Good adhesion to materials to be encapsulated
- Toughness and resiliency to accommodate differences in thermal expansion within a system
- Adequate dielectric properties
- Good thermal properties to dissipate heat quickly
- Satisfactory resistance to thermal shock and thermal cycling
- High-moisture, chemical, and solvent resistance
- Low degradation by ultraviolet radiation
- Wide useful temperature range
- Long service life without loss of properties
- Low cost

Epoxies generally satisfy these criteria best and are most widely specified. Urethanes, once widely accepted by the Military, fell from favor for critical applications

because of poor hydrolytic stability. Subsequently, however, their hydrolytic stability was improved and their use has increased significantly. Other encapsulants in common use are polyesters and silicone.

FILLERS

While unfilled systems have the least water absorption—a desirable dielectric feature—there are important advantages to be realized by judicious use of fillers in embedding applications for electrical/electronic parts. With most systems, the tendency of a casting to crack can be a major problem. This is caused by the difference in thermal expansion of the cast part and the embedding material. This disparity in expansions can be significantly reduced or eliminated by adding the proper filler in sufficient quantities to formulations.

Certain fillers increase thermal conductivity in resin systems, lessening the likelihood of overheating, weight loss, and shrinkage. Pot life on the system can also be extended by fillers. Dielectric properties, however, are usually not improved by fillers and may be adversely affected in humid environments by fillers which readily absorb water.

Fillers may be classified as follows:

- Bulk fillers
  - —Sand (lowest cost, good thermal conductivity and compressive strength, and low shrinkage)
  - —Silica (same features as sand, good dielectric properties)
  - —Talc (excellent machinability, low shrinkage, low cost)
  - —Clay (excellent machinability, good thermal shock resistance and compressive strength, low shrinkage, low cost)
  - —Calcium carbonate (excellent machinability, low shrinkage, low cost)
  - —Anhydrous calcium sulfate (excellent arc resistance, good thermal conductivity and compressive strength, low shrinkage, low cost)
- Reinforcing fillers
  - —Mica (excellent impact resistance, good thermal shock resistance, low cracking, low cost, good dielectric properties)
  - —Asbestos (same features as mica, but a known health hazard)
  - —Wollastonite (excellent impact resistance, good thermal conductivity and thermal shock resistance, low cost)
  - —Wood flour (low density, good thermal shock resistance, low cost)
  - —Sawdust (same features as wood flour)
- Specialty fillers
  - —Quartz (low coefficient of expansion, good thermal conductivity and mechanical properties, low shrinkage, low cracking, good dielectric properties)
  - —Alumina (low coefficient of expansion, good thermal properties and compressive strength, low shrinkage)
  - —Alumina trihydrate (excellent arc resistance, flame retardant)

—Lithium alumina silicate (low coefficient of expansion and shrinkage, high conductivity and compressive strength)
—Beryl (same features as lithium alumina silicate)
—Silica aerogel (excellent nonsettling)
—Bentonite (excellent nonsettling)
—Graphite (high electrical conductivity, good machinability)
—Ceramic spheres (low density)

Fillers should mix well in compounds without settling or excessively increasing viscosity. Most fillers tend to reduce compound cost, although not in direct ratio to the amount of filler incorporated because compound density is increased more than compound volume.

FEDERAL SPECIFICATION MIL-I-16923

The title of this specification is *Insulating Compound, Electrical, Embedding*. This specification is approved for use by all departments and agencies of the Department of Defense. It covers a general purpose casting and potting compound which has excellent electrical and hydrolytic stability characteristics, and which can preserve the electrical properties of the equipment to which it is applied by sealing against such environmental conditions as moisture, dirt, fumes, fungus, or other deleterious substances which may be encountered in military service. This is a performance specification, and all products that qualify are included in a qualified products list.

Key qualitative requirements include the following:

• The material shall cure throughout to a permanently infusible state without volatile loss. It shall be of sufficiently low viscosity, and shall have such wetting properties at the pouring temperature that it will flow between elements of the part

TABLE 6-1 Key Properties Required of Embedding Compounds (MIL-I-16923)

PROPERTY	VALUE
Dielectric strength, volts/mil, minimum, 1/8 in	325
Dielectric constant	
60 Hz, maximum	5.0
1 MHz, maximum	4.5
Dissipation factor	
60 Hz, maximum	0.04
1 MHz, maximum	0.05
Volume resistivity, Ω·cm, minimum	
As received	1×10^{13}
After conditioning	1×10^{12}

Note: The above are room temperature values and were obtained in accordance with Federal Specification FED-STD-406

or parts of the assembly to be embedded, displacing all air and leaving no voids, and both the pouring and curing temperature shall not exceed 266°F (130°C). The material shall be capable of mechanically supporting the part or assembly embedded and shall not require a case or other external support after curing has been completed, and shall not cause deterioration of materials in electronic assemblies and parts.

- Cast specimens shall be self-extinguishing when tested according to the specified procedure.
- Cast specimens shall not exhibit softening, blistering, or warping after moisture conditioning at 158°F (70°C), 95 percent relative humidity, for ten days.

Table 6-1 shows values for key properties required by this specification.

ASTM STANDARD FOR EMBEDDING COMPOUNDS

The American Society for Testing and Materials (ASTM) formerly established the following standard, now discontinued, but which contains a listing of current applicable property tests:

- D 1674, *Polymerizable Embedding Compounds Used for Electrical Insulation.*

These compounds must cure without pressure and may or may not require heat to accomplish the reaction. When cured, they are required to electrically insulate and mechanically protect and support the part or assembly without a case, pot, or other external support. Table 6-2 lists test methods.

TABLE 6-2 Property Tests for Embedding Compounds (ASTM D 1674)

PROPERTY MEASURED	ASTM TEST METHOD
Sampling	D 1674
Specimen preparation and conditioning	D 618
Hardness	D 2240
Coefficient of linear thermal expansion	D 696
Specific gravity	D 792
Coefficient of thermal conductivity	D 1674
Thermal shock resistance	D 1674
Dielectric constant and dissipation factor	D 1674
Dielectric strength	D 1674
Arc resistance	D 495
Effect of high humidity	D 1674
Flame resistance (ignition time and burning time)	D 229
Dielectric strength of embedded electrodes	D 149

EMBEDDING PROCESSES

There are several embedding processes in general use, with curing accomplished either at room or elevated temperature:

- *Bench casting* involves pouring the casting compound around the part to be protected placed in a mold. The cast part is removed from the mold after the material is cured. Precautions must be taken to eliminate air bubbles, including careful pouring, slowly warming the liquid to permit bubbles to escape before curing occurs, vibration, and vacuum degassing prior to pouring.
- *Vacuum casting* is best accomplished by pouring under vacuum, thus permitting escape of entrapped air and moisture from the part as well as air bubbles from the liquid. When pouring is done at room temperature, the liquid is likely to foam and froth, requiring precise control of the evacuation process.
- *Pressure casting*, often used after vacuum casting, involves pressurizing the chamber. Minute bubbles may form from somewhat volatile curing agents, making it necessary to increase the pressure by means of centrifugal action to 1,000 psi.
- *Dip casting* is simply dipping the part to be encased in the liquid, which is formulated to control runoff as the part is removed.
- *Spraying* is a suitable method where the configuration of a part permits a uniform coat to be applied.
- *Dropping* a precisely measured amount of material using a microsyringe, or "eyedropper," is a commonly employed technique for embedding small electronic parts. This process may be automated by moving the components on conveyors past automatic dispensers.
- *Potting* is similar to bench casting, but requires a permanent case.
- *Pot-on-sand* technique is employed for high-volume automotive parts. A two-component epoxy is used with a recommended sand in the ratio of approximately four parts of sand to one part mixed epoxy. The component case is vibrated to pack the sand to maximum density. Then, the case is heated to the curing temperature of the epoxy, after which the resin is poured on the sand in the desired amount. Curing is completed in a circulating air oven.
- *Fluidized-bed, or powder coating* is described under "Development Programs" (p. 206) in Chapter 7, *Magnet Wire Enamels*.
- *Compression molding* is described in Chapter 4, *Thermosetting Molding Compounds*.
- *Transfer molding* is described in Chapter 4, *Thermosetting Molding Compounds*.
- *Injection molding* is described in Chapter 4, *Thermosetting Molding Compounds*.

Barrier or stress-relief coatings are often applied first to attach electronic components prior to embedment. They serve as protection from mechanical and thermal shock and to relieve stresses from differences in coefficients of expansion between the

encapsulant and substrate. These coatings must be flexible and possess a low modulus of elasticity as well as providing protection from moisture, gases, and corrosion. Silicones are often used as barrier coatings for parts subsequently embedded in epoxies.

CURING SYSTEMS

In addition to traditional curing at room temperature or with applied heat, low-intensity ultraviolet (UV) light curing promoted by Polychem Corporation is suitable for specially formulated compounds, including epoxies, acrylics, polyurethanes, and blends. Ultraviolet light can be artificially produced by an arc lamp equipped with special glass transparent to UV rays. UV curing compounds for this system are single-component products requiring no mixing. Photoinitiators in the compound react to a specific wavelength of low-intensity UV light. The speed of the reaction is governed by the intensity of the light source, although the relationship between speed of curing and UV light intensity is not linear (doubling the intensity does not necessarily cut the curing time in half). This system is reported to be effective for deep curing sections of over 1 inch and is less than 1 minute with certain formulations.

DEVELOPMENT PROGRAMS

Development of improved embedding compounds focuses on materials with low toxicity that are easy to apply, have minimal shrinkage, and cure rapidly free of voids and volatile components.

MARKET TRENDS

There is increasing usage of polyurethanes, both for military and nonmilitary applications, now that hydrolytic stability of these resins has been improved.

While there may be pauses in the enactment and enforcement of environmental and worker safety regulations, the trend toward use of lower toxicity embedding materials will continue.

TABLE 6-3 Comparative Characteristics of Encapsulants

	CHARACTERISTIC					
Encapsulant	Dielectric	Adhesion	Shrinkage	Maximum Service Temp. °C	Chemical Resist.	Cost
Epoxy	Excellent*	Excellent	Low	155	Good	Moderate
Polyester	Good	Fair	High	180	Poor	Low
Polyurethane	Good*	Good	Moderate	130–155	Fair	Moderate
Silicone	Excellent	Low	Low	200+	Good	High

*PURs retain their dielectric properties better than epoxies at the upper end of their useful temperature range.

COMPARATIVE CHARACTERISTICS OF ENCAPSULANTS

Table 6-3 compares key properties of principal encapsulants. In terms of usage, epoxies predominate.

PRINCIPAL EMBEDDING POLYMERS FOR ELECTRICAL/ELECTRONIC USES

The chemistry, grades, properties, and electrical/electronic uses of principal embedding polymers are described in the sections which follow in this order:

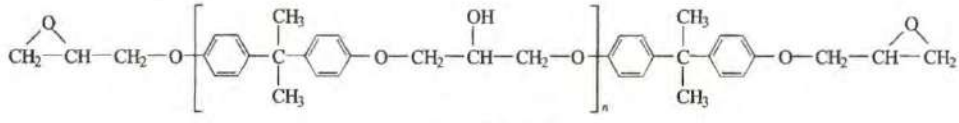
- Epoxies
- Polyesters
- Polyurethanes
- Silicones

Epoxies (Embedding Resins)

Epoxies have been in general use since 1947, and have since gained a predominant position as embedding resins. This section covers electrical grade epoxy embedding resins. Producers of epoxy polymers include Ciba Geigy (Araldite™), J. C. Dolph (Dolphon™), Dow Chemical (D.E.R.™, D.E.N.™, Quatrex™), P. D. George (Sterling—Thermopoxy™), Hoechst Celanese (Epi-Rez™), Shell (Epon™), and Union Carbide (Bakelite™). Principal formulators include Conap (Conapoxy™), Emerson & Cuming (Stycast™), Epoxylite, Epic Resins Division General Fiberglass Supply, Fiberite, Hysol Division The Dexter Corp., Rexnord (Norbak™), and Thermoset Plastics. Major users often formulate their own epoxies. For information on epoxies in coatings and impregnants, thermosetting molding compounds, and clad and unclad structures, see appropriate chapters.

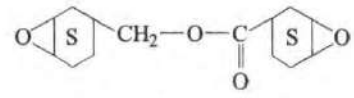
Chemistry

Although there are many variations, the basic epoxy resin is the polycondensation product of bisphenol-A and epichlorohydrin:



basic epoxy resin

Cycloaliphatic epoxies are produced by epoxidation of cyclic olefinic compounds with peracetic acid:



alicyclic diepoxy carboxylate

Epoxy novolacs are covered in "Epoxies" (p. 126) in Chapter 4, *Thermosetting Molding Compounds*.

To be made into useful end products, epoxies must be cured by the action of hardeners. Some hardeners cause curing by reacting with the epoxide group and becoming part of the polymer. Other hardeners promote the resin's self-polymerization by catalytic action. There are several types of hardeners:

- *Primary, secondary, and tertiary aliphatic amines* are the most commonly used hardeners in concentrations of 4 to 20 parts per hundred parts of resin (phr). Curing proceeds at room temperature. Properties may be improved by postcuring for 2 hours at 200°F (93°C). Systems may be toxic.
- *Primary, secondary, and tertiary aromatic amines* require elevated temperatures for curing. They impart longer pot life and improved thermal, mechanical strength, and chemical resistance properties. They produce harder cured systems than aliphatic amines. Systems may be toxic.
- *Polyamides* affect curing at room temperature, producing tough, resilient systems with good moisture resistance and excellent adhesive properties in low-heat applications. Polyamides are the condensation polymers of dimerized or trimerized vegetable oils, or of unsaturated fatty acids, with polyamines. Ratio of epoxy to polyamide may range from 80/20 to 40/60 by weight.
- *Anhydrides*, derived from dicarboxylic acids, require a temperature of 250°F (121°C) for rapid curing. These hardeners in concentrations of 30 to 140 phr produce cured systems with good thermal, mechanical, and dielectric properties. Systems have long pot life and are generally not toxic.
- *Tertiary amines* may be used as accelerators for other hardeners, but tend to increase toxicity.
- *Urea-formaldehyde or phenol-formaldehyde resins* may be crosslinked with epoxies, usually by baking, to produce high-molecular-weight polymers.

Flame resistance of epoxy systems may be improved by incorporating into recipes phenols and anhydrides containing bromine, chlorine, and phosphorous, as well as antimony oxide (antimony trioxide).

The viscosity of liquid epoxies may be reduced by reactive diluents such as allyl, butyl, and phenyl glycidyl ether, or styrene oxide. Unreactive diluents such as dibutyl phthalate are also used for this purpose, acting also to plasticize and add flexibility to cured systems.

Grades

For large-scale production, compounds are usually prepared in house. Formulations are tailored for each end use with little or no duplication because of the virtually

unlimited possible combinations of resins, hardeners, accelerators, fillers, and other additives.

Lower volume production requirements are served by scores of merchant compounds offering a wide range of formulations, including one- and two-part, room temperature and oven curing. Producers of basic resins provide technical service and make referrals to assist manufacturers with embedding applications suitable for epoxies.

Processing

Two-part epoxy systems, generally preferred for dielectric applications, may be either room temperature curing or oven curing. The pot life of room temperature curing systems is typically in the 30 minute to 2 hour range, although special formulations may extend pot life to one working day. The most commonly employed ratio of epoxy resin to hardener is one to one. However, practical ratios may be as high as 100 parts epoxy resin to one part hardener. To facilitate uniform mixing, resins and hardeners are usually of different colors. Mixing continues to the point where a uniform color is obtained.

For high-volume production, a heat curing system consisting of resin, hardener, and accelerator, with pot life of 2 to 4 days, is most satisfactory. Oven curing is accomplished at 250°F (121°C) for 2 to 4 hours.

Proper precautions are required to handle epoxy systems safely. Included in these systems are solvents used to clean equipment. Hazards include the following:

- Skin irritation—some workers are highly susceptible
- Ingestion—materials are toxic
- Inhalation—vapors and dust from materials are toxic
- Precutaneous absorption—materials are toxic when absorbed through the skin, as by direct contact with contaminated clothing
- Eyes—materials may cause severe eye burns
- Flammability—solvents are likely to be highly flammable

Some room temperature curing epoxy formulations, especially those with polyamines, are characterized by high exothermic reactions on curing, and measures should be taken to ensure that the temperature rise is adequately controlled. Thus, there may be an epoxy mass limit for some systems over which exotherm control becomes impractical.

See also "Embedding Processes" (p. 181) in this chapter.

Properties

Epoxies are the most widely used embedding resins because of their many outstanding characteristics:

- Excellent dielectric properties
- Superior adhesion to most surfaces
- Low shrinkage during cure

- Good thermal properties
- Good chemical resistance
- Good moisture resistance, depending on fillers
- Properties may be varied widely to suit specific end uses

Cycloaliphatic epoxies are characterized by superior arc-track resistance, high heat deflection temperatures, and good weathering properties.

The dielectric properties of epoxies tend to decrease more rapidly than for other polymers at the upper end of their useful temperature range.

Table 6-4 shows key property values for a typical electrical grade embedding resin.

Electrical/Electronic Uses

Epoxies are widely used for embedment of components for transformers, motors, generators, switchgear, coils, capacitors, resistors, and electronic modules. Cycloaliphatic epoxies are used for large, high-voltage bushings.

TABLE 6-4 Key Properties of Typical Two-Part Oven Curing Electrical Grade Epoxy Embedding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.14
Dielectric strength, 125 mils, short time, V/mil*	D 149	500
Dielectric constant*	D 150	
60 Hz		3.9
10^6 Hz		3.2
Dissipation factor*	D 150	
60 Hz		0.04
10^6 Hz		0.03
Volume resistivity, Ω·cm*	D 257	3.9×10^{14}
Arc resistance*	D 495	45
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.16
Deflection temperature, 264 psi, °F (°C)	D 648	
Maximum recommended service temperature °F (°C)		311 (155)
Tensile strength at break, psi*	D 638	2,400
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		0.40
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		na
Oxygen index, %	D 2863	
Standard grade		na

*At room temperature.

na = not available.

Polyesters (Embedding Resins)

The term *polyester* encompasses a variety of materials used in many forms as dielectrics, including thermoplastic and thermosetting molding compounds, embedding compounds, wire enamels, coatings and impregnants, and films, all covered in appropriate chapters in this handbook. Use as an encapsulant, while not uncommon, is overshadowed by epoxies for most dielectric applications. The principal supplier of polyester for embedding electrical and electronic parts is P. D. George (Sterling—Thermopoxy™).

Chemistry

For a discussion of the chemistry of polyesters used to make embedding resins, see "Alkyds/Polyesters" (p. 119) in Chapter 4, *Thermosetting Molding Compounds* and "Unsaturated Polyesters" (p. 248) in Chapter 8, *Insulating Coatings and Impregnants*.

Processing

High shrinkage, an inherent problem with polyesters, may be somewhat controlled by judicious use of selected fillers. Relatively high hydrolytic instability of polyesters compared with epoxies is another concern when high-humidity environments are encountered. When peroxide catalysts are used and the embedding compound comes into direct contact with exposed copper, corrosion may occur. See also "Embedding Processes" (p. 181) in this chapter.

Electrical/Electronic Uses

Polyesters are low cost, and are satisfactory for use in many applications not requiring the generally superior properties of epoxies and polyurethanes.

Polyurethanes (PURs) (Embedding Resins)

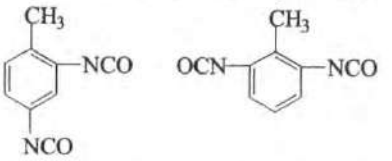
The basic work on polyurethanes was done in Germany in the late 1930s, but commercial products were not available in the U.S. until after World War II. The principal ingredients of polyurethane resins and their suppliers include the following:

- Diphenylmethane diisocyanate (MDI): Mobay, Rubicon, Upjohn
- Toluene diisocyanate (TDI): Allied, BASF, Dow Chemical, Du Pont, Mobay, Olin Chemicals, Rubicon, Spencer Kellogg, Union Carbide
- Aliphatic isocyanates: Mobay
- Polyols: about 20 producers, the majors being Du Pont, Dow, Olin Chemicals, Union Carbide, Upjohn, Witco, and Wyandotte
- Castor oil: Baker, Spencer Kellogg

Major suppliers of polyurethane embedding compounds are Conap (Conathane™), Dexter (Hysol™), and P. D. George (Sterling).

Chemistry

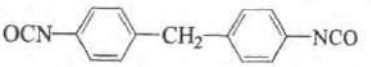
The basic building blocks of polyurethane resins are di- or poly-isocyanates, commonly a mixture of 80 percent toluene-2,4-diisocyanate and 20 percent toluene-2,6-diisocyanate:



toluene-2,4 diisocyanate

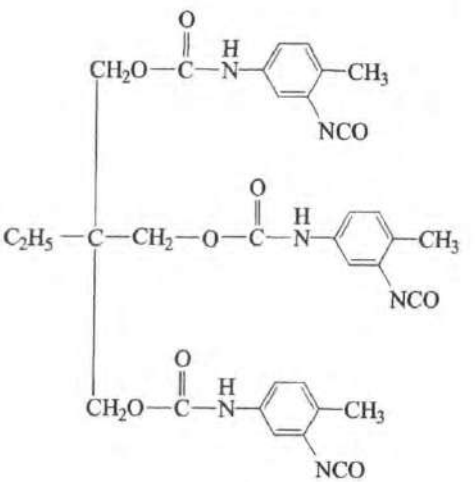
toluene-2,6 diisocyanate

or



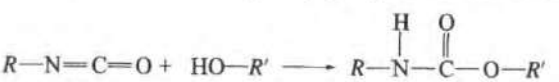
p,p'-diphenylmethane diisocyanate

Because of the high toxicity of toluene diisocyanate, it is usually formed into a prepolymer by reaction with a polyol, such as triethylolpropane, which combines with three of the six available isocyanate groups to form a low-vapor-pressure adduct safe to work with:



urethane adduct

The urethane linkage occurs when a hydroxyl group reacts with an isocyanate group:



isocyanate — hydroxyl compound — urethane resin

where R is an aliphatic or aromatic hydrocarbon group.

When polyisocyanates combine with polyols, the resulting products are polyurethanes. The polyurethanes used as embedding resins are usually two-component polyol-cured resins ASTM Type 5. With increasing ratio of triols to diols, crosslinking is increased. Commonly used materials include hydroxyl-terminated polyesters, polyethers, and castor oil, as well as epoxies with free hydroxyl groups in their structure.

Polyurethane Classification

The principal types of polyurethanes are classified by the American Society for Testing and Materials (ASTM) as follows:

Type 1: One-component urethane alkyds, or oil modified urethanes, are formed by the reaction of a diisocyanate with vegetable oils, or their fatty acids, and polyhydric alcohols. They cure rapidly by oxidation in as few as 10 minutes. Uses include insulation and conformal coatings, wood, metal, and marine finishes.

Type 2: One-component moisture-cured urethanes are isocyanate prepolymers made by reacting polyols with excess isocyanate. When exposed to humid air, the amino groups initially formed react with more isocyanate generating urea linkages and releasing carbon dioxide. Films, which must be thin to prevent entrapment of gas, are extremely tough and find use in seamless floors, bowling alleys, gym floors, industrial floors, and insulating coatings.

Type 3: One-component heat-cured urethanes contain phenol-blocked isocyanates. When heated to 160°C (320°F), the phenol is expelled and the liberated isocyanate then reacts with a polyol. This type is widely used in magnet wire enamels.

Type 4: Two-component catalyst cured urethanes are similar to Type 2 urethanes, but are cured with catalysts, such as tertiary amines, forming urea linkages. This type is used for textile finishes and also for floor coatings.

Type 5: Two-component polyol-cured urethanes are made by reacting isocyanate prepolymers with hydroxyl-terminated polyesters, or polyols such as castor oil. This is the principal type used in solvent-base and solventless insulating coatings.

Type 6: Thermoplastic urethanes are the reaction product of isocyanates with polyester or polyether diols. They have high molecular weight and are supplied as lacquers in ketone or ester solvents. They are used as textile coatings to give the "wet look."

Federal Specification MIL-M-24041

The title of this specification is *Molding and Potting Compound, Chemically Cured, Polyurethane*, and it covers the requirements of two-component, chemically cured, polyurethane compounds for the molding, encapsulating, and potting of watertight electrical connectors, cables, cable end seals, circuit boards, and other electrical and electronic components.

Compounds covered are of the following categories and types:

Category A—(4,4′ Methylene BIS (2-chloroaniline) cured)
Category B—(Non-4,4′ Methylene BIS (2-chloroaniline) cured)
Type I—Two-component units
Type II—Premixed, degassed, and frozen

Referenced standards include the following standards of the American Society for Testing and Materials (ASTM):

- ASTM D 149, *Dielectric Breakdown Voltage and Dielectric Strength of Electrical Insulating Materials at Commercial Power Frequencies*
- ASTM D 150, *A-C Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials*
- ASTM D 257, *D-C Resistance of Conductance of Insulating Materials*
- ASTM D 395, *Rubber Property—Compression Set*
- ASTM D 412, *Rubber Properties in Tension*
- ASTM D 495, *High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation*
- ASTM D 518, *Rubber Deterioration-Surface Cracking*
- ASTM D 624, *Rubber Property—Tear Resistance*
- ASTM D 792, *Specific Gravity and Density of Plastics by Displacement*
- ASTM D 1149, *Rubber Deterioration-Surface Ozone Cracking in a Chamber (Flat Specimens)*
- ASTM D 2240, *Rubber Property—Durometer Hardness*

Table 6-5 shows values for dielectric properties required by this specification.

TABLE 6-5 Dielectric Properties Required of Polyurethane Embedding Compounds (MIL-M-24041)

PROPERTY	VALUE
Dielectric strength, volts/mil, minimum, 1/8 in	250
Volume resistivity, Ω·cm, minimum	4×10^{11}
@ 250°F (121°C)	2.5×10^{9}
Surface resistivity, ohms, minimum	2.4×10^{12}
@ 250°C (121°)	2.4×10^{9}
Dielectric constant	
1 kHz, maximum	10
1 MHz, maximum	8
Power factor (approximate dissipation factor)	
1 kHz, maximum	0.08
1 MHz, maximum	0.10
Arc resistance, seconds, minimum	50

Note: The above are room temperature values unless otherwise stated.

Processing

A major concern in handling the ingredients for polyurethanes is their hygroscopic nature. When isocyanate and water react, an amine is formed, thereby decreasing urethane linkages. It is, therefore, essential to ensure that all ingredients and the storage environment are free of moisture. Isocyanates are also highly toxic, and precautions must be taken to control the environment where they are present and to provide adequate protection for workers handling them. See also "Embedding Processes" (p. 181) in this chapter.

Grades

Commercially available embedding products include Types 1, 2, and 5. Type 3 is used in wire enamel. Polyurethane modified polybutadiene grades are used where hydrolytic stability is a concern. Mixing ratios vary widely for electrical grades (13/100–100/39 by weight).

Properties

The outstanding feature of polyurethanes is their toughness and resistance to abrasion. Chemical resistance is fair to good, except for chlorinated solvents. Methylene chloride, for example, will strip polyurethanes off parts. Dielectric properties are retained better than those of epoxies at the upper end of their useful temperature range.

The formerly poor hydrolytic stability of polyurethanes has been overcome with the development and commercial availability of polyurethane-butadiene polymers.

TABLE 6-6 Key Properties of Selected Electrical Grade Polyurethane Embedding Resins

	ASTM TEST METHOD	TYPE 5 2-PART SOLVENTLESS FLEXIBLE VALUE	2-PART SOLVENTLESS POLYBUTYLENE-BASED VALUE
Specific gravity*	D 792	1.04	0.98
Dielectric strength 62.5 mils			
Short time, volts/mil*	D 149	645	610
Dielectric constant*	D 150		
100 Hz		5.71	3.14
10^6 Hz		3.42	2.87
Dissipation factor*	D 150		
100 Hz		0.123	0.030
10^6 Hz		0.038	0.011
Volume resistivity, Ω·cm*	D 257	3.1×10^{13}	2.1×10^{15}
Arc resistance, seconds*	D 495	180	>120
Water absorption, 24 h, %	D 570	0.40	0.40
Thermal class, °C		130	130
Tensile strength at break, psi*	D 638	800	1950
Cure time, days*		3–5	7

*At room temperature.

These materials pass government tests for 70 days at 100°C (212°F), 95 to 100 percent relative humidity, and for 120 days at 85°C (185°F), 95 to 98 percent relative humidity. Polyester polyurethanes are poorest in hydrolytic stability.

Table 6-6 shows key property values for typical electrical grade embedding resins.

Electrical/Electronic Uses

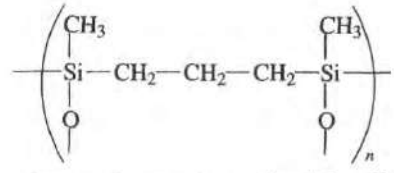
Polyurethanes are used for embedment of transformers, coils, switches, inductors, solid-state ignition systems, voltage regulators, ballasts, microcircuits, rectifiers, and printed circuit assemblies.

Silicones (Embedding Resins)

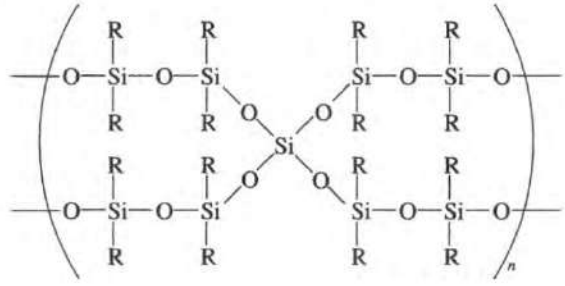
Silicones are used where parts are subject to higher or lower temperatures outside the operating limits of lower cost encapsulants. Electrical grade silicone encapsulating resins and room temperature vulcanizing (RTV) elastomers are made by Dow Corning, General Electric, Stauffer Chemical, and Thermoset Plastics.

Chemistry

Silicones for encapsulation of electrical/electronic parts are usually prepared by a process in which no water or other contaminant is produced during cure. Siloxane polymers containing methyl, vinyl, or allyl groups are polymerized by free-radical mechanism initiated by catalysts such as benzoyl, dichlorobenzoyl, or di-tertiary butyl peroxides. For example, it is hypothesized that when methyl vinyl silicone resin is heated with dichlorobenzoyl peroxide, two dichlorophenyl free radicals are formed as carbon dioxide is driven off. These free radicals add to the vinyl group of the silicone resin, thereby forming other free radicals which, in a complex exchange, develop into a methyl free radical on one polymer chain and an ethyl free radical on another. These chains now join, forming a propyl linkage with regeneration of dichlorophenyl free radicals:



Silicones which cure to room temperature vulcanizing (RTV) elastomers are prepared from mono-, di-, and trichlorosilanes, or mixtures thereof. These chemicals react with water to form silanols which may be polymerized by condensation with other hydroxy silicones or alkoxy silanes. Water or alcohol is a byproduct. Catalysts used to facilitate this reaction include triethanolamine, dibutyltin dilaurate, and metal salts of organic acids. Improved properties and shorter cures may be achieved by elevating curing temperatures. The structure of these cured silicones may be represented as follows:



Grades

Grades of the first type are available as clear or black, room temperature or heat curing. High-tear-strength and flame-retardant grades are also available. Grades are two-part, except for a one-part material, and are solventless.

RTV grades include pigmentable bases which are reversion-resistant. These grades are two-part.

Transparent dielectric gels are available for stress-free and vibration-dampening applications.

Federal Specification MIL-S-23586

The title of this specification is *Sealing Compound, Electrical, Silicone Rubber, Accelerator Required*. This specification is approved for use by all departments and agencies of the Department of Defense, and it covers the requirements for room temperature curing nonfuel-resistant silicone rubber compounds intended for use at temperatures ranging from –80° to 400°F (–62°–204°C) for various electrical applications on Military Weapons Systems.

There are three viscosities, low, intermediate, and high, and three curing rates, fast, medium, and slow. Three kinds of cure are specified:

Grade A—Condensation cure

Grade B1—Reversion resistant, condensation cure

Grade B2—Reversion resistant, addition cure

Referenced standards include the following standards of the American Society for Testing and Materials (ASTM)

- ASTM D 149, *Dielectric Breakdown Voltage and Dielectric Strength of Electrical Insulating Materials at Commercial Power Frequencies*
- ASTM D 150, *A-C Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials*
- ASTM D 257, *D-C Resistance or Conductance of Insulating Materials*
- ASTM D 412, *Rubber Properties in Tension*
- ASTM D 471, *Rubber Property—Effect of Liquids*
- ASTM D 495, *High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation*

TABLE 6-7 Dielectric Properties Required of Silicone Rubber Embedding Compounds (MIL-S-23586)

PROPERTY	LOW VISCOSITY GRADES		INTERMEDIATE VISCOSITY GRADES		HIGH VISCOSITY GRADES	
	A	B1, B2	A	B1, B2	A	B1, B2
Dielectric strength, volts/mil minimum*	400	400	400	400	400	400
Volume resistivity, Ω·cm, minimum	2×10^{14}	5×10^{13}	1×10^{14}	3×10^{13}	1×10^{14}	1×10^{14}
@ 300°F (140°C)	2×10^{12}	5×10^{11}	1×10^{13}	5×10^{11}	2×10^{12}	2×10^{12}
Surface resistivity, ohms, minimum	1×10^{15}	3×10^{14}	1×10^{15}	1×10^{15}	1×10^{15}	1×10^{15}
@ 300°F (149°C)	1×10^{14}	3×10^{13}	1×10^{14}	1×10^{14}	1×10^{14}	1×10^{14}
Dielectric constant						
1 kHz, maximum	4.5	4.5	4.5	4.5	4.5	4.5
1 MHz, maximum	4.5	4.5	4.5	4.5	4.5	4.5
Dissipation factor						
1 kHz, maximum	0.020	0.020	0.020	0.020	0.020	0.020
1 MHz, maximum	0.010	0.010	0.010	0.010	0.010	0.010
Arc resistance, seconds, minimum	100	100	100	100	100	100

*0.075 in thick sample.

Note: The above are room temperature values unless otherwise stated.

- ASTM D 746, *Brittleness Temperature of Plastics and Elastomers by Impact*
- ASTM D 2240, *Rubber Property—Durometer Hardness*

Table 6-7 shows values for dielectric properties required by this specification.

Processing

Working times depend primarily on resin composition, and catalyst type and concentration, and may vary from 1 minute to several hours. Materials are adaptable to automatic dispensing equipment. Grades which cure at room temperature require about 24 hours. Oven curing grades require 4 hours at 149°F (65°C). See also "Embedding Processes" (p. 181) in this chapter.

Properties

The two outstanding properties of silicone encapsulants are (1) their wide useful temperature range, –86° to 482°F (–65°–265°C), over which both dielectric and mechanical properties are quite stable; and (2) their extended life expectancy, which may be 100 times that of other suitable encapsulants. Class 180 insulation applies specifically

TABLE 6-8 Key Properties of Basic Clear Two-Part Heat Curing Electrical Grade Silicone Embedding Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.05
Dielectric strength, 125 mils, short time, V/mil*	D 149	550
Dielectric constant*	D 150	
60 Hz		2.7
10^6 Hz		2.7
Dissipation factor*	D 150	
60 Hz		0.001
10^6 Hz		0.001
Volume resistivity, Ω·cm*	D 257	2×10^{14}
Arc resistance*	D 495	na
Water absorption, 1/8 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		<0.10
Deflection temperature, 264 psi, °F (°C)	D 648	na
Maximum recommended service temperature °F (°C)		392 (200)
Tensile strength at break, psi*	D 638	900
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		na
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		V-1
Oxygen index, %	D 2863	
Standard grade		na

*At room temperature.

na = not available.

to silicones, indicating they may be used for long periods at 180°C (356°F). Dielectric properties are excellent.

The mechanical properties of silicones are lower than for other encapsulants and adhesion to most materials is inherently poor. The initial cost of silicones is significantly higher than for other encapsulants.

Table 6-8 shows key property values for a basic electrical grade embedding resin.

Electrical/Electronic Uses

The relatively high cost of silicones limits their usage to applications too demanding for other encapsulants. Uses include power supplies, relays, capacitors, amplifiers, coils, cores, connectors, circuit boards, subassemblies, and military components.

7

Magnet Wire Enamels

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INTRODUCTION

Magnet wire enamels are coatings which electrically insulate magnet coils used to energize electrical and electronic equipment, including motors, generators, transformers, solenoids, relays, and encapsulated units.

Because of their internal requirements, General Electric and Westinghouse were the pioneers in the early development of wire enamels. As the electrical industry rapidly expanded, Schenectady Varnish (now Schenectady International) and P. D. George became the principal enamel suppliers to magnet wire manufacturers without captive facilities. Today, most magnet wire companies produce at least some of their own enamel requirements.

COIL MANUFACTURE

To make field coils for motors and generators, magnet wire is wound to the desired shape on a mandrel or form. The coils are then bound by cord or tape. Coils for transformers are wound on tubes of insulating material. Layers of wire are separated by insulating grade paper or other dielectric material. Magnet wire is wound on bobbins specifically designed for each end use to make coils for electronic equipment. Most large coils are subsequently treated with insulating varnishes, which, on curing, provide additional insulation and give structural integrity to the coils. Small coils are often encapsulated with epoxy or polyester compounds.

BONDABLE MAGNET WIRE

Varnish impregnation of coils may be eliminated through the use of bondable top-coats such as polyvinyl butyral, polyamides, epoxies, and polyesters. The adhesive type is selected to retain bond strength at the rated thermal class of the magnet wire. Bondable magnet wire is formed into coils using the same equipment and techniques employed for standard magnet wire with the additional provision for activating the adhesive.

Adhesives are activated either by solvents or heat. In solvent bonding, the adhesive is activated either by passing the wire through a solvent-saturated wick or by spraying or brushing the solvent on the coil. The adhesive hardens as the solvent evaporates. In large, multilayer coils where evaporation paths are impeded, this process takes place slowly. This bonding method is for use in Classes 105 and 130 magnet wire. It is not recommended for higher classes. For Class 105, solvents include ethyl or methyl alcohol. Ethylene dichloride is suitable for Class 130 magnet wires.

Adhesives may also be activated by thermally curing coils formed with adhesive coated magnet wire. Baking temperatures are determined by the adhesive type and the thermal rating of the magnet wire. Baking time depends on coil configuration, and must be sufficient for heat to penetrate to inside windings. This can usually be accomplished within an hour.

Another method for heat bonding is to pass a high electric current, usually direct current, through the coil long enough to allow the temperature of the coil to rise to the flow

point of the bonding agent. Care should be taken to avoid hot spots within the coil. Where solderable insulation is used, temperatures throughout the coil should not exceed 180°C.

All these bonding methods produce fumes which must be effectively removed from the workplace with the minimum exposure to workers.

MAGNET WIRE MANUFACTURE

Magnet wire is composed of a copper or aluminum conductor covered with an insulating material, predominantly wire enamel. Other insulations include servings of paper, textiles, nylon, Dacron™, and glass with or without impregnants or coatings. Besides their dielectric function, these coverings provide protection against abrasion and winding stresses. Desirable properties in wire coverings include flexibility, windability, solderability without stripping, abrasion resistance, compatibility with insulating varnishes and compounds, and long service life.

In addition to round wire, conductors may have square or rectangular cross sections. When the thickness of rectangular conductors is less than 0.008 inch, they are termed *foils*. Above this thickness and with width-to-thickness ratios greater than 50 to 1, conductors are called *strip*. Insulated aluminum strip conductors are used in distribution and power transformers, field coils in rotating electrical equipment, lift magnet coils, and in many other electromagnetic devices where they provide better heat transfer and stronger coil structure than round wire.

Although traditionally comprising little more than 10 percent of the weight of all magnet wire conductors, aluminum has some advantages over copper, including:

- Aluminum may be anodized, adding insulation properties and mechanical protection to conductors.
- Aluminum is only 30 percent the weight of an equal volume of copper, a possible advantage in some applications. However, aluminum, with 61.8 percent of the conductivity of copper, requires larger wire sizes for the same current-carrying capacity, with resultant greater coil bulk, possibly requiring a larger equipment housing.
- Copper wire, which oxidizes at temperatures over 200°C, needs silver or nickel coatings for use at these temperatures. Nickel plating permits use up to 260°C, and nickel cladding is needed for use up to 400°C.
- The same insulation usually has a thermal rating of one class higher on aluminum.

Copper magnet wire is manufactured from electrolytic tough pitch copper for which these specifications are applicable:

- ASTM B 49, *Hot-Rolled Copper Rods for Electrical Purposes*
- ASTM B 115, *Electrolytic Cathode Copper*

Aluminum magnet wire is derived from high-purity electrical grade aluminum covered by ASTM B 230, *Aluminum 1350-H19 Wire, for Electrical Purposes*.

Conductor sizes for magnet wire typically range from 0.002 inches nominal diameter for American Wire Gauge size 44 to 0.0641 inches nominal diameter for size AWG

14, with other sizes available. It is desirable to keep insulation thickness to the necessary minimum. A measure of design efficiency is the *space factor*, or ratio of the space occupied by the bare wire of an insulated conductor to the space occupied by the insulated wire. A higher space factor means more conductor for a given volume, imparting higher electrical conductance and thermal conductivity to the coil and permitting more current to flow with less temperature rise.

NEMA STANDARD AND FEDERAL SPECIFICATION FOR MAGNET WIRES

The National Electrical Manufacturers Association (NEMA) has developed standard MW 1000 for magnet wires. Coating thicknesses are designated as single film, heavy film, and triple film. The related Federal Specification is J-W-1177, *Wire, Magnet.*

ASTM STANDARDS FOR FILM-INSULATED MAGNET WIRE

The American Society for Testing and Materials has developed the following test methods for enameled magnet wire:

- D 1676, *Film-Insulated Magnet Wire*

Table 7-1 lists test methods described in this standard.

TABLE 7-1 Property Tests for Film-Insulated Magnet Wire (ASTM D 1676)

PROPERTY MEASURED
Film flexibility and adherence
Stiffness
Oiliness
Continuity
Heat shock
Unidirectional scrape resistance
Elongation
Dielectric breakdown voltage
Resistance to softening in liquids
Solderability
Electrical resistance of conductors
Measure of diameter and film addition of round magnet wire
Cut-through temperature of film-coated round wire
Dielectric breakdown voltage at elevated temperature
Percent extractables of magnet wire insulation by refrigerants
Dielectric breakdown voltage after conditioning in refrigerant atmosphere
High voltage dc continuity bench test
Bond strength of round magnet wire self-bonding coating by the helical coil text

- D 4880, *Salt Water Proofness of Insulating Varnishes Over Enamelled Magnet Wire*
- D 4881, *Thermal Endurance of Varnished Fibrous or Film Wrapped Magnet Wire*
- D 4882, *Bond Strength of Electrical Insulating Varnishes by the Twisted Coil Test*

PROCESSING WIRE ENAMEL

In the production of magnet wire, it is essential that the conductor present a smooth, clean surface, as free as possible of oxides. Otherwise, coatings will not have good adhesion and will tend to have pinholes and other imperfections that degrade dielectric and mechanical properties.

Traditionally, magnet wire is made by passing copper to aluminum wire through tanks containing a solution of insulating enamel. Enameling dies regulate film thickness after which the coated wire passes through a vertical oven with controlled temperature where solvent removal and curing take place. Multiple passes permit complete curing and solvent removal, and reduce likelihood of pinholes in the insulation. Solvent vapors must be burned or recycled so that emissions are in compliance with EPA and OSHA standards and regulations. See "Federal Air Pollution Program," p. 517.

Bondable, nylon, polyamide-imide, or modified polyester topcoats are applied over basecoats in much the same way in a tandem or separate tower.

MAGNET WIRE THERMAL CLASSIFICATION

The thermal classification of a magnet wire insulation is determined by the test method described by American Society for Testing and Materials Publication 2307, *Thermal Endurance of Film-Insulated Round Magnet Wire*. Twisted pairs of enameled wire are subjected to increasing temperature levels for a specified number of days at each temperature level. Factors influencing test results include wire size and film thickness and oven operating properties. To be qualified for a given temperature class, an enamel should remain effective for a period of 5,000 hours when exposed to a temperature 20°C above the class rating, and its extrapolated life must be at least 20,000 hours at the claimed thermal rating. This test method notes: "The temperature index determined by this test method is a nominal or relative value expressed in degrees Celsius at 20,000 hours. It is to be used for comparison purposes only and is not intended to represent the temperature at which the film insulated wire could be operated."

Since copper oxidizes rapidly at temperatures above 200°C, magnet wire enamels coated on copper wire tend to lose their adhesion at these temperatures, thereby lowering useful operating life. Therefore, testing performed on enameled copper wires below 200°C produces more meaningful results than testing at higher temperatures.

Following are the generally recognized thermal classes:

CLASS	FOR PROLONGED LIFE AT °C
A or 105	105
B or 130	130
F or 155	155
H or 180	180
200	200
220	220
Over 220	Over 220

Since temperatures vary at different points within operating electrical apparatus, the thermal class of every insulation in the system does not necessarily have to meet hot spot requirements, and in practice often does not. Where there is no possibility that an insulation will be exposed to high temperatures existing at some point in the apparatus, a lower thermal class insulation may be sufficient. Exceptions to this practice are found in apparatus manufactured to government specifications or approved by Underwriters Laboratories.

See also "Temperature Index of Dielectric Materials," p. 21.

MAGNET WIRE ENAMEL TESTING

Standards and testing procedures for wire enamels are described in ASTM Publication D 3288, *Magnet Wire Enamels*.

Federal Specification J-W-1177 describes tests for the following properties:

- Adhesion and flexibility
- Heat shock
- Elongation
- Scrape resistance
- Springback
- Thermoplastic flow
- Dielectric strength (at room and rated temperature)
- Low-voltage continuity
- High-voltage continuity
- Solubility
- Completeness of cure
- Solderability
- Heat and solvent bonding

NEMA testing procedures for essentially the same properties are contained in Standard MW 1000. The significance of selected lists and brief descriptions follow.

Adhesion, necessary to prevent cracks in the film as the magnet wire is stretched, is determined by elongating a 10 inch specimen, sizes 13 AWG and heavier, 25–30 percent at a rate of 12 inches per minute. Normal visual inspection should reveal no cracks. For sizes 14 AWG and finer, the wire is given a sudden jerk with minimum elongation of 15–20 percent (depending on the wire size), or to the breaking point, whichever is less. Magnification of 6× to 15× (depending on wire size) is used to determine cracks in the film for 31 AWG and finer wires.

Flexibility is the ability of magnet wire after preelongation of 15–30 percent (depending on wire size) to be wrapped not more than ten turns around a mandrel one–five times (depending on wire size) the AWG size of the wire without film failure. The smaller the mandrel diameter without film failure, the higher the flexibility rating for a given size wire. Normal visual inspection is used to determine film failure for 30 AWG and heavier wires. Magnification of 6× to 15× (depending on wire size) is used for 31 AWG and finer wires.

Heat shock resistance indicates how well an insulation holds up when elongated magnet wire is wrapped not more than ten times around a mandrel typically one–three times the AWG size of the wire. The specimen is then removed from the mandrel and placed in a circulating air oven for $^1/_2$ hour at 20°C above the specified thermal rating of the magnet wire. There should be no cracks on subsequent normal visual inspection for sizes 30 AWG and heavier wire or under magnification of 6× to 10× for 31 AWG and finer wires. Polymers with low heat shock resistance require gradual preheating before varnishing or encapsulation.

Scrape or abrasion resistance indicates the mechanical abuse a magnet wire will withstand. This property is determined by a procedure in which a special needle is rubbed on the coated wire at a specified rate with a constantly increasing load until dielectric failure occurs at a potential of 7.5 volts between the needle and the wire. The load weight of failure measures the scrape resistance. An alternative method measures the number of strokes to failure with a constant load.

Springback measures the tendency of a coil to spring open when removed from the form. A low springback indicates high formability. A specimen of film-coated wire is wound three turns around a mandrel having a specified diameter ranging from $^3/_4$ inch for size 30 AWG wire to $3^1/_4$ inch for size 14 AWG wire, under tension ranging from 2 ounces for size AWG 30 wire to 16 ounces for size AWG 14 wire. A special device measures the degree of springback when tension is removed.

Thermoplastic flow, or *cut-through resistance*, indicates the temperature at which the insulation film fails. Two lengths of the specimen positioned at right angles to each other are loaded with 2,000 grams for size 18 AWG or 100 grams for size 36 AWG. The test equipment applies a voltage of 115 volts ac through the crossover of the wires as the temperature is increased at a rate of less than 5°C per minute to the point of dielectric failure.

Dielectric strength is an indication of the film thickness needed to withstand operating and surge voltages. The specimen may be either two layers of magnet wire or two twisted wires with specified number of twists. The ac voltage applied between the wire layers or twisted wires is increased gradually so that breakdown does not occur in less than 5 seconds. The voltage at breakdown is the basis for determining the dielectric strength of the specimen.

Low-voltage continuity measures the film defects of magnet wire sizes 31–56 AWG through dielectric failure at low voltage. Formerly, a 100-foot specimen of magnet wire was passed through a 1 inch long mercury bath at a speed of 100 feet per minute. A direct-current potential of 20–75 volts (depending on wire size) was applied between the bath and the wire. A discontinuity indicating device operated when the resistance between the bath and the wire was less than 5,000 ohms but did not operate when the resistance was 10,000 ohms or more. The number of faults per minute indi-

cated the low-voltage continuity. This test is being revised to eliminate mercury with its potential health hazard.

High-voltage continuity measures the film defects of magnet wire sizes 14–30 AWG through dielectric failure at high direct-current voltage. A 100-foot specimen of magnet wire is passed with contact over an energized sheave at a speed of 60 feet per minute. Before and after the contact sheave is a similar grounded guide sheave. The sheaves are arranged so that the length of wire contacting the energized center sheave is one inch. The specimen wire is grounded. The specified open-circuit voltage applied to the contact sheave ranges from 500 volts for sizes 25–30 AWG single film to 2,000 volts for sizes 14–24 AWG triple film. The sensitivity of the fault detection device is such that the circuit is capable of detecting any fault having a resistance of less than 30 megohms, but will not operate when the insulation resistance of the test wire film exceeds 180 megohms. The number of faults per minute indicates the high-voltage continuity.

Solubility in certain liquids is tested by immersing stress-relieved specimens of magnet wire 12 inches long at least 6 inches in the liquids specified. After removal from the liquids, specimens are promptly drawn once between the folds of cheesecloth held firmly between the forefinger and the ball of the thumb. Removal of the coating indicates failure. Another test for solubility is performed on samples removed from liquids and placed in a device in which a needle scrapes the surface of the film at right angles to the lengths of wire. The needle is loaded with 580 grams when testing copper magnet wire and 340 grams when testing aluminum magnet wire. Film failure is indicated by shorting in a circuit having a potential of 7.5 volts between the needle and the conductors. Perhaps the simplest method is to immerse the magnet wire specimens in specified liquids for 24 hours at 25°C. Following removal of specimens, the coating is rated *pass* (no effect), *fair* (some surface softening or crazing), or *fail* (severe surface softening or crazing).

Solderability without the necessity of stripping insulation is a highly desirable property which facilitates assembly operations. Soldering tests are made for wire sizes 14–23 AWG by forming a loop of a 12 inch length of magnet wire and twisting the ends together for a distance of $^3/_4$–1 inch with five–ten turns. The loop is first immersed in a rosin-alcohol flux, and then immersed in a soldering pot of 50/50 tin–lead solder for 8–10 seconds at 430°C. For sizes 24–46 AWG, a magnet wire specimen is wound with five–ten turns for a distance of $^1/_2$–$^3/_4$ inch around the end of a 6 inch length of 20 AWG tinned, hot-dipped copper wire. The sample is then immersed in a rosin-alcohol flux, and then immersed in a soldering pot of 50/50 tin–lead solder at 360°C for 4–6 seconds. Magnification of 6× to 10× is used to inspect sizes 37–46 AWG wire. Normal vision is used to examine larger sizes.

Heat and solvent bonding are methods used to bond coils of magnet wire coated with bonding agents, thus eliminating the necessity of subsequent varnish treatment or encapsulation. Specimens are prepared from sizes 18, 26, and 36 AWG wires. Size 18 and 26 AWG wires are formed into a 3-inch single-layer coil around mandrels with diameters of 0.250 and 0.157 inch, respectively. Size 36 AWG wire is formed into a coil of 50 turns around a mandrel with diameter of 0.0394 inch. *Heat bonding* is accomplished in a forced air oven for 1 hour at 150°C, after which specimens are cooled to room temperature. *Solvent bonding* is performed by dipping specimens in specified solvent for 5 seconds with subsequent drying for 1 hour at room temperature.

Bond strength is measured in a special device which applies a specified load or, alternatively, an increasing load to the center of the coil suspended at its ends.

DEVELOPMENT PROGRAMS

One of the prime objectives of magnet wire development programs is the reduction or elimination of organic solvents, with resultant material cost savings, significantly fewer pollution control problems, energy and feedstock conservation, and lower fire or explosion hazard. It is well to remember, however, the key role solvents have played in the improvement in magnet wire technology over the years. Solvent systems not only provide a practical means for applying resins to conductors, but function to wet the conductor to ensure strong film adhesion and provide for timely solvent release during film formation, thereby minimizing pinholes, blistering, and other film defects. Eliminating solvents thus requires changes in resin composition as well as processing methods.

The following are programs under development for several years, but which so far have not produced results to encourage widespread commercialization.

High solids coatings, with fewer than 25 percent solvents by volume, have long been a goal in the magnet wire industry. The problem is to maintain practical viscosity and flow characteristics within the limitations of present processing equipment. Solvent content in the 55–70 percent range is about the present limit in the U.S. It is reported that 50–60 percent solids enamels are in use in Germany. Preheating would lower the viscosity, but would introduce problems of pot life and solvent loss.

Water-borne systems development has been suspended or abandoned. A major problem with these systems is the high surface tension of water which impedes proper wetting of the conductor by the enamel, causing borderline mechanical and dielectric properties.

Hot melt enamels have also not met expectations. The manufacturing process consists essentially of extruding a heated thermoplastic resin on a preheated conductor. Although available equipment can be used with these enamels, extensive modification would be required to achieve high productivity with resultant profit improvement. Since hot melts have much higher viscosities than solvent enamels, they produce thicker films per pass. Two passes using hot melts build film thickness equal to six passes with solvent enamels. However, fewer passes increase the likelihood of film defects. Polyester hot melts have a tendency to craze and crack with shelf aging. Nylon hot melts are better in this respect, but have high water absorption with significant reduction in dielectric properties. Thermal properties of hot melt films could be improved by crosslinking, which should also enhance physical and electrical characteristics, but this could present production problems of adequate pot life and maintaining constant viscosity.

Powder coating is another intriguing technology which would eliminate solvents and permit higher operating speeds with a single coating process. Hysol, 3M, and Westinghouse have developed powder coatings and techniques for applying them. Epoxies and polyesters are the base resins employed. In the electrostatic fluidized bed application method, a fluidized bed is formed by charged dry air passing through powder on a porous

membrane. This air has been ionized by passing through a high-voltage charging medium. The charged powder forms a cloud and is attracted to the grounded wire moving through the chamber. The coating thickness is controlled by the amount of charged air, the charging voltage, and the speed of the wire. Drawbacks to powder coatings include difficulty in producing uniform thin films, poor corona resistance, relatively high cost for finer powders, and a potential explosion hazard when using fine powders. The main end use so far for powder coated magnet wire has been in liquid filled transformers.

Radiation curing employing ultraviolet (UV) or electron beam (EB) technology can be used to produce crosslinked, tough, flexible films. This approach would employ relatively compact production equipment in comparison with conventional ovens, and higher throughput should improve productivity. Development using this technology still has a long way to go to produce magnet wire with properties equal to those resulting from conventional manufacturing methods. The achievement of a concentric coating and film homogeneity are major problems with radiation curing.

MARKET TRENDS

The earliest use of magnet wire insulated with silk, cotton, or paper dates back to the late 1830s. Since then, magnet wire development has kept pace with the requirements of the electrical, and more recently, electronic industries. For many decades, the principal usage for magnet wire has been in rotating electrical equipment and transformers. Changes are now underway in motor design to achieve greater energy efficiency with lower operating temperature. This may permit use of lower thermal class insulation in some cases. The desire to achieve high space factor will probably also influence selection of insulating film to some degree.

The trend toward smaller cars implies use of smaller electrical and electronic components requiring less magnet wire. Imported cars use little, if any, U.S. made magnet wire. Thus, the near-term outlook is for decreasing usage of domestic magnet wire in motor vehicles. The advent of battery powered electric vehicles incorporating dc motor drives would, of course, require more magnet wire than present vehicles, but production of electric vehicles in volume is not likely to occur, if it occurs at all, before the late 1990s.

In other industries, there is also a trend toward smaller units, but magnet wire usage may remain stable due to increasing volume of units and new applications as, for example, in small motors for computer peripheral equipment.

Bondable magnet wire with thermosetting coating is reported to be used increasingly in Germany, and may gain greater favor in the U.S. than is now the case. Bondable wire avoids the necessity of varnish impregnation.

COMPARATIVE CHARACTERISTICS OF MAGNET WIRES

Table 7-2 shows advantages and limitations of commercially available enameled magnet wires.

TABLE 7-2 Summary of Enameled Magnet Wire Characteristics

INSULATION TEMP. CLASS, °C	ADVANTAGES	LIMITATIONS
Plain enamel (oleoresinous) 105	Low cost Good film continuity Good cut-thru resistance Good overload resistance Ease of mechanical and chemical stripping Tight dimensional tolerances	Low abrasion resistance Not for heavy duty winding Limited compatibility with other varnishes
Modified polyvinyl formal resin 105	Excellent windability High adhesion rating Compatible with most varnishes, waxes, and impregnating compounds Suitable for use with transformer oil Good overall chemical and physical properties	Must be stripped before soldering Crazes when exposed to varnish solvents unless stress relieved first
Polyurethane 105, 130, 155	Solderable at 360°C–425°C (film vaporizes) Self fluxing Superior Q characteristics at high frequencies and humidities Good film adhesion and flexibility Will operate at 120°C continuously—highest in Class 105—with newer versions qualifying for Classes 130 and 155	Not for use where severe overloads may occur Lower abrasion resistance than Formvar or nylon jacketed wires Susceptible to softening through prolonged exposure to solvents Poor radiation stability
Polyurethane with nylon overcoat 130	Solderable with better windability than straight polyurethane Excellent abrasion resistance High heat shock resistance Compatible with most varnishes and encapsulants Excellent solvent resistance	Not for use where severe overloads may occur Dielectric strength lower than straight PUR Not for use in hot transformer oil or fluorocarbon gases Poor radiation stability
Epoxy 130	Outstanding oil and Askarel resistance (wet transformer usage) Good adhesion and flexibility Good resistance to chemicals and moisture Good corona resistance	Must be stripped before soldering
Polyester 155	Good overload characteristics Excellent dielectric properties	Must be stripped before soldering Not for use in oil-filled transformers May hydrolyze in sealed systems
Solderable polyester 155	Solderable at 482°C Long thermal endurance at 175°C Good heat shock resistance Good overload characteristics for solderable wire Good radiation stability	Not for use in oil-filled transformers Not for use with systems using amine type catalysts
Solderable nylon polyester 155	Solderable at 482°C Better windability than unjacketed grade Good resistance to heat and solvent shock	Not for use in oil-filled transformers Not for use with systems using amine type catalysts Not as resistant to moisture as unjacketed wire
Isonel* polyester with polyamide-imide overcoat 200	Physical and electrical properties almost equal to Formvar Excellent cut-thru resistance Excellent resistance to Freon	Must be stripped before soldering Not for use in oil-filled transformers Not for use in systems containing chlorine compounds

TABLE 7-2 (*Continued*)

INSULATION TEMP. CLASS, °C	ADVANTAGES	LIMITATIONS
	Good solvent resistance Compatible with most varnishes and impregnating compounds	Not for use with systems using amine catalysts
Polyester with nylon overcoat 155–180	Excellent windability Resistant to heat and solvent shocks Excellent in flexibility, scrape abrasion and film adhesion Good overload characteristics	Must be stripped before soldering Not for use in enclosed equipment Poor radiation stability
Polyester/ polyamide-imide 200, 220	Polyester base coat with amide-imide topcoat Good windability More resistant to heat and solvent shocks than conventional polyesters Excels regular polyesters in resistance to cut-thru and abrasion resistance High resistant to Freon and solvents Excellent dielectric properties Suitable for use in hermetic motors	Must be stripped before soldering Not for use in enclosed equipment where moisture or chlorine compounds are present
Polyesteramide-imide 200	Single film coating Excellent overload characteristics Compatible with epoxy casting and encapsulating compounds Compatible with most varnishes and impregnating compounds Long thermal endurance at 180–210°C For use in oil-filled transformers Withstands high speed winding applications	Must be stripped before soldering High price
Isomid* polyester-polyimide 180, 200	Single film coating Excellent cut-thru, flexibility and adhesion properties Excellent wet and dry dielectric properties Highly resistant to Freon and solvents Improved resistance to heat shock Compatible with most varnishes and impregnating compounds	Must be stripped before soldering High price
Pyre-ML** polyimide 220 (240 pe MW 1000)	Single film coatings Retains high dielectric properties at operating temperatures of 220°C Highest heat shock resistance and thermal stability of all insulations Highest resistance to radiation High dielectric strength and low loss characteristics Compatible with most varnishes and impregnating compounds May be used in hermetic motors and oil-filled transformers Highly resistant to attack by solvents and chemicals Highest overload rating	Very difficult to strip before soldering Subject to hydrolysis or sealed systems containing moisture Will solvent craze unless stress relieved Highest price film coated wire

*Schenectady International.

**DuPont™.

MAGNET WIRE DATA

Tables 7-3–7-10 show useful data for magnet wires:

TABLE	TITLE	UNITS
7-3	Round Copper Film Coated Wire Data	English
7-4	Round Copper Film Coated Wire Data	Metric
7-5	Round Aluminum Film Coated Wire Data	English
7-6	Round Aluminum Film Coated Wire Data	Metric
7-7	Square Copper Film Coated Wire Data	English
7-8	Square Copper Film Coated Wire Data	Metric
7-9	Square Aluminum Film Coated Wire Data	English
7-10	Square Aluminum Film Coated Wire Data	Metric

TABLE 7-3 Round Copper Film Coated Wire Data (English Units)

SINGLE FILM

WIRE SIZE AWG*	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C (68°F)
	MINIMUM inch	MAXIMUM inch	inch	lb/M ft	ft/lb	Ω/lb
14	0.0651	0.0666	0.0016	12.5	80.0	0.202
15	0.0580	0.0594	0.0015	9.95	101	0.321
16	0.0517	0.0531	0.0014	7.78	127	0.511
17	0.0462	0.0475	0.0014	6.27	159	0.803
18	0.0412	0.0424	0.0013	4.97	201	1.28
19	0.0367	0.0379	0.0012	3.94	254	2.04
20	0.0329	0.0339	0.0012	3.14	318	3.21
21	0.0293	0.0303	0.0011	2.49	402	5.15
22	0.0261	0.0270	0.0011	1.97	508	8.23
23	0.0234	0.0243	0.0010	1.58	633	12.8
24	0.0209	0.0217	0.0010	1.24	806	20.7
25	0.0186	0.0194	0.0009	0.988	1,010	32.8
26	0.0166	0.0173	0.0009	0.780	1,280	52.6
27	0.0149	0.0156	0.0008	0.623	1,610	82.5
28	0.0133	0.0140	0.0008	0.492	2,030	133
29	0.0119	0.0126	0.0007	0.396	2,530	205
30	0.0106	0.0112	0.0007	0.311	3,220	334
31	0.0094	0.0100	0.0006	0.247	4,050	530
32	0.0085	0.0091	0.0006	0.200	5,000	810
33	0.0075	0.0081	0.0005	0.158	6,330	1,300
34	0.0067	0.0072	0.0005	0.124	8,060	2,100
35	0.0059	0.0064	0.0004	0.0980	10,200	3,380
36	0.0053	0.0058	0.0004	0.0782	12,800	5,310
37	0.0047	0.0052	0.0003	0.0634	15,800	8,080
38	0.0042	0.0047	0.0003	0.0501	20,000	12,900
39	0.0036	0.0041	0.0002	0.0385	26,000	22,000
40	0.0032	0.0037	0.0002	0.0302	33,100	35,700
41	0.0029	0.0033	0.0002	0.0246	40,700	53,700
42	0.0026	0.0030	0.0002	0.0196	51,000	84,700
43	0.0023	0.0026	0.0002	0.0153	65,400	140,000
44	0.0020	0.0024	0.0001	0.0126	79,400	206,000

TABLE 7-3 (*Continued*)

HEAVY FILM

WIRE SIZE AWG*	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C (68°F)
	MINIMUM inch	MAXIMUM inch	inch	lb/M ft	ft/lb	Ω/lb
4	0.2060	0.2098	0.0037	127.5	7.843	0.001949
5	0.1837	0.1872	0.0036	101.0	9.901	0.003103
6	0.1639	0.1671	0.0035	80.09	12.49	0.004934
7	0.1463	0.1491	0.0034	63.55	15.74	0.007838
8	0.1305	0.1332	0.0033	50.40	19.84	0.01246
9	0.1165	0.1189	0.0032	39.97	25.02	0.01983
10	0.0140	0.1061	0.0031	31.73	31.52	0.03148
11	0.0928	0.0948	0.0030	25.2	39.7	0.05004
12	0.0829	0.0847	0.0029	20.0	50.0	0.07950
13	0.0741	0.0757	0.0028	15.9	62.9	0.126
14	0.0667	0.0682	0.0032	12.6	79.4	0.209
15	0.0595	0.0609	0.0030	10.0	100	0.318
16	0.0532	0.0545	0.0029	7.94	126	0.510
17	0.0476	0.0488	0.0028	6.32	158	0.798
18	0.0425	0.0437	0.0026	5.02	199	1.27
19	0.0380	0.0391	0.0025	3.99	251	2.02
20	0.0340	0.0351	0.0023	3.17	315	3.19
21	0.0304	0.0314	0.0022	2.52	397	5.08
22	0.0271	0.0281	0.0021	2.00	500	8.10
23	0.0244	0.0253	0.0020	1.60	625	12.7
24	0.0218	0.0227	0.0019	1.26	794	20.4
25	0.0195	0.0203	0.0018	1.00	1,000	32.4
26	0.0174	0.0182	0.0017	0.794	1,260	51.6
27	0.0157	0.0164	0.0016	0.634	1,580	81.1
28	0.0141	0.0147	0.0016	0.501	2,000	130
29	0.0127	0.0133	0.0015	0.404	2,480	201
30	0.0113	0.0119	0.0014	0.317	3,150	328
31	0.0101	0.0108	0.0013	0.252	3,970	520
32	0.0091	0.0098	0.0012	0.204	4,900	794
33	0.0081	0.0088	0.0011	0.161	6,210	1,280
34	0.0072	0.0078	0.0010	0.127	7,870	2,050
35	0.0064	0.0070	0.0009	0.101	9,900	3,280
36	0.0057	0.0063	0.0008	0.0805	12,400	5,160
37	0.0052	0.0057	0.0008	0.0652	15,300	7,830
38	0.0046	0.0051	0.0007	0.0516	19,400	12,600
39	0.0040	0.0045	0.0006	0.0397	25,200	21,300
40	0.0036	0.0040	0.0006	0.0311	32,200	34,700
41	0.0032	0.0036	0.0005	0.0254	39,400	52,000
42	0.0028	0.0032	0.0004	0.0203	49,300	81,800
43	0.0025	0.0029	0.0004	0.0159	62,900	135,000
44	0.0023	0.0027	0.0004	0.0131	76,300	198,000

*Half sizes are also available.

TABLE 7-4 Round Copper Film Coated Wire Data (Metric Units)

SINGLE FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C
	MINIMUM mm	MAXIMUM mm	mm	kg/m	m/g	Ω/kg
14	1.654	1.692	0.041	18.6	0.0538	0.445
15	1.473	1.509	0.038	14.8	0.0679	0.708
16	1.313	1.349	0.036	11.7	0.0853	1.13
17	1.173	1.206	0.036	9.33	0.107	1.77
18	1.046	1.077	0.033	7.40	0.135	2.82
19	0.932	0.963	0.030	5.86	0.171	4.50
20	0.836	0.861	0.030	4.67	0.214	7.08
21	0.744	0.770	0.028	3.71	0.270	11.3
22	0.633	0.686	0.028	2.93	0.341	18.1
23	0.594	0.617	0.025	2.35	0.425	28.2
24	0.531	0.551	0.025	1.85	0.542	45.6
25	0.472	0.493	0.023	1.47	0.679	72.3
26	0.422	0.439	0.023	1.16	0.860	11.6
27	0.378	0.396	0.020	0.927	1.08	182
28	0.338	0.356	0.020	0.732	1.36	293
29	0.302	0.320	0.018	0.589	1.70	455
30	0.269	0.284	0.018	0.463	2.16	736
31	0.239	0.254	0.015	0.368	2.72	1,170
32	0.216	0.231	0.015	0.298	3.36	1,790
33	0.190	0.206	0.013	0.235	4.25	2,870
34	0.170	0.183	0.013	0.185	5.42	4,630
35	0.150	0.163	0.010	0.1458	6.85	7,450
36	0.135	0.147	0.010	0.1164	8.60	11,700
37	0.119	0.132	0.008	0.0943	10.6	17,800
38	0.107	0.119	0.008	0.0746	13.4	28,400
39	0.091	0.104	0.005	0.0573	17.5	48,500
40	0.081	0.094	0.005	0.0449	22.2	78,700
41	0.074	0.084	0.005	0.0366	27.4	118,000
42	0.066	0.076	0.005	0.0292	34.3	187,000
43	0.058	0.066	0.005	0.0227	44.0	309,000
44	0.051	0.061	0.0025	0.0188	53.4	454,000

TABLE 7-4 (*Continued*)
(Metric Units)

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C
	Minimum mm	Maximum mm	mm	kg/m	m/g	Ω/kg
4	5.232	5.329	0.094	189.7	0.00527	0.004297
5	4.666	4.755	0.091	150.3	0.00665	0.006841
6	4.163	4.244	0.089	119.2	0.00839	0.01088
7	3.716	3.787	0.086	94.57	0.01057	0.01728
8	3.315	3.383	0.084	75.00	0.01333	0.02747
9	2.959	3.020	0.081	59.48	0.01681	0.04372
10	2.642	2.695	0.079	47.22	0.02118	0.06940
11	2.357	2.408	0.076	37.5	0.0267	0.1103
12	2.106	2.151	0.074	29.8	0.0336	0.1753
13	1.882	1.923	0.071	23.7	0.0423	0.278
14	1.694	1.732	0.081	18.8	0.0534	0.461
15	1.511	1.547	0.076	14.9	0.0672	0.701
16	1.351	1.384	0.074	11.8	0.0847	1.12
17	1.209	1.240	0.071	9.41	0.106	1.76
18	1.080	1.110	0.066	7.47	0.134	2.80
19	0.965	0.993	0.064	5.93	0.169	4.45
20	0.864	0.892	0.058	4.71	0.212	7.03
21	0.772	0.798	0.056	3.75	0.267	11.2
22	0.688	0.714	0.053	2.97	0.336	17.9
23	0.620	0.643	0.051	2.38	0.420	28.0
24	0.554	0.577	0.048	1.88	0.534	45.0
25	0.495	0.516	0.046	1.49	0.672	71.4
26	0.442	0.462	0.043	1.18	0.847	113
27	0.399	0.417	0.041	0.943	1.06	179
28	0.358	0.373	0.041	0.746	1.34	287
29	0.322	0.338	0.038	0.601	1.67	443
30	0.287	0.302	0.036	0.472	2.12	723
31	0.257	0.274	0.033	0.375	2.67	1,150
32	0.231	0.249	0.030	0.303	3.29	1,750
33	0.205	0.224	0.028	0.204	4.17	2,820
34	0.183	0.198	0.025	0.189	5.29	4,520
35	0.162	0.178	0.023	0.150	6.65	7,230
36	0.145	0.160	0.020	0.120	8.33	11,400
37	0.132	0.145	0.020	0.0970	10.3	17,300
38	0.117	0.130	0.018	0.0768	13.0	27,800
39	0.102	0.114	0.015	0.0591	16.9	47,000
40	0.091	0.102	0.015	0.0463	21.6	76,500
41	0.081	0.091	0.013	0.0378	26.5	115,000
42	0.071	0.081	0.010	0.0302	33.1	180,000
43	0.064	0.074	0.010	0.0237	42.3	298,000
44	0.058	0.069	0.010	0.0195	51.3	437,000

TABLE 7-5 Round Aluminum Film Coated Wire Data (English Units)

SINGLE FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C (68°F) 61.8% CONDUCTIVITY
	MINIMUM inch	MAXIMUM inch	inch	lb/M ft	ft/lb	Ω/lb
14	0.0651	0.0666	0.0016	3.87	258	1.33
15	0.0580	0.0594	0.0015	3.08	325	1.67
16	0.0517	0.0531	0.0014	2.44	410	2.66
17	0.0462	0.0475	0.0014	1.95	512	4.19
18	0.0412	0.0424	0.0013	1.55	645	6.6
19	0.0367	0.0379	0.0012	1.23	813	10.6
20	0.0329	0.0339	0.0012	0.983	1,017	16.7
21	0.0293	0.0303	0.0011	0.778	1,285	26.6
22	0.0261	0.0270	0.0011	0.620	1,612	42.2
23	0.0234	0.0243	0.0010	0.501	1,996	65.7
24	0.0209	0.0217	0.0010	0.391	2,556	106
25	0.0186	0.0194	0.0009	0.313	3,195	167

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C (68°F) 61.8% CONDUCTIVITY
	MINIMUM inch	MAXIMUM inch	inch	lb/M ft	ft/lb	Ω/lb
4	0.2060	0.2098	0.0037	39.60	25.25	0.0102
5	0.1837	0.1872	0.0036	31.27	31.98	0.0162
6	0.1639	0.1671	0.0035	24.80	40.32	0.0258
7	0.1463	0.1491	0.0034	19.68	50.81	0.0409
8	0.1305	0.1332	0.0033	15.62	64.02	0.0650
9	0.1165	0.1189	0.0032	12.40	80.64	0.103
10	0.1040	0.1061	0.0031	9.86	101	0.163
11	0.0928	0.0948	0.0030	7.87	127	0.259
12	0.0829	0.0847	0.0029	6.22	161	0.413
13	0.0741	0.0757	0.0028	4.97	201	0.651
14	0.0667	0.0682	0.0032	3.97	252	1.03
15	0.0595	0.0609	0.0030	3.13	319	1.64
16	0.0532	0.0545	0.0029	2.50	400	2.60
17	0.0476	0.0488	0.0028	2.00	500	4.09
18	0.0425	0.0437	0.0026	1.60	625	6.50
19	0.0380	0.0391	0.0025	1.28	781	10.1
20	0.0340	0.0351	0.0023	1.01	990	16.2
21	0.0304	0.0314	0.0022	0.808	1,238	25.6
22	0.0271	0.0281	0.0021	0.650	1,538	40.3
23	0.0244	0.0253	0.0020	0.521	1,919	63.2
24	0.0218	0.0227	0.0019	0.411	2,433	100
25	0.0195	0.0203	0.0018	0.325	3,077	161

TABLE 7-6 Round Aluminum Film Coated Wire Data (Metric Units)

SINGLE FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C (68°F) 61.8% CONDUCTIVITY
	MINIMUM mm	MAXIMUM mm	mm	kg/km	m/g	Ω/kg
14	1.654	1.692	0.041	5.76	0.173	2.93
15	1.473	1.509	0.038	4.58	0.218	3.69
16	1.313	1.349	0.035	3.63	0.276	5.88
17	1.173	1.206	0.035	2.90	0.344	9.23
18	1.046	1.077	0.033	2.31	0.433	14.6
19	0.932	0.963	0.030	1.83	0.546	23.3
20	0.836	0.861	0.030	1.46	0.683	36.7
21	0.744	0.770	0.028	1.16	0.863	58.6
22	0.633	0.686	0.028	0.923	1.083	93.1
23	0.594	0.617	0.025	0.746	1.341	144
24	0.531	0.551	0.025	0.581	1.718	234
25	0.472	0.493	0.023	0.453	2.147	369

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION		MINIMUM FILM ADDITION	WEIGHT		dc RESISTANCE AT 20°C (68°F) 61.8% CONDUCTIVITY
	MINIMUM mm	MAXIMUM mm	mm	kg/km	m/g	Ω/kg
4	5.232	5.329	0.094	58.93	0.0170	0.0225
5	4.666	4.755	0.091	46.53	0.0215	0.0357
6	4.163	4.244	0.089	36.91	0.0271	0.0569
7	3.716	3.787	0.086	29.29	0.0341	0.0902
8	3.315	3.383	0.084	23.24	0.0430	0.143
9	2.959	3.020	0.081	18.45	0.0542	0.228
10	2.642	2.695	0.079	14.67	0.0679	0.359
11	2.357	2.408	0.076	11.71	0.0853	0.571
12	2.106	2.151	0.074	9.26	0.108	0.910
13	1.882	1.923	0.071	7.40	0.135	1.43
14	1.694	1.732	0.081	5.91	0.169	2.27
15	1.511	1.547	0.076	4.66	0.214	3.62
16	1.351	1.384	0.074	3.72	0.269	5.73
17	1.209	1.240	0.071	2.98	0.336	9.02
18	1.080	1.110	0.066	2.38	0.420	14.3
19	0.965	0.993	0.064	1.90	0.525	22.4
20	0.864	0.892	0.058	1.50	0.665	35.8
21	0.772	0.798	0.056	1.20	0.832	56.5
22	0.688	0.714	0.053	0.967	1.033	88.8
23	0.620	0.643	0.051	0.775	1.290	139
24	0.554	0.577	0.048	0.612	1.635	222
25	0.495	0.516	0.046	0.484	2.068	355

TABLE 7-7 Square Copper Film Coated Wire Data (English Units)

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION MINIMUM inch	DIAMETER OVER INSULATION MAXIMUM inch	MINIMUM FILM ADDITION inch	WEIGHT lb/M ft	WEIGHT ft/lb	dc RESISTANCE AT 20°C (68°F) Ω/lb	WIRE SIZE AWG
1	0.2894	0.2972	0.0030	318.4	3.141	0.0003106	1
2	0.2580	0.2652	0.0030	251.5	3.976	0.0004988	2
3	0.2301	0.2367	0.0030	198.4	5.040	0.0008009	3
4	0.2053	0.2113	0.0030	156.3	6.398	0.001291	4
5	0.1831	0.1887	0.0030	122.8	8.143	0.002089	5
6	0.1634	0.1686	0.0030	98.25	10.18	0.003268	6
7	0.1469	0.1507	0.0030	77.34	12.93	0.005280	7
8	0.1302	0.1348	0.0030	60.74	16.46	0.008575	8
9	0.1163	0.1205	0.0030	48.67	20.55	0.01338	9
10	0.1039	0.1079	0.0030	38.17	26.20	0.02177	10
11	0.0927	0.0967	0.0030	30.7	32.5	0.0336	11
12	0.0828	0.0868	0.0030	24.0	41.7	0.0549	12
13	0.0740	0.0780	0.0030	19.3	51.8	0.0850	13
14	0.0661	0.0701	0.0030	15.2	65.8	0.138	14

TABLE 7-8 Square Copper Film Coated Wire Data (Metric Units)

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION MINIMUM mm	DIAMETER OVER INSULATION MAXIMUM mm	MINIMUM FILM ADDITION mm	WEIGHT kg/km	WEIGHT m/g	dc RESISTANCE AT 20°C Ω/kg	WIRE SIZE AWG
1	7.351	7.549	0.076	473.8	0.002111	0.0006847	1
2	6.553	6.736	0.076	374.3	0.002672	0.001100	2
3	5.845	6.012	0.076	295.2	0.003387	0.001766	3
4	5.215	5.367	0.076	232.6	0.004300	0.002846	4
5	4.651	4.793	0.076	182.7	0.005472	0.004605	5
6	4.150	4.282	0.076	146.2	0.006841	0.007205	6
7	3.731	3.828	0.076	115.1	0.008689	0.01164	7
8	3.307	3.424	0.076	90.4	0.01106	0.01890	8
9	2.954	3.061	0.076	72.4	0.01381	0.02950	9
10	2.639	2.741	0.076	56.8	0.01761	0.04667	10
11	2.355	2.456	0.076	45.7	0.0218	0.0741	11
12	2.103	2.205	0.076	35.7	0.0280	0.121	12
13	1.880	1.981	0.076	28.7	0.0348	0.187	13
14	1.679	1.781	0.076	22.6	0.0442	0.304	14

TABLE 7-9 Square Aluminum Film Coated Wire Data (English Units)

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION MINIMUM inch	DIAMETER OVER INSULATION MAXIMUM inch	MINIMUM FILM ADDITION inch	WEIGHT lb/M ft	WEIGHT ft/lb	dc RESISTANCE AT 20°C 61.8% CONDUCTIVITY Ω/lb	WIRE SIZE AWG
1	0.2894	0.2972	0.0030	97.26	10.28	0.001646	1
2	0.2580	0.2652	0.0030	76.92	13.00	0.002637	2
3	0.2301	0.2367	0.0030	60.76	16.46	0.004233	3
4	0.2053	0.2113	0.0030	48.00	20.83	0.006802	4
5	0.1831	0.1887	0.0030	37.76	26.48	0.01101	5
6	0.1634	0.1686	0.0030	30.32	33.10	0.01720	6
7	0.1469	0.1507	0.0030	23.85	41.93	0.02771	7
8	0.1302	0.1348	0.0030	18.80	53.19	0.04485	8
9	0.1163	0.1205	0.0030	15.13	66.09	0.06966	9
10	0.1039	0.1079	0.0030	11.88	84.18	0.1132	10
11	0.0927	0.0967	0.0030	9.51	105.2	0.176	11
12	0.0828	0.0868	0.0030	7.41	135.0	0.287	12
13	0.0740	0.0780	0.0030	5.99	166.9	0.444	13
14	0.0661	0.0701	0.0030	4.75	210.5	0.714	14

TABLE 7-10 Square Aluminum Film Coated Wire Data (Metric Units)

HEAVY FILM

WIRE SIZE AWG	DIAMETER OVER INSULATION MINIMUM mm	DIAMETER OVER INSULATION MAXIMUM mm	MINIMUM FILM ADDITION mm	WEIGHT kg/km	WEIGHT m/g	dc RESISTANCE AT 20°C 61.8% CONDUCTIVITY Ω/kg	WIRE SIZE AWG
1	7.351	7.549	0.076	144.7	0.006908	0.003629	1
2	6.553	6.736	0.076	114.5	0.008736	0.005816	2
3	5.844	6.012	0.076	90.42	0.011061	0.009332	3
4	5.215	5.367	0.076	71.43	0.013997	0.014996	4
5	4.651	4.793	0.076	56.19	0.017794	0.02427	5
6	4.150	4.282	0.076	44.96	0.02224	0.03792	6
7	3.731	3.828	0.076	35.49	0.02818	0.06109	7
8	3.307	3.424	0.076	27.98	0.03574	0.09888	8
9	2.954	3.061	0.076	22.52	0.04441	0.1536	9
10	2.639	2.741	0.076	17.68	0.05657	0.250	10
11	2.355	2.456	0.076	14.15	0.0707	0.388	11
12	2.103	2.205	0.076	11.03	0.0907	0.633	12
13	1.880	1.981	0.076	8.91	0.112	0.979	13
14	1.679	1.781	0.076	7.07	0.141	1.57	14

MAGNET WIRE MANUFACTURERS

Major broad line magnet wire manufacturers include: Elekrisola, Essex, Phelps Dodge, Rea, and Westinghouse.

All of these companies formulate or modify some of the enamels used.

BASIC WIRE ENAMEL TYPES

The chemistry, grades, processing, properties, and electrical/electronic uses of basic wire enamel types are described in the sections which follow and are covered in this order:

- Plain enamel
- Polyvinyl formal
- Polyurethane (PUR)
- Nylon
- Epoxy
- Polyester
- Polyamide-imide (PAI)
- Polyester-amide-imide
- Polyester-imide (PEI)
- Polyimide (PI)

Plain Enamel (for Wire Enamel Class 105)

This original wire enamel has been largely superseded by enamels with significantly superior performance.

Chemistry

The first enamels were oleoresinous types made from drying oils and natural resins such as rosin and copal. These were superseded by proprietary improvements based on isophthalic polyesters with alkyd modifiers.

Grades

A typical enamel is supplied in 50 percent solution in xylol or other aromatic solvent.

Processing

Plain enamel coated magnet wire is covered by Federal Specification J-W-1177/1, Type E. The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

This low-cost enamel has adequate dielectric, physical, mechanical, and chemical resistant properties for many applications. The film is easy to strip mechanically or chemically for soldering. Dimensional tolerances on fine wires insulated with plain enamel are easier to control than for most other enameled wires. Care should be taken to ensure that the plain enamel film is compatible with varnishes and encapsulating compounds used in subsequent operations.

Electrical/Electronic Uses

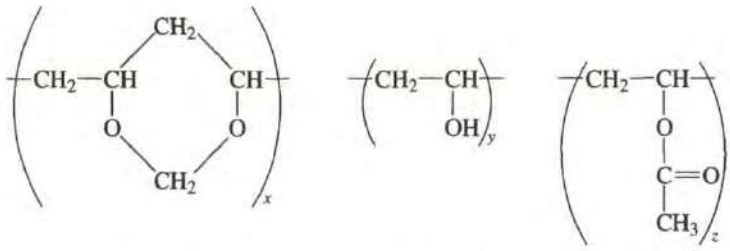
Principal uses include small transformers, and telephone, automatic ignition, and solenoid coils.

Polyvinyl Formal (for Wire Enamel Class 105)

The first successor to plain enamel for magnet wire insulation was polyvinyl formal enamel, in use since 1938 and still used extensively where solderability is not required in Class 105 applications. Monsanto is the developer of polyvinyl formal resin, Formvar™, marketed in solution by Schenectady International and P. D. George.

Chemistry

Polyvinyl formal is a condensation product of formaldehyde and hydrolyzed polyvinyl acetate. The molecular structure contains vinyl formal, vinyl alcohol, and vinyl acetate units:



vinyl formal vinyl alcohol vinyl acetate

The inherent poor solvent resistance and soft film characteristics of polyvinyl formal are significantly improved by incorporation into the enamel of phenolic resin, polyisocyanate, or butylated melamine-formaldehyde resin.

Grades

Solutions of polyvinyl formal resin for wire enamel are supplied at 15–17 percent solids. Weight is 8.3 pounds per gallon.

Processing

The applicable NEMA MW 1000 and Federal J-W-1177 designations for various wire constructions are:

WIRE CONSTRUCTION	MW 1000	J-W-1177
Round	15	/4, T, T2, T3
Square and rectangular	18	/6, T, T2, T3
Nylon overcoat	17	/5, TN, TN2
Bondable	19	/6, TB, T2B, T3B

The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

Modified polyvinyl formal film, with thermal rating of 105°C, has high adhesion to base wire and provides excellent windability, abrasion resistance, and compatibility with most varnishes and encapsulating compounds. It exhibits good overall dielectric and physical properties, and may be used with automatic winding equipment without loss of dielectric properties. It resists attack by most solvents, but is soluble in cresylic acid and other coal tar solvents and reactants. It withstands thermal shock very well. A nylon jacket improves physical properties and solvent resistance.

Polyvinyl formal based coatings tend to craze under stress and tension in winding operations when exposed to toluol or xylol. This may be prevented by annealing at 125°C for 2–4 hours before varnishing. The film must be stripped before soldering.

Electrical/Electronic Uses

Polyvinyl formal magnet wire is still used extensively in random wound stators and armatures, motor and generator windings, and dry and oil-filled transformers.

Polyurethane (PUR) (for Wire Enamel Classes 105, 130, 155)

Polyurethane coatings, primarily because they permit soldering without stripping, are the most widely used coatings for magnet wire suitable for temperatures up to 130°C. They have taken a significant market share from Formvar™, which requires stripping before soldering and is limited to an operating temperature of 105°C. The leading supplier of polyols and toluene diisocyanate, the basic ingredients for polyurethane resins, is Mobay Chemical. Enamels are made from these and other components by Schenectady International and P. D. George.

Chemistry

Polyurethane resins used in wire enamel are one-component ASTM Type 3 derived from polyester or polyesterimide polyols and toluene diisocyanate, which has been

blocked with phenol to prevent premature reaction. When heated to 320°F (160°C), the phenol adduct unblocks, freeing the isocyanate group to polymerize with a hardener such as Mobay's Multron R-2. Recipes often contain polyvinyl formal, which reacts with isocyanate, improving film physical properties. See also "Polyurethanes (Embedding Resins)" in Chapter 6, *Embedding Compounds*.

Grades

A typical polyurethane enamel is supplied 25 percent solids in solvent which is two parts cellulose acetate, one part xylene. Weight is 8.5 pounds per gallon.

Processing

The applicable NEMA MW 1000 and Federal J-W-1177 designations for various wire constructions are:

WIRE CONSTRUCTION	THERMAL CLASS	MW 1000	J-W-1177
Round	105	2	SU/2
Round	155	79	SPU/41
Round (improved solderability)	130	75	SP/37
Bondable (butyral overcoat)	105	3	SUB/44
Bondable (polyurethane/nylon/butyral)	130	29	SUN/30
Nylon overcoat			
(14–24 AWG)	130	28	SUN/9
(25–46 AWG)	155	80	SPUN/42

The enameling process is described in the section "Processing Wire Enamel," p. 202 in this chapter.

Properties

The property which has led to the popularity of polyurethane enameled magnet wire, with or without nylon overcoat, is solderability at 680° to 797°F (360°–425°C) without the necessity of fluxing or stripping the film, which vaporizes in this temperature range. Soldering at higher temperatures produces unsatisfactory results. Polyurethane-coated magnet wire without overcoat or with polyvinyl overcoat has a thermal rating of 105°C, although it will operate continuously at 120°C, highest in its class. With nylon overcoat, polyurethane-enameled magnet wire has a thermal rating of 130°C. This topcoat improves windability and resistance to abrasion, heat shock, and solvents.

Another feature of polyurethane insulated wire is its superior "Q" characteristics at high frequencies and humidities, making it attractive for many electronic applications. The "Q" value is the reciprocal of the dissipation factor. The film also has good adhesion and flexibility.

Without topcoat, polyurethane film has lower abrasion resistance than polyvinyl formal film or nylon-jacketed wires, and is susceptible to softening on prolonged exposure to alcohol, acetone, and methylethyl ketone. Certain catalysts and hardeners used in encapsulated systems may also cause softening. Radiation stability is poor.

An overcoat of polyvinyl butyral provides a surface which is bondable with heat or solvents.

With or without overcoat, polyurethane-enameled magnet wire should not be used where there is the possibility of severe overload resulting in high temperature causing the film to vaporize.

Electrical/Electronic Uses

Polyurethane insulated magnet wire with or without nylon jacket is the logical candidate where soldering is required, with consideration given to its temperature and other limitations discussed above. Its superior 'Q' characteristics make it the leading choice for electronic applications where this feature is required.

Nylon
(for Wire Enamel Classes 105, 130, 155)

Nylon has limited use as primary insulation for magnet wire, but is used extensively as an overcoat to improve physical, mechanical, and solvent resistant properties of polyvinyl formal, acrylic, polyurethane, and polyester-enameled wires. Du Pont is the only U.S. supplier of Nylon 6/6 used in wire enamel. Solutions of this nylon are marketed by Du Pont, Schenectady International, and P. D. George.

Chemistry

Nylon 6/6 is obtained by heating hexamethylene diamine with adipic acid:

$$n\mathrm{H_2N(CH_2)_6NH_2} + n\mathrm{HOOC(CH_2)_4COOH} \xrightarrow[-\mathrm{H_2O}]{\text{heat}} -\!\left[\mathrm{NH(CH_2)_6NHCO(CH_2)_4CO}\right]\!-_n$$

Grades

Solutions of Nylon 6/6 are 15–20 percent solids, 8.7 pounds per gallon.

Processing

Magnet wire with a base coat of nylon is covered by NEMA Designation MW 6 and Federal Specification J-W-1177/3, Types N, N2. This magnet wire has a thermal rating of 105°C. When used as a jacket, where it amounts to 10–15 percent of total coating weight, the following standards, specifications, and thermal classes apply:

BASE COAT	THERMAL CLASS	NEMA DESIGNATION	FEDERAL SPECIFICATION
Polyvinyl formal	105	MW 17	J-W-1177/5, Types TN, TN2
Solderable acrylic	105	MW 39	J-W-1177/8 Types SAN, SAN2
Polyurethane	130	MW 28	J-W-1177/9 Types UN, UN2
Polyester	155	MW 24	J-W-1177/11 Types LN, LN2, LN3

The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

The outstanding features of nylon film are excellent windability and high abrasion and solvent resistance. The coating is compatible with most varnishes and encapsulating compounds. The nylon coating is solderable without mechanical or chemical stripping.

Nylon should not be used in humid environments as it has relatively high moisture absorption.

Electrical/Electronic Uses

Nylon-jacketed magnet wire is suitable for use where physical and mechanical requirements are demanding, such as in rotating equipment and transformer coils.

Epoxy
(for Wire Enamel Class 130)

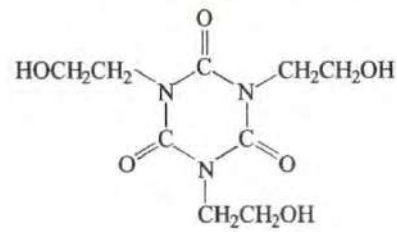
Epoxy-enameled magnet wire, once widely used in wet transformers because of its outstanding resistance to Askarel liquids, has been phased out of general use along with the withdrawal of Askarel from the market for environmental reasons.

Polyester
(for Wire Enamel Classes 155, 180, 200)

Polyesters of several types are the most widely used resins in wire enamels. The most recent improvements are covered by patents held by Schenectady International, and are supplied under the trademark Isonel. P. D. George also makes proprietary polyesters.

Chemistry

Polyesters are the reaction products of polyhydric alcohols with polybasic acids. The ingredients for making Isonel are tris (2 hydroxyethyl isocyanurate (Theic™, Allied Corporation, now AlliedSignal Corporation), terephthalic acid, and glycol). Theic confers superior thermal properties over earlier polyesters made with glycerin. The polyhydric structure of Theic with its cyclic urethane linkages is shown here. Thus, although Isonel is classed as a polyester, it may also be considered a polyurethane.



Theic

Grades

Isonel enamel is supplied in 31 percent solids solution, 9.2 pounds per gallon.

Processing

The applicable NEMA MW 1000 and Federal J-W-1177 designations for various wire constructions are:

WIRE CONSTRUCTION	THERMAL CLASS	MW 1000	J-W-1177
Polyester-imide solderable	155	26	SPE/28
	180	77	SPE/39
Above with nylon overcoat	155	27	SPEN/29
	180	78	SPEIN/40
Polyester, polyester-imide	180	30	H/12
	200	74	PEAI/43
Polyester with nylon overcoat	155	24	LN/11
	180	76	PEIN/38
Polyester with polyamide-imide overcoat	200	35, 73	K14
Above with bondable overcoat	180/200	—	—

The enameling process is described in the section "Processing Wire Enamel," p. 202 in this chapter.

Properties

Tris-based polyester has a thermal rating of up to 200°C, depending on its formulation and topcoat, if any. Physical and dielectric properties approach Formvar. Resistance to cut-through is excellent, as is resistance to Freon™. Solvent resistance is good, and the enamel is compatible with most varnishes and encapsulating compounds, with the exception of some epoxies and epoxy hardeners. Radiation stability is good, but not as high as polyimide enamel.

This magnet wire enamel will hydrolyze, and is not for use in oil-filled transformers or in systems containing chlorine compounds or amine catalysts. The film has a tendency to heat shock, and parts wound with this magnet wire should be gradually preheated before varnishing or encapsulating. The film must be stripped before soldering.

Electrical/Electronic Uses

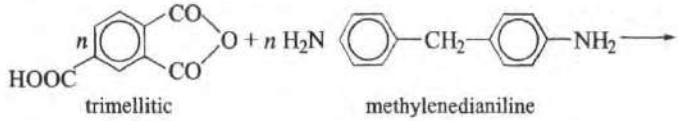
Tris-based polyester-enameled magnet wire is suitable for a variety of applications where operating temperatures are as high as 200°C. Good radiation resistance qualifies it for use where most other enamels (except polyimide) would fail.

Polyamide-Imide (PAI) (for Wire Enamel Classes 200, 220)

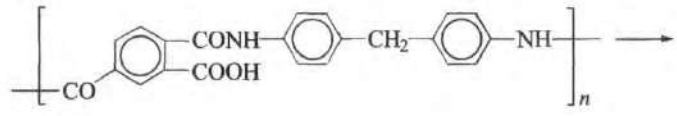
Polyamide-imide enamels are used primarily as topcoats to improve the temperature rating of magnet wires with polyester basecoats. Proprietary polyamide-imide resins have been developed by magnet wire manufacturers and by Schenectady International.

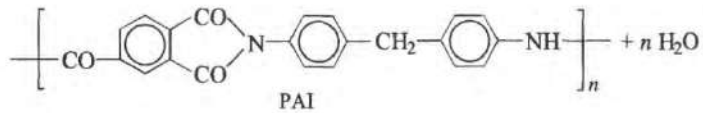
Chemistry

Polyamide-imide resin is the reaction product of trimellitic anhydride and methylenedianiline:



trimellitic anhydride — methylenedianiline





PAI

Grades

Grades are supplied as 26 percent solids solution in an N-methylpyrrolidone/xylene blend.

Processing

Polyamide-imide overcoated magnet wire with a modified polyester basecoat is covered by NEMA Designation MW 35 and by Federal Specification J-W-1177/14 Types K, K2. The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

Polyamide-imide overcoated magnet wire with a basecoat of modified polyester enamel has a thermal rating of 200°C on copper conductor and 220°C on aluminum conductor. The polyamide-imide contributes toughness and good windability which withstands automatic winding operations. It is more resistant to heat and solvent shock than con-

ventional polyesters, and has less tendency to solvent craze. It exceeds regular polyesters in cut-through and abrasion resistance, and may be used continuously up to its thermal rating. It is highly resistant to attack by Freon™ and most solvents. Wet and dry dielectric properties are excellent.

Polyamide-imide overcoated magnet wire should not be used in closed systems with materials containing moisture or chlorine. Best results are obtained by gradual preheating wound components before varnish operations. Polyamide-imide enamel requires mechanical or chemical stripping before soldering.

Electrical/Electronic Uses

Polyamide-imide overcoated magnet wire is suitable for use in hermetic motors and where resistance to attack by Freon or most solvents is required. Its superior temperature resistance and mechanical properties give it advantages over conventional polyesters for many applications.

Polyester-Amide-Imide (for Wire Enamel Class 200)

This high-temperature resin, first developed by Westinghouse, is now also produced by P. D. George and Schenectady International.

Chemistry

Polyester-amide-imide is prepared by reacting fewer than 2 mols of trimellitic anhydride with 1 mol of a diamine, followed by esterification of the carboxy groups.

Processing

Polyester-amide-imide insulated wire is covered by NEMA Designation MW 35. The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

Magnet wire insulated with polyester-amide-imide has a thermal rating of 200°C. It is reported to be equal to two-coat polyester systems in solvent shock, heat shock, and thermal stability properties. It is compatible with most insulating varnishes and encapsulating compounds. This coating withstands high-speed winding and is resistant to attack by R22 refrigerant. The film requires stripping before soldering.

Electrical/Electronic Uses

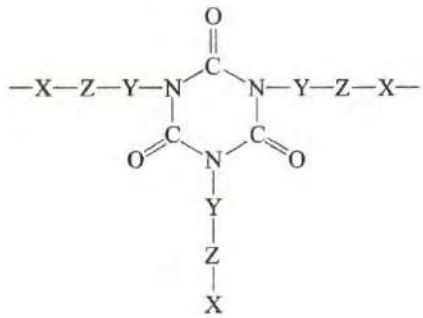
This magnet wire is especially suited for use with high-speed winding devices. High physical properties encourage its use in demanding applications for dry and oil-filled transformers, and in rotating equipment.

Polyester-Imide (PEI)
(for Wire Enamel Classes 180, 200)

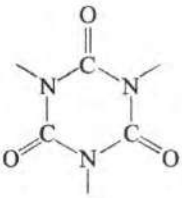
Polyester-imide for high-temperature wire enamel is produced in the United States by Schenectady International (Isomid™). P. D. George is licensed by Schenectady International to make polyester-imide using the trademark Teramid. In Europe, there are four producers, all in Germany: Kurt Herberts, Schramm, Dr. Beck, and Cella Lackfabrik.

Chemistry

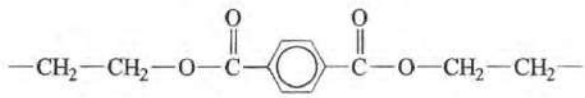
The process for making Isomid is covered by British Patent #1,082,818 (1967) and French Patent #1,478,938. Isomid is the complex reaction product of Theic, tris (2-hydroxyethyl) isocyanurate, with dimethylterephthalate, ethylene glycol, trimellitic anhydride, and aromatic diamine. It has the following structure:



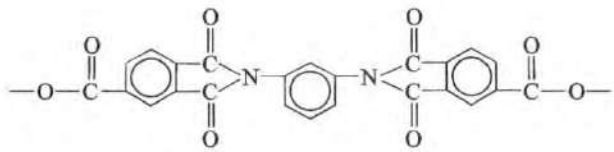
where *X* is:



Y is:



and *Z* is:



Grades

Polyester-imide is supplied in 31 percent solids solution in cresylic acid, 9.2 pounds per gallon.

Processing

Polyester-imide enameled wire is covered by NEMA Designation MW 30 for thermal class 180 and MW 74 for thermal class 200. The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

Polyester-imide insulated wire has thermal ratings of 180°C/200°C. Because of its excellent cut-through properties and toughness, polyester-imide enameled wire does not require a jacket. It has high resistance to Freon, solvents, and heat shock. The coated wire is highly flexible with good adhesion of enamel to wire. Dielectric properties, both wet and dry, are excellent. The coating is compatible with most varnishes and encapsulating compounds, but must be stripped before soldering.

Electrical/Electronic Uses

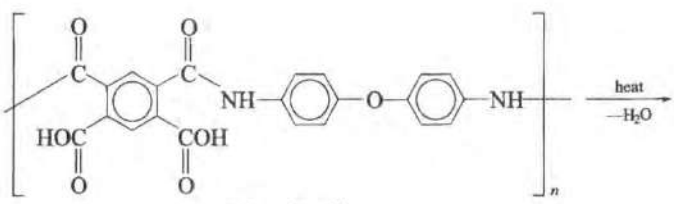
Polyester-imide provides a coating with outstanding features, and is suitable for a wide range of electrical/electronic high-temperature applications, although not as high temperature as polyimide (220°C). Polyester-imide is, however, much lower in price.

Polyimide (PI)
(for Wire Enamel Class 220)

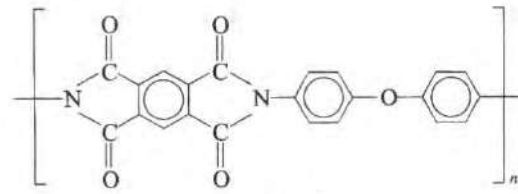
Of the many varieties of polyimides, the unmodified polyimide widely used in high-temperature wire enamels is produced by Du Pont, trademarked Pyre-ML. Major magnet wire manufacturers supply Pyre-ML coated wire as their top-of-the-line product. With the expiration in 1982 of Du Pont's basic patent, Schenectady International and P. D. George have introduced competitive products to Pyre ML.

Chemistry

Pyre-ML resin is the condensation product of polyamic acid when exposed to heat in enameling ovens:



polyamic acid



polyimide

Grades

Polyamic acid is offered to magnet wire manufacturers in 15–17 percent solids solution in N-methylpyrrolidone and dimethyl-acetamide blended in a 2:1 ratio. Weight per gallon is 8.7 pounds.

Processing

Polyimide-coated wire is covered by NEMA Designation MW 16 for round wires and MW 20 for square and rectangular wires, and by Federal Specification J-W-1177/15, Types M, M2, M3, and J-W-1177/18, Types M2, M4. The enameling process is described in the section "Processing Wire Enamel" in this chapter.

Properties

Polyimide-enameled wire has the highest thermal stability, and is the most resistant to cut-through, chemicals, and radiation of all enameled wires. It has a thermal rating of 220°C and retains high dielectric values at that temperature. Despite its high price, its high space factor may permit the total cost of finished products to be competitive with equivalent products made with bulkier high-temperature insulations. The coated wire is chemically compatible with a wide range of varnishes and encapsulating compounds.

On the negative side, polyimide insulated wire is not as abrasion resistant as Formvar, or nylon overcoated wire, which, however, have a much lower temperature rating. Polyimide film will hydrolyze in sealed systems containing moisture, and will solvent craze unless winding stresses are relieved by preheating $^1/_2$ hour at 150°–170°C. Because of its high resistance to attack by virtually all chemicals, polyimide-coated wire is very difficult to strip, requiring highly corrosive strippers.

Electrical/Electronic Uses

Polyimide-insulated wire has the highest temperature rating of all enameled wires. This property, plus highest cut-through, chemical, and radiation resistance, permit it to be used in applications and environments where other enameled wires would be unsuitable. Its high price limits its use where these outstanding properties are not required. It is recommended for use in hermetic units with no entrapped moisture, high-temperature rotating equipment, and aerospace applications.

8

Insulating Coatings and Impregnants

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INTRODUCTION

Insulating coatings and impregnants are of three principal types:

- Varnishes composed of resins or polymers in solution, dispersion, or emulsion in nonreactive liquids, with or without thixotropes or other additives. (A *thixotrope* is an additive that permits varnish viscosity to decrease under shear and recover its original viscosity when the shear force is removed.)
- Varnishes composed of resins or polymers liquefied by a reactive solvent, with or without additives, and without volatile, nonreactive liquids.
- Powder coatings.

Insulating coatings and impregnants covered in this chapter have these principal uses:

- To insulate and bond coils in rotating electrical equipment and transformers
- To insulate circuit materials and electronic inductive components (transformers, chokes, coils, yokes, etc.) from harmful environments.

Magnet wire enamels are covered in Chapter 7.

An important consideration in selecting a coating or impregnant is its compatibility with other system components, especially magnet wire. Since no two systems are exactly alike even for equivalent equipment made by different manufacturers, successful systems are the result of evolution over a long period of use.

While manufacturers are reluctant to adopt new materials and techniques for small economic or quality benefits, changes are sometimes necessary to comply with deadlines for implementation of standards and regulations of the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and state and local governments.

SUPPLIERS OF COATINGS AND IMPREGNANTS

There are four major broad line producers of insulating coatings and impregnants:

- *John C. Dolph* is a major supplier to apparatus service shops, as well as to original equipment manufacturers. Products include polyesters, epoxies, and polyurethanes.
- *P. D. George (Sterling)* is a principal producer of magnet wire enamels, as well as polyester and epoxy varnishes and enamels.
- *Schenectady International* features polyesters in its magnet wire enamel and varnish product lines. Some epoxies for hermetic motors are also produced.
- *Westinghouse* produces varnishes and wire enamels for its internal consumption, and also supplies these to other equipment manufacturers. The product line includes polyesters, epoxies, and polyurethanes.

Companies which do not produce a broad line of products, but which make significant quantities of special types of coatings and impregnants include:

- *Conap*, produces conformal coatings;
- *Dow Chemical*, produces epoxies;
- *Dow Corning*, the largest producer of silicones;
- *Emerson and Cuming*, produces epoxies, including powder resins;
- *Epolylite Corporation*, produces epoxies;
- *General Electric*, produces silicones;
- *Hysol Division, The Dexter Corporation*, produces epoxies, including powder resins;
- *3M*, produces epoxies, including powder resins;
- *Polymer Corporation*, produces polyester and epoxy powders;
- *Union Carbide*, produces silicone and parylene resins;
- *Viking Products*, produces phenolic and modified epoxy coatings.

DIELECTRIC STRESSES

There are several factors which tend to shorten the useful life of coatings and impregnants:

- Aging in service of organic insulations causes loss of plasticizers and flexible ingredients through volatilization or migration, leading to embrittlement and ultimately to mechanical breakdown.
- Where polymers contain unsaturated linkages, oxidation and subsequent chain cleavage cause embrittlement and eventual disintegration.
- Prolonged exposure to voltage stress through a solid insulation or along its surface will cause dielectric failure. Corona discharge occurring at high ac voltages, with its formation of ozone, will greatly accelerate dielectric breakdown, focusing on voids and contaminants in the insulation.
- Harsh environments containing chemicals, water or water vapor, radiation, and abrasive materials will encourage dielectric failure.
- Strong vibration and mechanical shock will reduce the useful life of a dielectric.
- Thermal cycling and exposure to temperatures above its rated thermal class will cause rapid deterioration of an insulation.

CRITICAL PROPERTIES

Designers of electrical apparatus and electronic components are performance oriented and are continually searching for dielectrics, whatever their composition, which are effective, easy to apply, durable, energy efficient, free from environmental and worker health and safety problems, and low cost. To meet these requirements, formulators of

insulating coatings and impregnants are challenged to develop products with these properties:

- Better temperature resistance to prolong operating life
- Improved moisture resistance both before and after curing
- Greater thermal conductivity for lowering equipment operating temperature
- Higher bonding strength to permit rotating equipment to operate faster and to be more resistant to shock
- Greater dielectric strength to permit thinner insulation films for equivalent protection
- Improved resistance to corona damage
- Lower dielectric losses to reduce internal heating of insulations
- Higher impulse strengths to withstand current surges without damage
- Improved flame resistance to reduce fire hazard
- Greater resistance to environmental attack
- Decomposition products that are nonconducting and are not harmful to health, to other insulations, or to the environment
- Reduction or elimination of solvents to reduce voids in insulations, and to conform to environmental and health legislation
- Reduction or elimination of objectionable or harmful odors during storage or processing
- Shorter curing cycles to reduce manufacturing time
- Greater stability in storage and in processing equipment.

THERMAL CLASSIFICATION OF COATINGS AND IMPREGNANTS

See "Magnet Wire Thermal Classification" in Chapter 7, p. 202 *Magnet Wire Enamels*.

FEDERAL SPECIFICATIONS AND PRACTICES

There are several Federal specifications for insulating varnishes, compounds, and enamels, among which the following are significant:

- MIL-1-24092, *Insulating Varnish, Electrical, Impregnating, Solvent Containing*. This performance specification covers clear, air drying, and baking varnishes, thermal classes 130–220. The intended use is on all types of electrical coils and windings. There are three grades:

  Grade CA—clear, air drying varnish, classes 130 and 155
  Grade CB—clear, flexible, baking varnish, classes 155, 180, 200, and 220
  Grade CBH—clear, semi-rigid, baking varnish, classes 155, 180, and 200

In practice, the preponderance of usage is for modified polyester baking varnish, class 155, with minimum nonvolatile content of 40 percent. Silicone varnishes may not be substituted where other varnishes are required.

• MIL-I-46058, *Insulating Compound, Electrical (for Coating Printed Circuit Assemblies)*. This specification is approved for use by all departments and agencies of the Department of Defense. Covered are conformal coatings suitable for application to printed circuit assemblies by dipping, brushing, spraying, or vacuum deposition. The following types of conformal coatings are included:

TYPE	MAXIMUM CURING TIME (hours) AT 125°C
AR—Acrylic Resin	4
ER—Epoxy Resin	8
SR—Silicone Resin	24
UR—Polyurethane Resin	24
XY—Para-xylylene	vacuum deposition

The specification contains specific requirements for:

- Compatibility
- Appearance
- Coating thickness on test specimens
- Fungus resistance
- Shelf life
- Insulation resistance
- Dielectric withstanding voltage
- Q (resonance)
- Thermal shock
- Moisture resistance
- Flexibility
- Hydrolytic stability
- Flame resistance

• MIL-E-22118, *Enamel, Electrical, Insulating*. This specification is approved for use by all departments and agencies of the Department of Defense. Requirements for the coating include the following:

- The color shall be characteristic of red iron oxide pigment
- The vehicle shall be phthalic alkyn resin, together with necessary addition of volatile solvents and driers
- The volatile content shall have:
  a. 5 percent maximum solvents having an olefinic or cyclo-olefinic type of unsaturation
  b. 8 percent maximum combination of aromatic compounds with eight or more carbon atoms to the molecule except ethyl benzene

c. 20 percent maximum combination of ethyl benzene, ketones having branched hydrocarbon structures, or toluene
d. Total of 20 percent maximum a + b + c.

Quantitative requirements are shown in Table 8-1.

TABLE 8-1 Quantitative Requirements for Red Insulating Enamel (MIL-E-22118)

CHARACTERISTICS	MINIMUM	MAXIMUM
Total solids, percent by weight of enamel	58	—
Pigment, percent by weight of enamel	25	—
Vehicle solids, percent by weight of enamel	32	—
Phthalic anhydride, percent by weight of nonvolatile vehicle	30	—
Iron oxide (Fe_2O_3), percent by weight of pigment	28	—
Calcium oxide, percent by weight of pigment	—	1.5
Coarse particles and skins, percent by weight of pigment	—	0.5
Extenders, percent by weight of pigment	—	70
Water, percent by weight of enamel	—	0.5
Viscosity, Krebs Stormer	61	69
Weight per gallon, pounds	9	—
Drying time, air drying		
Tack free, hours	—	1/2
Dry through, hours	—	4
Baking at 230°F (110°C)		
Dry through, hours	—	2
Dielectric strength (ASTM D 115)		
Dry, volts/mil	1,200	—
Wet, volts/mil	300	—

• MIL-V-173, *Varnish, Moisture-and-Fungus-Resistant (for Treatment of Communications, Electronic, and Associated Equipment)*. This specification is mandatory for use by all departments and agencies of the Department of Defense. The document covers one type of moisture-and-fungus-resistant varnish consisting of a para-phenyl phenol-formaldehyde resin in combination with tung oil and suitable solvents which has been made fungistatic by the addition of 7.0 ± 1.0 percent salicylanilide or one percent copper 8-quinolinolate. The resin shall conform to Federal Specification TT-R-271 and the tung oil shall conform to Federal Specification TT-T-775. The solvent shall not constitute a hazard to personnel applying the varnish. Methanol, benzene, or chlorinated hydrocarbons shall not be used. Nonvolatile content of the varnish shall be a minimum of 50 percent of the weight of the varnish excluding fungistatic agents. Of this, 55 ± 2 percent shall be tung oil with the balance resin.

• EPA-450/3-84-019, *Determination of Volatile Content Procedures for Certifying Quantity of Volatile Organic Compounds Emitted by Paint, Ink, and other Coatings*.

ASTM STANDARDS FOR ELECTRICAL INSULATING VARNISHES

The American Society for Testing and Materials (ASTM) has established these standards for electrical insulating varnishes:

D 115, *Testing Varnishes Used for Electrical Insulation*

D 374, *Tests for Thickness of Solid Electrical Insulation*

D 618, *Conditioning Plastics and Electrical Insulating Materials for Testing*

D 1932, *Test for Thermal Endurance of Flexible Electrical Insulating Varnishes (up to 180C)*

D 2369, *Standard Test Method for Volatile Content of Coatings*

D 2436, *Specifications for Forced-Convection Laboratory Ovens for Electrical Insulation*

D 2519, *Test for Bond Strength of Electrical Insulating Varnishes by the Helical Coil Test*

D 2756, *Weight Loss of Electrical Insulating Varnishes*

D 3056, *Gel Time for Solventless Varnishes*

D 3145, *Test for Thermal Degradation of Electrical Insulating Varnishes by Helical Coil Method*

D 3251, *Test Method for Thermal-Aging Characteristics of Electrical Insulating Varnishes Applied Over Film-Insulated Magnet Wire*

D 3312, *Percent Reactive Monomer in Solventless Varnishes*

D 3377, *Weight Loss of Solventless Varnishes*

D 4217, *Gel Time of Thermosetting Coating Powder*

D 4733, *Test Methods for Solventless Electrical Insulating Varnishes*

The Manual on the Determination of Volatile Organic Compounds in Paints, Inks, and Related Products, ASTM Manual Series, MNL-4, contains a review of the regulations, methods of measurement, and calculation of VOC compound in solvent-containing compositions.

UL STANDARD 1446, SYSTEMS OF INSULATING MATERIALS—GENERAL

Although varnishes are only one component of an insulation system, they come into contact with all other components, serving to bond the system into a solid unit. It is, therefore, essential that a varnish be compatible with other elements in the system. Otherwise, the system may be subject to premature failure. UL 1446 deals with this issue. Noteworthy sections of this standard include the following:

• Covered are test procedures to be used in the evaluation of Class 130 or higher electrical insulation systems intended for connection to branch circuits rated 600 volts or less.

• An insulation system is an intimate combination of insulating materials used in electrical equipment.

• Insulation system components include ground insulation, magnet wire coating, encapsulant, phase-to-phase insulation, varnish, wedges, tapes, lead wire, tie cord, sleeving, and all similar parts.

• Insulating materials having different assigned temperature classes may be combined to form an insulation system having a temperature class that may be higher or lower than that of any of the individual components.

• The compatibility of an insulating material with other materials in the same insulation system shall be investigated to determine whether thermal aging of such components makes the system vulnerable to unacceptable deterioration in normal service at the assigned temperature class of the system.

APPLICATION METHODS

The first method for applying insulating coatings and impregnants to electrical apparatus was by brushing or dipping followed by curing at room temperature or in ovens. This method is still used by service shops for repair and rehabilitation of rotary equipment and transformers. However, faster and more effective processing is needed where production volumes and energy consumption are high and compliance with environmental, health, and safety legislation is required. The most widely used modern methods are summarized in this section.

Vacuum Pressure Impregnation (VPI)

This technique, now in general use, features better impregnation of absorbent materials and elimination of voids. Suitable impregnants include solventless epoxies and polyesters. Key steps in this process include:

1. Loading the preheated part in the treatment tank
2. Evacuating the air from the tank to the desired pressure (1 mm of mercury for some solventless varnishes)
3. Introducing the varnish and holding low pressure
4. Pressurizing the tank and holding under pressure with inert gas
5. Relieving pressure
6. Repeating the vacuum/pressure cycle for the appropriate number of cycles
7. Removing the part from the treatment tank
8. Curing the varnish by oven baking, infrared, or resistance heating.

Trickle Impregnation

This method requires preheating the parts, dispensing on them a measured amount of varnish, and heat-curing the coating. In this method, 100 percent of the varnish is utilized, thereby minimizing material losses. Solventless two-part types of both polyester and epoxy varnishes are widely used, with polyesters predominating in the U.S. and epoxies in Europe. Polyesters are lower cost and are easier to process, but have higher shrinkage. Epoxies have better adhesion. Varnishes are cured with a very active catalyst such as tertiary butyl perbenzoate.

In this process, varnishes are trickled on rotating parts preheated at 180° to 250°F (82°–121°C). Volume and rate of application of varnish and rotation speed must be carefully controlled for best results.

Several types of equipment are used for the trickle impregnation method, ranging from single-station machines for large parts to continuous flow-through machines utilizing conveyor belts for high-volume parts as they pass through the preheat, dispensing, and post-curing zones. Final cure at 250° to 350°F (121°–171°C) is accomplished by one of these means:

- Convection oven with gas or electric heat
- Radiant heat using infrared or ceramic heaters
- Resistance heat generated by passing a current through the wound coils of the part
- Heat generated by the high exotherm of the catalyzed varnish.

Fluidized Bed

Dry, powdered resin may be applied to parts by the fluidized bed process where film thickness of 5 mils and over is permissible and impregnation is not required. This method is suitable for coating slots in electrical apparatus, where it competes with polyamide paper (Nomex™) and polyester ribbon (Mylar™). To be effective, powder must be applied at a rate to produce a 10–15 mil coating to the face of the part so that slots are coated with at least 6–10 mils and corners have a minimum of 5–6 mils coating, as required by Underwriters Laboratories.

In this process, dry, powdered resin is suspended in a chamber by controlled velocity hot air or inert gas introduced from the bottom of the chamber through a screen and porous plats. The suspended powder is in constant motion and acts as a low-viscosity, low-surface-tension fluid. Before passing through the chamber, the part is treated to facilitate adhesion of powder by heating or application of an adhesive primer. After coating, the resin is cured by a conventional method. The complete process may be a continuous operation.

To be effective, this method requires precise control of several process variables:

- Polymer type
- Powder particle size
- Pretreatment techniques and temperature
- Chamber zone temperatures

- Time of exposure
- Curing method, temperature, and time.

Electrostatic techniques may be incorporated with this process by applying a high-voltage dc field to give resin particles a negative charge. The part to be coated is electrically grounded so that particles are electrostatically attracted to it as it passes through or is suspended above the fluidized bed. This eliminates the need to heat the part or coat it with an adhesive, and permits powder to be easily removed by air knife or other method from areas where coating is not desired. Due to their excellent adhesive and other physical properties, epoxies are the most commonly used resins, although other polymers are also used, including silicones, polyesters, phenolics, nylon, and polyvinyl chloride.

Radiation Curing

This method employs ultraviolet light (UV) or electron beam (EB) technology and cures only resins reached by the light or beam. A baking step is subsequently required to cure resins not exposed to radiation.

With UV or EB radiation curing there is no energy wasted in heating the process equipment, atmosphere, or apparatus; or in evaporating solvents. For example, a UV curable class H (180°C) solventless varnish requires for curing 4 hours at 150°C from the time the part is at temperature compared with 5–7 seconds when exposed to UV light at 200 watts per linear inch supplied by mercury vapor lamps. The arc between lamp electrodes generates electromagnetic energy of varying wavelengths, giving off infrared and visible light as well as the desired ultraviolet radiation.

Conformal Coating

Circuit materials and delicate electrical/electronic components may be protected dielectrically and from the environment by a coating which conforms closely to the shape of the part. Commonly used coatings, such as epoxy, acrylic, urethane, and silicone, may be applied in several ways, including:

- Dip coating
- Spraying with both pressure and atomizing sprayers
- Flow-coating and brushing

A unique conformal coating and method of application, the parylene process, has been developed by Union Carbide. Parylene, a polymer based on para-xylylene or its substituted derivatives, cannot effectively be melted, extruded, molded, calendered, or dissolved to form solvent systems. In this process, a solid dimer is converted to a reactive vapor of the monomer, which when passed over parts at room temperature coats them with polymer in thicknesses of 0.25–1.5 mils. No catalysts are employed. Although the process requires high heat at one point, vapor-phase deposition occurs at room temperature; thus, temperature-sensitive parts are not damaged. The process basically consists of these steps:

1. Vaporizing the para-xylene dimer at 175°C (347°F) and 1 torr (the pressure to support 1 mm of mercury at 0°C (32°F)
2. Pyrolizing the dimer at 680°C (1256°F), 0.5 torr, to form the monomer
3. Formation of the polymer as it deposits on the part at 25°C (77°F), 0.1 torr
4. Treatment in a cold trap at –70°C (–94°F) and reduction of pressure to 0.001 torr.

DEVELOPMENT PROGRAMS

The emphasis in development programs is on replacing varnishes containing hazardous volatile organic compounds (VOCs) in the following ways:

- *High solids* (up to 100 percent), low volatile liquid varnishes which reduce or eliminate emissions to levels in compliance with Environmental Protection Agency and Occupational Safety and Health Administration standards and regulations.
- *Water-based varnishes* are now produced by most broadline manufacturers of insulating coatings and impregnants. Earlier versions had poor moisture resistance, inadequate physical properties, and were lacking in tank stability. While formulations are proprietary, a distinction may be made between water-soluble systems and water-borne systems. The former may be diluted 100 percent with water, while the latter requires a cosolvent for extreme dilution with water.

One commercially available product is an alkyd-phenolic modified polyester in which carboxyl terminated backbones are reacted with an amine to form amine salts. The amine salt and coupling agent, butyl cellosolve, blend in water at pH 8.2–8.5 (controlled by triethylamine) to form the resin system. On baking at 275° to 325°F (135°–163°C), the amine is driven from the film, permitting the carboxyl group to react with the other ingredients, forming a film which is resistant to moisture and chemicals, and possesses good mechanical strength. As supplied, the varnish is 40 percent minimum nonvolatile. Weight is approximately 8.3 pounds per gallon. Flash point is over 200°F (93°C). Thermal rating is Class 180. Thinning to the desired application consistency is done by adding water.

Another product, a water-borne system, contains by weight 50 percent resins such as phenolic, melamine, and solvent-based modified polyester. The volatile portion is a mixture of 80 percent water and 20 percent cosolvent 2-butoxyethanol. The pH is maintained at 7.5–8.0 for optimum water solubility by t-alkanolamine. As this varnish is cured, all water is evaporated at 225°F (107°C), well below the polymerizing temperature of the resin system. Thus, the likelihood of premature surface curing is greatly reduced compared with solvent-based varnishes containing solvents evaporating at much higher temperatures. After the water is driven off, curing is completed at 300° to 325°F (147°–163°C). It is claimed that this varnish has excellent humidity resistance and chemical resistance superior to traditional polyester varnishes. It may be formulated to offer very high bond strength, especially at ele-

vated temperatures, where it competes with epoxies. As supplied, specific gravity is 1.040–1.060. Flash point is over 200°F (93°C). Thermal endurance for 20,000 hours is over 180°C. Dilution should be with a blend of 80 parts water, 20 parts butoxyethanol.

Both of the above varnishes may be used in vacuum pressure impregnation processing.

Although the specific heat and heat of vaporization of water are significantly higher than for varnish solvents, some authorities claim that water-based varnishes take less energy to cure for these reasons:

- Water has less affinity than solvents have for resins (lower hydrogen bond strength).
- The film formed in curing water-based varnishes stays open during curing. With solvent-based varnishes, solvents have to fight their way through the film that forms early in the curing process.
- Lower air volumes are required in curing waterbased varnishes.

• *Powder coating* employing fluidized-bed technology is practical where there is high-volume production for a part and its configuration is open to powder deposition. Typically, the powder is a one-component epoxy. Polyester powders are also used, but since they are made from solvents, they may contain residual solvent which could cause pinholing during the curing process. Uniformity of film thickness, especially at edges, is often a problem with powder coatings. To obtain sufficient coverage at critical points, it is often necessary to coat other surfaces with thicker-than-required film. The powder coating process is discussed in the "Fluidized Bed" section of this chapter and in "Development Programs," p. 206.

MARKET TRENDS

There is increasing emphasis on compatibility of coatings and impregnants with other components of insulation systems. It is especially important that the insulating varnish is compatible with the magnet wire enamel in the same system. Otherwise, bonding may be inadequate, leading to system failure. Both magnet wire and varnish manufacturers are concerned with system compatibility, and many will furnish helpful information on this subject.

Varnish producers and users must now comply with increasingly more stringent Environmental Protection Agency and Occupational Safety and Health Administration standards and regulations, especially with regard to solvents. The ideal is to eliminate solvents entirely, but because of the large investment in production equipment designed for solvent systems, it is often more practical to use varnishes made with exempt (acceptable) solvents or to provide for recycling or disposal of nonexempt vapors safely and effectively. There is little doubt, however, that most new systems will be designed to use solventless, water-based, or high-solids varnishes.

INHERENT CHARACTERISTICS OF COATING AND IMPREGNATING VARNISHES

- *Oleoresinous* varnishes are lowest cost with adequate properties for many applications.
- *Alkyd polyesters* are moderate cost and the most widely used solvent-type varnishes, with good overall properties over a wide useful temperature range.
- *Unsaturated polyesters* are the most commonly used solventless VPI varnishes, and are lower cost than solventless epoxies.
- *Epoxies* are noted for their good dielectric properties strong bond strength, and resistance to chemicals and high humidity. They are higher cost than polyesters.
- *Parylene* has excellent dielectric and barrier properties, and is highly resistant to attack by most solvents and chemicals. It may be applied only by a special process and is high cost.
- *Polyurethanes* have good film adhesion and flexibility, but are not as resistant to moisture and chemicals as other varnishes.
- *Silicones* have the best thermal properties and water resistance, but have relatively low mechanical properties and adhesion, and are high cost.

PRINCIPAL TYPES OF COATINGS AND IMPREGNANTS

The chemistry, grades, properties, and electrical/electronic uses of principal types of coatings and impregnants are described in the sections which follow in this order:

- Early Oleoresinous Insulating Varnishes
- Alkyd Polyesters
- Unsaturated Polyesters
- Epoxies
- Parylene
- Phenolics
- Polyurethanes (PURs)
- Silicones

Early Oleoresinous Insulating Varnishes

Electrical apparatus will not function without adequate insulation. At first, modified wood finishing varnishes made in open kettles sufficed. Those varnishes were made with drying vegetable oils, such as linseed and China-wood (tung) oils, cooked at temperatures up to 600°F (316°C) together with rosin, ester gum, copal, and other resins, and reduced on cooling to usable consistency with compatible solvents. The drying, or

oxidizing, process was facilitated by addition to formulations of cobalt and manganese compounds, such as acetates and napththenates.

It was soon found that incorporation into varnishes of materials such as gilsonite, pitches, coal tars, and petroleum asphalts resulted in improved dielectric properties and resistance to moisture, acids, and alkalis. Yellow varnishes were still superior in oil resistance and physical properties. Further improvement resulted when the equipment was baked after treating it with varnish. This led to the development of varnishes with lower oil content (short-oil varnishes) specifically designed for oven curing. Some of these varnishes are still used.

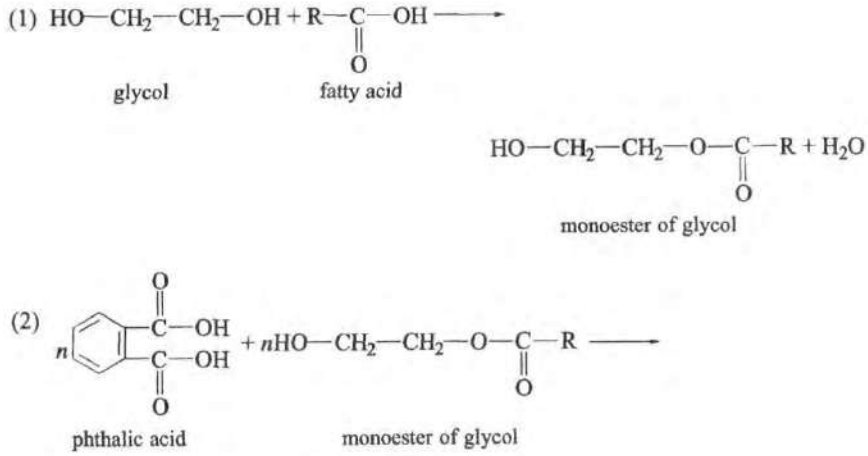
Alkyd Polyesters (Varnish Resins)

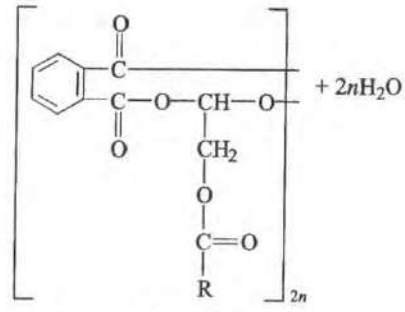
In the coatings field, the generic term *polyester* applies to reaction products of a polyhydric alcohol with a polybasic acid. There are two types of polyesters used in the manufacture of varnishes. This section covers alkyd polyesters, also called *glyptals*, the most widely used, which are polyesters modified with fatty acids of vegetable oils. The section following this discusses unsaturated polyesters, which may be crosslinked by reaction with a monomer such as styrene, vinyl toluene, or diallyl phthalate.

Alkyd polyesters became available in the mid-1920s, and soon became the predominant polymers for coatings and impregnants for application to all types of electrical equipment.

Chemistry

The sequence of steps in producing an alkyd resin is, first, the partial esterification of a polyhydric alcohol with a fatty acid, followed by reaction with a dibasic acid:





modified alkyd polymer

Commonly used polyols, in addition to glycol, are glycerol, polyglycerol, and pentaerythritol (a key ingredient in insulating varnishes). Polybasic acids, other than phthalic, include isophthalic, maleic, adipic, and sebasic, with longer chain acids yielding softer resins that made good polymeric plasticizers for harder resins. Fatty acids are derived from vegetable oils such as linseed, tung (China-wood), soya, safflower, perilla, and castor. The resin can be prepared by either bulk or solution polymerization methods with cooking and refluxing continued until the viscosity and acid number of the reaction mixture reach predetermined values. The resin may be supplied in solution which the user may further reduce. Long-oil alkyds are soluble in mineral spirits, but short-oil alkyds require stronger solvents such as xylene or toluene.

Alkyds may be further modified to achieve certain properties by blending with other varnishes or by reacting with other resins, including phenolics for improved water and alkali resistance, epoxies for better adhesion, silicones for better thermal and dielectric properties, and aminos for greater durability. Alkyds may also be combined with reactive monomers, such as styrene, vinyl toluene, and diallyl phthalate for fast curing varnishes.

Grades

A wide variety of alkyd grades is marketed by major varnish manufacturers. Representative baking grades are listed in Table 8-2. Air drying/baking grades are also available, but these usually have lower properties.

Processing

See "Application Methods" in this chapter.

Properties

As is shown in Table 8-2, alkyds may be formulated with excellent dielectric, mechanical, and chemical resistance properties covering a wide useful temperature range.

TABLE 8-2 Key Properties of Representative Baking-Type Alkyd Varnishes

FEATURE	MAXIMUM USEFUL TEMPERATURE (°C)	CURING (hours)	CURING (°C)	DIELECTRIC STRENGTH ASTM D 115 (volts/mil) dry	DIELECTRIC STRENGTH ASTM D 115 (volts/mil) wet	BOND STRENGTH ASTM D 2519 (pounds) 23°C	BOND STRENGTH ASTM D 2519 (pounds) 155°C	CHEMICAL RESISTANT WATER	CHEMICAL RESISTANT (10% H_2SO_4)	CHEMICAL RESISTANT (1% NaOH)	OIL ASTM D 115
Water soluble	180	1½–6	135–163	4,000	2,900	30	5	na	na	na	na
Alternative to silicone	180	2–8	135–177	4,100	3,000	15	2.5	Ex	Ex	Ex	Passed
Phenolic modified flexible	195	½–4	135–163	4,100	2,900	35	5	Ex	Ex	Ex	Passed
Phenolic modified with alkyd Rule 66 compliance	200	½–4	121–163	3,400	2,800	35	4.5	Ex	Ex	Ex	Passed
Flash point 38°C+ general purpose	215	1–5	135–163	4,000	2,900	28	2.5	Ex	Ex	Ex	Passed

Note: All of the above except water soluble comply with Federal Specification MIL-I-24092.

na—not available.

Ex—excellent.

Electrical/Electronic Uses

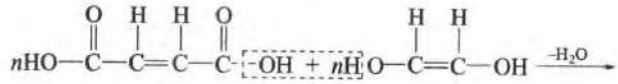
Alkyds are the most widely used coatings and impregnants for application to all types of electrical/electronic items, including rotating equipment, transformers, and electronic components.

Unsaturated Polyesters (Varnish Resins)

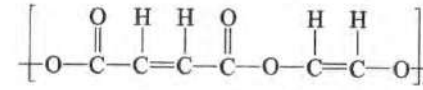
The trend in insulating varnishes is toward greater use of solventless types suitable for vacuum pressure impregnation (VPI). Unlike films formed by solvent-type varnishes, solventless varnish films do not contain voids formed by solvent evaporation during curing. Solventless polyester varnishes have been available since the late 1940s, and are the most commonly used in the VPI process. Solventless epoxies are also used, but to a lesser extent.

Chemistry

Unsaturated polyesters are formed by reacting an unsaturated polybasic acid, most frequently maleic or fumaric, with a dihydroxy alcohol, such as ethylene, propylene, diethylene, or dipropylene glycol. Saturated acids, for example, phthalic and adipic, may also be included in the formulation to control unsaturation and make the final resin tougher and more flexible.



maleic acid — ethylene glycol



unsaturated polyester resin

To this resin is added a vinyl-type monomer such as styrene, alphamethylstyrene, vinyl toluene, diallyl phthalate, divinylbenzene, and triallylcyanurate, or a mixture of these. Curing proceeds by free-radical addition across double bonds, and is initiated by organic peroxides, for example, dicumyl peroxide, heat, or ultraviolet light. The base resin formulation and monomer selection each significantly affect all varnish properties.

Grades

Several manufacturers offer a selection of one- and two-component solventless, unsaturated polyesters with varying thermal classifications, gel time, and properties. Representative grades are shown in Table 8-3.

TABLE 8-3 Key Properties of Representative VPI Baking-Type Solventless Polyester Varnishes

FEATURE	THERMAL CLASS (°C)	GEL TIME @ 100°C (minutes)	DIELECTRIC STRENGTH ASTM D-1346 @ 23°C (volts/mil)	DIELECTRIC CONSTANT** ASTM D-150		DISSIPATION FACTOR** ASTM D-150		INSULATION RESISTANCE ASTM D-257 (megohms)		BOND STRENGTH ASTM D-2519 (pounds)	
				23°C	155°C	23°C	155°C	23°C	155°C	23°C	155°C
Rigid 2-part	180	40*	1,800	5.2	8.7	0.046	0.082	1×10^6	1×10^4	32	7.5
Semi-flexible high bond strength thixotropic 2-part	180	90*	2,000	4.5	7.4	0.017	0.076	1×10^6	1×10^5	45	8.5
Rigid high bond strength high flash (165°C) Freon resistant 1-part precatalyzed	205	125	1,750	3.1	na	na		na		42	20

*With 1% dicumyl peroxide.

**At 100 Hz.

na—not available.

Processing

See "Application Methods," p. 239 in this chapter.

Properties

Solventless polyesters are significantly lower cost than solventless epoxies, and have dielectric, mechanical, and chemical resistance properties adequate for most applications. However, where a part or unit must withstand submersion or prolonged exposure to high humidity, or where the highest bond strength is required, epoxies are recommended. Because of the virtual elimination of voids on curing, solventless varnishes provide better heat dissipation and reduce the possibility of corona damage.

Table 8-3 lists key properties of representative baking-type solventless polyester varnishes.

Electrical/Electronic Uses

Unsaturated solventless polyesters are the most widely used vacuum pressure impregnation varnishes in the manufacture of high-volume electrical equipment.

Epoxies (Varnish Resins)

Epoxy resins, available commercially since 1947, are second in usage in insulation varnishes only to polyesters, and are favored for critical applications requiring high bond strength, toughness, and chemical resistance. Epoxies may be solventless, with solvent, or in the form of powder.

Chemistry

While the basic epoxy resin is the reaction product of epichlorohydrin, bisphenol A, and sodium hydroxide, countless variations are available with a wide range of properties and applications in the coatings field. For convenience in discussion, epoxies may be classified as follows:

- *Unmodified epoxy resins* useful in making coatings include the basic resin and cycloaliphatic epoxies produced by epoxidation of cyclic olefinic compounds with peracidic acid. Formulas for these resins are shown in the "Epoxies" section of Chapter 6, *Embedding Compounds*. Widely used resins have an excess of epichlorohydrin over bisphenol A (typically a ten–one ratio) and are cured with amine hardeners. Cycloaliphatics are unreactive with amines and are usually cured with anhydride hardeners. A common practice is to blend these resins with urea–formaldehyde or phenol–formaldehyde varnishes.
- *Epoxy novolac resins* are formed by reacting epichlorohydrin with novolac resin obtained by condensing phenol or ortho-cresol with formaldehyde under acidic conditions. For additional information on novolacs, including formula, see "Epoxies" in Chapter 4, *Thermosetting Molding Compounds*.

Hardeners for the above epoxy types are discussed in the "Epoxies" section in Chapter 6, *Embedding Compounds*.

• *Epoxy ester resins* are synthesized by esterification of epoxy resins with fatty acids derived from tall oil, dehydrated castor oil, and other drying oils at 250°C under a nitrogen blanket to prevent oxidation. The ratio of acid to epoxy varies from 60/40 for long-oil esters to 40/60 for short-oil types. The addition of saturated fatty acids increases film flexibility and slows drying. Epoxy esters are usually supplied at 50 percent solids in xylol. Drying properties are enhanced by the addition of small percentages of metallic naphthenates.

Grades

Epoxies are available in solvent-type air-drying/baking grades, typically 50 ± 5 percent solids. Solventless grades for VPI processing are widely used for critical applications. Representative grades are shown in Table 8-4.

Processing

See "Application Methods," p. 239 in this chapter.

Properties

Used mostly for Class 130 and Class 155 applications, epoxies possess outstanding bond strength, along with resistance to high humidity and chemicals. Dielectric properties, however, tend to drop off sharply as temperatures approach the thermal class ratings of epoxy varnishes.

Table 8-4 lists key properties of representative baking-type varnishes.

Electrical/Electronic Uses

Because of their higher cost, epoxies are generally used for critical applications not well suited to polyesters, such as in hermetic motors and heavy-duty rotating equipment. They are also used in conformal coatings for circuit boards.

Parylene (Varnish Resin)

A thin-layer protection of electrical/electronic components and assemblies is provided by parylene in a process and equipment developed by Union Carbide and commercialized in 1965.

Chemistry and Processing

Di-para-xylylene is produced by heating para-xylene to about 900°C in the presence of steam. This dimer, when vaporized at about 175°C, forms the monomer, para-xylylene. When heated to about 680°C at reduced pressure, the monomer pyrolyses to the di-radical, which then forms a polymeric coating on parts at room temperature and further reduced pressure. See also the description of the process in "Conformal Coating" in this chapter.

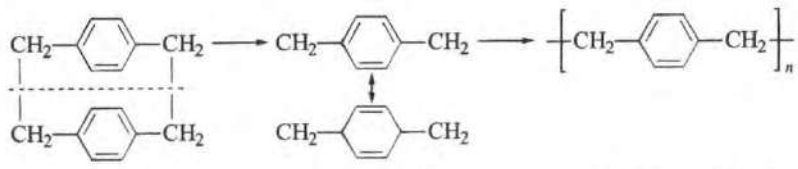
TABLE 8-4 Key Properties of Representative Baking-Type Epoxy Varnishes

FEATURE	THERMAL CLASS (°C)	GEL TIME @ 140°C (minutes)	DIELECTRIC STRENGTH ASTM D-115 @ 23°C (volts/mil)	DIELECTRIC CONSTANT** ASTM D-150		DISSIPATION FACTOR** ASTM D-150		INSULATION RESISTANCE ASTM D-257 (megohms)		BOND STRENGTH ASTM D-2519 (pounds)	
				23°C	155°C	23°C	155°C	23°C	155°C	23°C	155°C
Solventless rigid low viscosity 1-part	155	20–35	2,300	3.9	>5.0	0.004	>0.20	1×10^6	6×10^3	98	14
Solventless semi-flexible excellent H_2O resistance thixotropic 1-part	155	12–16	2,100	4.2	>6.0	0.004	>0.20	1×10^6	4×10^2	107	10
Solventless semi-rigid high bond strength, dielectric properties, chemical resistance thixotropic 1-part	155	7–10	2,700	2.8	3.8	0.0024	0.080	1×10^6	3×10^5	144	63
Solvent type for hermetic motors	210	60**	4,600	3.3	na	0.003	na		na	55	18

*At 100 Hz.

**Baking time @ 149°C (minutes).

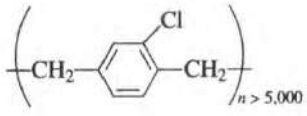
na—not available.



Grades

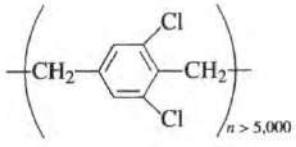
Commercially available versions of parylene include:

- Parylene N, poly-para-xylylene, shown in the preceding diagram. This polymer exhibits superior dielectric strength and exceptionally high surface and volume resistivities, that are virtually unchanged over its useful temperature range exceeding 220°C in the absence of oxygen.
- Parylene C, poly-monochloro-para-xylylene:



This version is characterized by significantly lower permeability to moisture and gases, while retaining excellent dielectric properties.

- Parylene D, poly-dichloro-para-xylylene:



This polymer withstands continuous exposure to air at temperatures up to 150°C.

Parylene coatings are approved under Military Specification MIL-I-46058, *Insulating Compound, Electrical (for Coating Printed Circuit Assembles)*.

Properties

Noteworthy properties of parylene include:

- Uniform coating thickness over edges, points, and internal areas of parts
- Precise control of pinhole-free coating thickness from 0.004 to 1.25 mils
- Excellent dielectric values up to 150°C in air or to over 220°C in oxygen-free atmosphere

- Barrier properties superior to most other coatings
- Good mechanical properties over the temperature range from –200°C to 275°C
- High resistance to attack by most solvents and corrosive chemicals.

Table 8-5 shows key property values for parylene N, most widely used for electrical/electronic applications.

Electrical/Electronic Uses

A principal application of parylene is to protect circuit boards or modules from hostile environments, such as airborne contaminants, moisture, salt spray, and corrosive vapors. Other uses include protection of hybrid circuits, ferrites, resistors, thermistors, thermocouples, sensing probes, and photocells. A parylene coating on metal foil is suitable for making capacitors.

TABLE 8-5 Key Properties of Parylene N Conformal Coating Resin

	ASTM TEST METHOD	VALUE
Specific gravity*	D 792	1.11
Dielectric strength, 1 mil, short time, V/mil*	D 149	7,000
Dielectric constant*	D 150	
60 Hz		2.65
10^6 Hz		2.65
Dissipation factor*	D 150	
60 Hz		0.0002
10^6 Hz		0.0006
Volume resistivity, Ω·cm*	D 257	1×10^{17}
Arc resistance*	D 495	na
Water absorption, 0.029 in thick specimen, %	D 570	
24 h @ 73°F (23°C)		0.06
Deflection temperature, 264 psi, °F (°C)	D 648	405 (207)
Maximum recommended service temperature °F (°C)		428 (220)
Tensile strength at break, psi*	D 638	6,500
Izod impact strength	D 256	
Foot pounds per inch notched 1/8 in specimen*		na
Flammability ratings		
UL Standard 94, 1/16 in specimen		
Standard grade		na
Oxygen index, %	D 2863	
Standard grade		na

*At room temperature.

na = not available.

Phenolics (Varnish Resins)

Phenolic resins were developed by Belgian chemist L. H. Baekeland in 1907, and became commercially available a few years later. Today, phenolic resins are widely used as modifiers to improve temperature resistance of other resins, permitting some formulations to qualify as Class 180 insulations where they offer a low-cost alternative to silicone varnishes.

Chemistry

Phenolic resins are the condensation reaction products of a phenol with an aldehyde. The basic resin is formed by reacting phenol with aqueous 37–50 percent formaldehyde at a temperature of 100°C or under in the presence of an alkaline catalyst. While formaldehyde is the commonly used aldehyde because of its relatively low price, many substituted phenols and acids as well as alkaline catalysts are employed to produce resins of different types and with different characteristics. Alkaline catalysts and high proportions of formaldehyde encourage formation of heat-reactive, highly crosslinked, insoluble resins. Acid catalysts yield thermoplastic resins, called novolacs, that are fusible and miscible in certain solvents. See also "Phenolics/Furfurals (Molding Resins)," p. 127.

Grades (Types)

The principal types of phenolics used in coatings and impregnants are as follows:

- Modified, oil-soluble resins
- Pure (100 percent) phenolic resins
  - oil-soluble, thermoplastic
  - oil-soluble, heat-reactive
  - alcohol- and ketone-soluble, oil-insoluble, thermosetting
- Phenolic dispersion resins

Modified, oil-soluble phenolics were the first phenolic resins used in the coatings field, and were usually modified with rosin or its glyceryl ester, ester gum, to make the resin soluble in drying oils. These resins replaced the natural resins of oleoresinous varnishes, improving drying properties, water and alkali resistance, and durability. Other phenolics, rendered oil-soluble, are based on m-cresol and 3,5-xylenol. These resins, although not as highly resistant and durable as the pure phenolics developed later, are lower in cost, have better adhesion properties, and are well-suited for spar varnishes and porch and deck enamels. Other types, however, are better suited for insulating varnishes.

Oil-soluble, thermoplastics, pure (100 percent) phenolics are made by condensing approximately equimolar proportions of a para-substituted phenol with formaldehyde in the presence of an acid catalyst. This resin is covered by Federal Specification

TT-R-271, *Resin, Phenol-Formaldehyde, Para-Phenyl*, and is required under Federal Specification MIL-V-173, *Varnish, Moisture-and-Fungus-Resistant* described in the "Federal Specifications and Practices" in this chapter.

Oil-soluble, heat-reactive, pure (100 percent) phenolics are the reaction products of a para-substituted phenol with formaldehyde in the presence of an alkaline catalyst. About 2 moles of formaldehyde are used to 1 mole of substituted phenol. The reaction is interrupted at an intermediate stage at which the resinous condensate is still oil-soluble, although reactive. The partly polymerized resin is subsequently heat-reacted with drying oils to produce varnishes with very rapid bodying properties. Short-oil industrial banking varnishes of this type make excellent insulating and impregnating varnishes for electrical equipment because of their fast, deep-curing characteristics and their good dielectric properties. These resins are often incorporated into formulations with lower grade resins to improve drying speed, water resistance, hardness, and durability.

Alcohol- and ketone-soluble, oil-insoluble, thermosetting, pure (100 percent) phenolics are produced by reacting oil-insoluble phenol or meta-substituted, phenol with formaldehyde in alkaline solution. A high ratio of formaldehyde to phenol imparts greater reactivity to these resins. The reaction is stopped at an intermediate stage of polymerization while the resin is still alcohol-soluble and reactive. The partially polymerized resin is supplied as a solution in an appropriate solvent. The applied coating, when heated, converts to a completely polymerized thermoset, insoluble film that is highly resistant to corrosion, abrasion, and chemical attack. In these respects, this type is superior to other types of pure phenolic resins. Room temperature curing is facilitated by adding amine-type or other alkaline catalysts, although heat curing imparts maximum chemical and solvent resistance.

Phenolic dispersion resins are highly polymerized phenolic resin-oil complexes dispersed in volatile organic solvents. They are nonoxidizing and dry quickly by evaporation of solvent to form weather-resistant films with a high degree of impermeability to moisture, and good resistance to alcohols, ketones, esters, ethers, and dilute alkalis. These resins are often blended with other resins for property enhancement.

Processing

See "Application Methods," p. 239 in this chapter.

Properties

See discussion in this section under "Grades" of properties of various types of phenolic varnishes. A table of specific properties is not meaningful because of the limitless number of possible formulations for the various types of phenolic varnishes.

Electrical/Electronic Uses

Principal uses for phenolic varnishes are for moisture-and-fungus-resistant varnish, and to blend with other varnishes for improved temperature and chemical resistance.

Polyurethanes (PURs) (Varnish Resins)

Polyurethane chemistry originated in Germany in the late 1930s, but commercial production by U.S. manufacturers did not start until after World War II. Although not as widely used in insulating coatings as polyesters or epoxies, polyurethanes are available for this purpose.

Chemistry

Polyurethanes used in embedding compounds and wire enamels are covered in other chapters. Principal types of polyurethanes are discussed in "Polyurethanes" in Chapter 6, *Embedding Compounds*.

Type 1 one-component urethane alkyds are used in insulating varnishes, enamels, and conformal coatings. The manufacturing process involves partial hydrolysis of drying oils to produce a mixed hydroxy ester with free hydroxyl groups which can then react with a diisocyanate to form a prepolymer resin. The reaction is controlled so that isocyanate groups are fully reacted while leaching the unsaturated fatty acid portion of the polymer free to combine with oxygen, or cure when catalyzed by metallic naphthenates. Curing can be rapid (a few minutes), especially at low baking temperatures.

Type 2 one-component moisture-cured systems, 50 percent solids content, are used for conformal coatings. Curing is dependent on evaporation of solvents followed by reaction with ambient moisture where relative humidity is 30 percent or higher. To extend shelf life, precautions should be taken to ensure that the atmosphere in containers is moisture-free.

Type 5 two-component resins are used in both solventless and solvent-type coatings (30–60 percent solids). Pot life of mixed components is limited. Coatings may emit toxic fumes and cause skin problems unless precautions are taken.

Grades

Table 8-6 lists some representative grades of polyurethane coatings.

Processing

See "Application Methods," p. 239 in this chapter.

Properties

As shown in Table 8-6, polyurethanes serve Class 155 applications, with abrasion resistance being their outstanding feature.

Electrical/Electronic Uses

Principal uses of polyurethane coatings are for conformal coatings on circuit boards and for enamel coatings on electrical equipment.

TABLE 8-6 Key Properties of Representative Polyurethane Coatings

FEATURE	THERMAL CLASS (°C)	CURING (hours)	CURING (°C)	DIELECTRIC STRENGTH ASTM D-115 (volts/mil) DRY	DIELECTRIC STRENGTH ASTM D-115 (volts/mil) WET	CHEMICAL RESISTANCE WATER	CHEMICAL RESISTANCE (10% H_2SO_4)	CHEMICAL RESISTANCE (1% NaOH)	OIL ASTM D-115
Clear conformal coating superior abrasion resistance fast cure Meets MIL-I-24092	155	1/4	23	2,000	1,200	Ex	Ex	Ex	Passed
Red enamel superior abrasion resistance fast cure	155	1/2	23	2,000	1,200	Ex	Ex	Ex	Passed
Black enamel same features as red enamel	155	1/2	23	1,800	1,200	Ex	Ex	Ex	Passed

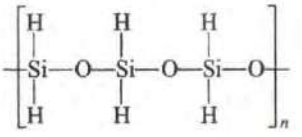
Ex—excellent.

Silicones (Varnish Resins)

Silicone resins have been commercially available since about 1944. Varnishes made from these resins are characterized by excellent thermal stability and water resistance, but because of their high cost, they are used only where other varnishes are not suitable.

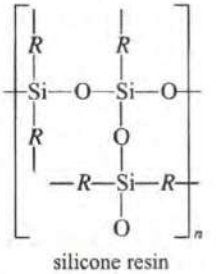
Chemistry

The basic reaction in making silicones is a condensation of hydroxy silanes (silanols) derived from mono-, di-, and trichlorosilanes. Commercial processes are either direct or employ a Grignard reagent. Pure silicones have the following structure:



Practical resins, however, are organosilicon compounds of high molecular weight in which some of the hydrogen atoms are replaced with various alkyl and aryl groups capable of both linear and crosslinked polymerization. Linear polymers are used in embedding resins and elastomers, discussed in Chapter 6, *Embedding Compounds* and in Chapter 5, *Extrusion Compounds*.

Crosslinked types are formulated into varnishes. Crosslinking is accomplished by introducing at intervals along the siloxane chain a third oxygen atom in place of one of the organic groups. This leads to oxygen bridges between trifunctional atoms on different chains. There is also crosslinking through polyfunctional organic side groups. Thus, the useful resin has a structure represented by the following, where *R* is an alkyl or aryl group:



silicone resin

Silicone resins are often modified with lower cost resins, resulting in economical formulations with better thermal properties than the lower cost resin alone and improved physical properties over pure silicones. Modifications with alkyds and epoxies are especially useful in making insulating varnishes. The introduction of halogen

atoms or groups containing halogens into recipes renders resins nonflammable or less flammable.

Grades

A variety of grades used in insulating coatings and impregnants is commercially available, including room temperature curing and baking versions of both solvent and solventless types. Representative grades are listed in Table 8-7.

Processing

See "Application Methods," p. 239 in this chapter.

Properties

Outstanding features of silicones include:

- Excellent dielectric properties over a wide temperature range
- Long term service at temperatures up to 482°F (250°C)
- Greater resistance to corona than other coatings and impregnants
- Excellent water and moisture resistance.

Mechanical properties and adhesion are inherently lower than epoxies, polyesters, and polyurethanes. Solubility, chemical resistance, and compatibility with other materials vary with the nature of the side chains and molecular weight.

Table 8-7 lists key properties of representative silicones.

TABLE 8-7 Key Properties of Representative Silicone Varnishes and Conformal Coatings

	ASTM TEST METHOD*	BAKING VARNISH	ROOM TEMP. CURING NONCORROSIVE 1-PART CONFORMAL COATING
Dielectric strength	D 115	2,000	500
Dielectric constant	D 150		
100 Hz		3.10	2.64
100 kHz		3.00	2.63
Dissipation factor	D 150		
100 Hz		0.010	0.0016
100 kHz		0.007	0.0006
Volume resistivity	D 257	1×10^{14}	5×10^{14}
Maximum recommended service Temperature °F (°C)		356–428 (180–220)	356 (180)
Meets federal specifications		MIL-I-24092	MIL-I-46058 MIL-A-46146

*At room temperature.

Electrical/Electronic Uses

The high cost of silicones limits their use to applications not suitable for other coatings and impregnants, including high-temperature rotating equipment and conformal coatings for electronic parts exposed to harsh environments.

9

Unclad and Clad Structures

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UNCLAD STRUCTURES

INTRODUCTION

Unclad structures have a long history of use as dielectrics, dating back to the earliest days of the electrical industry. As used in this handbook, unclad structures include high-pressure laminates, polyester glass laminates, sheet and bulk molding compounds, and pultrusion materials. In general, these materials are characterized by exceptionally high strength-to-weight ratios as well as good formability and machineability, under prescribed conditions, which dictate their use as dielectrics where these properties are required.

Since reinforcing materials are also used in thermoplastic and thermosetting compounds, this chapter is oriented toward production methods other than those covered in preceding chapters.

REINFORCEMENTS

The most common reinforcement used for resins is known as "E" glass. This glass was designed especially for dielectric applications, although it is now more widely used. E glass has 50–55 percent SiO_2, which is less than in most other glasses. Boric oxide (B_2O_3) content for E glass is 8–13 percent, among the highest of all glasses. Other major ingredients are Al_2O_3, Fe_2O_3, and CaO. Another glass used for dielectric applications is "S" glass. This glass, about 65 percent SiO_2, 0.25 percent B_2O_3, and 35 percent Al_2O_3 and MgO, has higher tensile strength than E glass, and is used in fabrics for laminates in high-performance parts where its strength-to-weight ratio is greater than that of most metals.

Glass reinforcements are supplied in the following forms:

- Continuous roving is made from 50 or more filaments to form a continuous strand. Spun roving is prepared by spinning staple fibers 8–15 inches long to form a continuous strand held together by a slight twist and sizing. Rovings are used in the pultrusion process.
- Chopped strands are made from continuous or spun roving cut in lengths of $^1/_8$–2 inches. Longer strands are mixed with resins to make compounds for compression and transfer molding, and for bulk molding compound (BMC). Shorter strands are more suitable for injection molding compounds.
- Cloth woven on textile looms is available in a variety of textures, weights, and thicknesses, and in plain, twill, and satin weaves. Unidirectional properties are obtained by emphasizing warp (lengthwise) yarns over weft (filling) yarns. Plain weave is used for most laminates. Satin weaves are better for parts with compound curves.
- Mats are composed of either continuous or chopped strands. Chopped strand mats have strands about 2 inches long, randomly distributed and bound together with resin to form flat sheets used primarily in hand lay-up, low-pressure laminating. Con-

tinuous strand mats are made from multiple layers of continuous filaments laid down in a swirl pattern and bonded with resin. Continuous strand mats are used as substrates for complex shapes.

All glass fibers must have a surface treatment, or sizing, that serves as a lubricant and bonding agent. Untreated filaments are prone to abrasion by one another and, unless bonded together, they would be difficult to handle in later operations. A temporary size is applied to warp (lengthwise) yarns preparatory to weaving into glass cloth. This size is usually composed of one or a combination of these materials: gelatin, hydrogenated vegetable oil, polyvinyl alcohol, dextrin, nonionic emulsifier, and cationic lubricant. This sizing is temporary since it must be burned off prior to resin treatment. Otherwise, satisfactory bonding of resin to glass would not be achieved.

After burning, another coating, called a compatible sizing, is applied to the glass cloth to promote bonding with resin and as a lubricant. A widely used product with polyester resins is trademarked Volan (methacrylatochromic chloride) by Du Pont. Organofunctional silanes and organo-titanates are also used.

Other reinforcing fibers used infrequently or not at all in dielectric applications include:

- Carbon (graphite) fibers, used in aerospace and sports equipment
- Aramid fibers, trademarked "Kevlar" by Du Pont, are also used primarily for aerospace and sports equipment
- Boron fibers, the strongest and most expensive fibers, used exclusively for military applications
- Sisal, low-cost vegetable fibers, are used alone or with glass in applications such as air conditioner and heater housings, and electrical outlet boxes.

RESINS

The principal resins employed in the manufacture of unclad and clad structures are the following:

- Epoxies
- Polyesters
- Phenolics
- Melamines
- Silicones
- Diallyl phthalate
- Polyimides

The standards, properties, and features of these resins are detailed in the sections which follow.

DEVELOPMENT PROGRAMS

The focus of development programs continues to be on achieving stronger, lighter, low-profile (low-shrink) composites through improved resin technology, new reinforcements, and more sophisticated fabrication methods. Lower cost materials and production methods are under continuous evaluation, especially for large, high-volume parts.

MARKET TRENDS

The principal impetus for above normal growth in the use of reinforced resins was the oil embargo of 1972–74. These materials, with their high strength-to-weight ratios, corrosion resistance, and versatility in fabrication techniques, were logical replacements for heavier metal parts, especially in the motor vehicle industry, where manufacturers were mandated to increase dramatically the fuel efficiency of vehicles according to a Department of Transportation time schedule.

Because of technological advances, these materials have become more attractive for a wide spectrum of uses in other industries, most notably in structural applications for calculators, computers, and business equipment such as copiers, typewriters, and electronic financial and retail terminals.

Unsaturated polyester resins with glass reinforcements will continue to predominate, although there will be greater use of other fibers, such as carbon (graphite), aramid, and boron, for specialized applications such as in sports and military/aerospace equipment.

PRINCIPAL UNCLAD STRUCTURES FOR ELECTRICAL/ELECTRONIC USES

The chemistry, grades, processing, properties, and electrical/electronic uses of principal unclad structures are described in the sections which follow.

Unclad High-Pressure Thermoset Laminates

Usually referred to as industrial laminates, these materials are fabricated by machine tools into countless parts for electrical and electronic applications. Principal producers include Haysite Reinforced Plastics, Iten, Norplex, NVF, Spaulding, and Westinghouse.

Chemistry

The principal laminating resins, usually captively produced, are phenolics, epoxies, melamines, and silicones:

Phenolics are typically one-step liquid resins obtained by alkali-catalyzed condensation of phenol or cresol with excess formaldehyde.

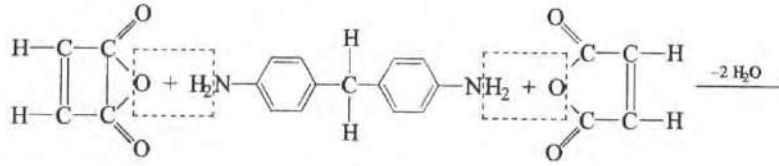
Epoxies used as laminating resins are based principally on the polycondensation of bisphenol-A and epichlorohydrin, as described in "Epoxies" (p. 183) in Chapter 6, *Embed-*

ding Compounds. A widely used hardener is dicyandiamide (dicy), which cures through its four nitrogen-containing functional groups, consuming both epoxide and hydroxyl groups. It is a latent curing agent, relatively stable at room temperature, but activated by heat. Formulations may also contain 5–10 percent epoxy novolacs. Flame-retardant grades containing 20 percent bromine by weight are made by replacing bisphenol-A with tetrabromobisphenol-A. Epoxy glyoxyl resin is added to brominated resin for FR-5 grade.

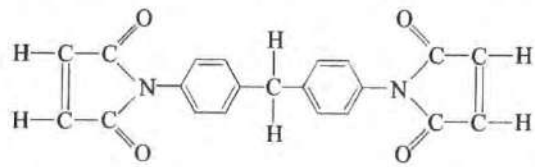
Melamine laminating resins are based normally on the reaction of 1 mole of melamine with 2 moles of formaldehyde. The nature and degree of polymerization depend on the pH of the reaction, usually in the eight–ten range.

Silicone laminating resins of the crosslinking type are discussed in "Silicones" in Chapter 8, *Insulating Coatings and Impregnants*.

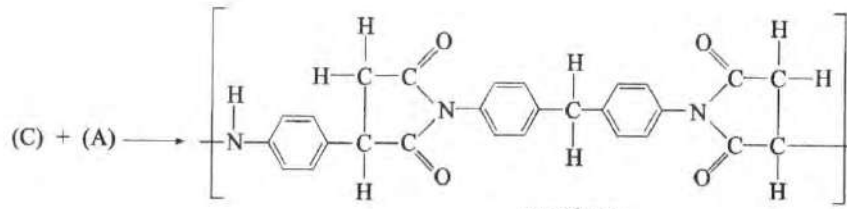
Polyimide laminating resins may be prepared as follows:



(A) maleic anhydride (B) methylene dianiline (A) maleic anhydride



(C) bismalemide



prepolymer

The prepolymer is finally cured in the laminating operation with pressure and at elevated temperature.

Another process is described in "Polyimide," p. 228.

Federal Specifications for Unclad Laminates

The following Federal specifications have been developed for unclad laminates:

- L-P-509, *Plastic Sheet, Rod and Tube, Laminated, Thermosetting*
- MIL-P-997, *Plastic Material, Laminated, Thermosetting, Electric Insulation, Sheets, Glass Cloth, Silicone Resin*
- MIL-P-13949/11, *Plastic Sheet, Laminated, Materials (for Printed Wiring Boards), GE Base Material, Glass Cloth, Resin Preimpregnated (B-Stage)*
- MIL-P-13949/12, *Plastic Sheet, Laminated, Materials (for Printed Wiring Boards), GF Base Material, Glass Cloth, Resin Preimpregnated (B-Stage)*
- MIL-P-13949/13, *Plastic Sheet, Laminated, Materials (for Printed Wiring Boards), GI Base Material, Glass Cloth, Resin Preimpregnated (B-Stage)*
- MIL-P-15035, *Plastic Sheet, Laminated, Thermosetting, Cotton Fabric Base, Phenolic Resin*
- MIL-P-15037, *Plastic Sheet, Laminated, Thermosetting, Glass Cloth, Melamine Base*
- MIL-P-15047, *Plastic Material, Laminated Thermosetting Sheets, Nylon Fabric Base, Phenolic Resin*
- MIL-P-18177, *Plastic Sheet, Laminated, Thermosetting, Glass Fiber Base, Epoxy Resin*
- MIL-P-19161, *Plastic Sheet, Laminated, Glass Cloth, Polytetrafluoroethylene Resin*
- MIL-I-24204, *Insulation, Electrical, High Temperature, Bonded, Synthetic Fiber Paper*
- MIL-P-25525, *Plastic Material, Phenolic Resin, Glass-Fiber Base, Laminated*

ASTM Standards for Laminated Thermosetting Materials

The American Society for Testing and Materials (ASTM) has established these standards for laminated thermosetting materials:

D 229, *Testing Rigid Sheet and Plate Materials Used for Electrical Insulation*

D 257, *Tests for D-C Resistance or Conductance of Insulating Materials*

D 348, *Testing Rigid Tubes Used for Electrical Insulation*

D 349, *Testing Laminated Round Rods Used for Electrical Insulation*

D 495, *Test for High-Voltage, Low-Current Dry Arc Resistance of Solid Electrical Insulation*

D 618, *Conditioning Plastics and Electrical Insulating Materials for Testing*

D 621, *Tests for Deformation of Plastics Under Load*

D 668, *Measuring Dimensions of Rigid Rods and Tubes Used for Electrical Insulation*

D 709, *Standard Specification for Laminated Thermosetting Materials*

D 785, *Test for Rockwell Hardness of Plastics and Electrical Insulating Materials*

D 883, *Definitions of Terms Relating to Plastics*

D 2304, *Thermal Evaluation of Rigid Electrical Insulating Materials*

Underwriters Laboratories has developed the following standards:

- UL 746D, *Polymeric Materials—Fabricated Parts*
- UL 746E, *Polymeric Materials—Industrial Laminates*

NEMA Grades for Unclad Laminates

The National Manufacturers Association (NEMA) in Standard LI 1 has established the following grade designations for industrial laminates:

- Grade X: phenolic resin, paper reinforced. Good mechanical properties, fair dielectric values, low resistance to moisture.
- Grade XX: phenolic resin, paper reinforced. Good mechanical properties, better dielectric than Grade X, and more resistant to moisture.
- Grade XXX: phenolic resin, paper reinforced. Mechanical properties about the same as Grade XX, but better dielectric because of high resin content. Suitable for use at radio frequencies and in high-humidity environments.
- Grade XP: phenolic resin, paper reinforced. May be punched up to $^1/_{16}$ inch at room temperature and punched hot up to $^1/_8$ inch. Dielectric properties and moisture resistance intermediate between Grades X and XX.
- Grade XPC: phenolic resin, paper reinforced. More flexible than XP with better cold punching and shearing properties.
- Grade XXP: phenolic resin, paper reinforced. Similar to Grade XP in machinability and to Grade XX in dielectric and moisture-resistant properties.
- Grade XXXP: phenolic resin, paper reinforced. Better than Grade XXX in dielectric properties and easier to hot punch. Highly moisture resistant.
- Grade XXXPC: phenolic resin, paper reinforced. Similar to XXXP, but easier to punch at lower temperatures.
- Grade FR-1: phenolic resin, paper reinforced. Similar to Grade XP, but less flammable.
- Grade FR-2: phenolic resin, paper reinforced. Similar to Grade XXXPC, but less flammable.
- Grade C: phenolic resin, cotton fabric reinforced. Good mechanical properties, but not recommended for dielectric use.
- Grade CE: phenolic resin, cotton fabric reinforced. Tougher than Grade XX and more resistant to moisture than Grade C, with dielectric properties suitable for low-voltage applications.
- Grade L: phenolic resin, fine weave cotton fabric reinforced. Not as tough as Grade C, but machines more easily. Not recommended for dielectric use.
- Grade LE: phenolic resin, fine weave cotton fabric reinforced. Similar to Grade L in mechanical and machining properties, but better in moisture resistance. Dielectric properties suitable for low-voltage applications.
- Grade N-1: phenolic resin, nylon fabric reinforced. Excellent dielectric properties, even under high-humidity conditions. Fungus resistant.
- Grade G-3: phenolic resin, glass fabric reinforced. High impact and flexural strength, but bond strength lowest of glass-base grades.

- Grade G-5: melamine resin, glass fabric reinforced. High mechanical strength and hardest laminated grade. Low burning rate and second only to silicone laminates in heat and arc resistance. Excellent dielectric properties under dry conditions.
- Grade G-9: melamine resin, glass fabric reinforced. Higher mechanical strength than Grade G-5. Dielectric properties similar to Grade G-5 with better moisture resistance.
- Grade G-7: silicone resin, glass fabric reinforced. Glass H insulation with excellent dielectric properties. Second only to Grade G-5 in low rate of burning.
- Grade G-10: epoxy resin, glass fabric reinforced. Excellent mechanical and good dielectric properties under both dry and humid conditions.
- Grade G-11: epoxy resin, glass fabric reinforced. Similar to Grade G-10, but with improved flexural strength.
- Grade FR-3: epoxy resin, paper reinforced. Superior in dielectric characteristics to Grade XXPC. Good mechanical properties. Suitable for punching at room temperature. Flame retardant. Used extensively as printed circuit substrate.
- Grade FR-4: epoxy resin, glass fabric reinforced. Similar to Grade G-10, but with reduced burning rate.
- Grade FR-5: epoxy resin, glass fabric reinforced. Similar to Grade G-11, but with reduced burning rate.
- Grade CEM-1: epoxy resin, glass fabric surfaces, cellulose paper core. Good punching grade. Low burning rate.
- Grade CEM-3: epoxy resin, glass fabric surfaces, glass paper core. Properties approach those of Grade FR-4.

Prepreg Manufacture

The basic materials for making industrial laminates are called *prepregs*. A prepreg is composed of a substrate, usually paper, cotton, or glass fabric, impregnated with a thermosetting resin, generally phenolic, epoxy, or melamine. Resin-to-substrate ratios typically range on a weight basis from 40/60 to 60/40.

The continuous manufacturing process consists of the following steps:

- Impregnation of substrate with resin is accomplished as it is fed from a roll by a series of rollers into a resin tank.
- After impregnation of the substrate, excess resin is removed by doctor blades, wire-wound rod, or reverse gravure roller.
- The material then passes through a single- or multizone oven in which temperature, dwell time, and air flow are critical factors and are tailored to each resin system.
- The resin is partially cured to make it relatively tack free.
- The B-stage (partially cured) prepreg is then rolled, sometimes with a polyethylene interlayer to prevent blocking.
- The prepreg roll is then stored in a refrigerated room at 40° to 60°F (4°–16°C), 50 percent relative humidity, to minimize further curing.

Manufacturers of industrial laminates produce virtually all the prepregs they require internally.

Unclad Laminates Manufacture

To make an industrial laminate, the prepreg is cut to size and laid up to the desired thickness, with allowance made for compression. A number of plies are thus required to form a "book." As many as ten such books separated by polished stainless steel plates are stacked in a press opening. Press pressure is equalized over the book surface by cushion sheets and additional steel plates on the top and bottom of the book stack. Books of different substrate styles, resins, and resin content may be cured in the same stack. A press cycle is about 3 hours and consists of these steps:

- Loading laminate books with cushions and plates onto a platen with temperature under 150°F (66°C).
- Closing the press and applying the required pressure (100–600 psi).
- Increasing temperature to intermediate range of 200° to 250°F (93°–121°C) and holding to allow the resin to flow, binding the layers of the laminate together at the desired thickness.
- After the resin has gelled, increasing the temperature to 325° to 400°F (162°–204°C) for final cure.
- Holding the laminate at the cure temperature for the required period of time.
- Cooling the press hydraulically and removing the laminate.

Compression presses may have five–ten openings, and may be heated by steam, oil, or electricity. Standard sizes (in inches) for finished laminates are 36 × 36, 36 × 48, 36 × 72, 48 × 60, 48 × 72, 48 × 96, and 48 × 120. The prepreg is cut 1 inch larger than the finished size to allow for trimming.

Thermoset laminates may also be made into convolutely wound tubing. After curing under high pressure and heat, an easily machineable material is formed with dielectric properties similar to those of high-pressure laminated sheets.

Processing Polyimide Laminates

The processing of polyimide/glass laminates is more critical than for other laminates. Powdered resin is dissolved in N-methylpyrrolidone (NMP) to form a 45–55 percent impregnating bath. After impregnation and passing through the oven, the prepreg should have a resin content of approximately 35 percent, with a flow rate of between 20 and 40 percent, and a solvent content between 7 and 9 percent for high-pressure laminating. This requires oven temperatures and dwell times between 250°F (120°C) for 75 minutes and 320°F (160°C) for 10 minutes. Prepregs packaged in polyethylene bags may be stored for two–three months at 32°F (0°C) and for longer periods at lower temperatures.

In the laminating operation, the following steps are recommended:

- The stack of prepreg sheets is placed between foils of aluminum on the press platen.
- Through press plates at 250°F (120°C), a pressure of 210–800 psi (depending on the stack thickness) is applied.

- The temperature is then increased to 360°F (180°C) at a predetermined rate for a stack no thicker than $^3/_8$ inch (a longer period is required for thicker stacks).
- Cure for 1 hour at 360°F (180°C).
- The laminate may be removed hot from the press.
- Post-cure for 24 hours at 480°F (250°C) or for 48 hours at 390°F (200°C).

Properties and Uses

There are numerous characteristics of laminated thermosetting materials that make them desirable for a wide spectrum of applications:

- They possess an exceptionally high strength-to-weight ratio, with specific gravity about half that of aluminum and one-sixth that of steel, making laminates desirable for uses where high strength and minimum weight are requirements.
- Gears cut from cotton cloth based laminates run more quietly than metal gears, require no lubrication, and are durable. Applications range from clock gears to gears for rolling mills.
- Industrial laminates are highly resistant to corrosion, and to attack by organic acids, most solvents, and dilute inorganic acids (but not to alkalis). Combined with easy machineability and good mechanical properties, these materials are suitable for use, where metals are not, in the chemical and allied industries.
- Excellent dielectric values, good structural properties, light weight, and ease of fabrication make laminates favorites for a multitude of applications in the manufacture of electrical and electronic equipment. Laminate types include:
  - Phenolic resin glass-reinforced laminates which retain good dielectric properties at moderately high temperatures and are stronger than paper-reinforced phenolics.
  - Epoxy resin paper-reinforced laminates which have good mechanical properties with low burning rate. Dielectric properties remain stable in humid environments.
  - Epoxy resin glass-reinforced laminates which have higher mechanical strength than paper-reinforced epoxies. Dielectric values are excellent. These laminates are used extensively as substrates for printed circuits.
  - Diallyl phthalate glass-reinforced laminates which have excellent dielectric properties, are easy to process, and are useful up to 450°F (230°C). They are suitable for multilayer printed circuits.
  - Melamine resin glass-reinforced laminates which have outstanding resistance to arcing and burning, and have high mechanical strength.
  - Silicone resin glass-reinforced laminates which have excellent thermal properties and arc resistance, and are also excellent dielectrics.
  - Fluorocarbon resin glass-reinforced laminates which have stable dielectric properties, low moisture absorption, are chemically inert and flame resistant, and remain useful up to 500°F (260°C).
  - Polyimide resin glass-reinforced laminates which have exceptional thermal properties and remain useful over 500°F (260°C). They have high

TABLE 9-1 Typical Values for High-Pressure Electrical Grade Thermoset Laminates

	TEST METHOD	GRADE										
NEMA/ASTM Grade		X	XX	XXX	XP	XPC	XXP	XXXP	XXXPC	FR-1	FR-2	FR-3
MIL-P Grade			PBG	PBE-E				PBE-P	PBE-P	—	—	PEE
Federal L-P-509/513 Grade		X	PBG	PBE	XP	XPC	XXP	PBE-P	PBE-P	—	FR-2	—
PROPERTY												
Tensile strength, 10^3 psi	ASTM D 638											
Lengthwise		20	16	15	12.4	10.5	11	12	12.4	12	12.5	14
Crosswise		16	13	12	9	8.5	8.5	9.5	9.5	9	9.5	12
Compressive strength, 10^3 psi	ASTM D 695											
Flatwise		36	34	32	25	22	25	25	25	25	25	29
Edgewise		19	23	25.5	—	—	—	—	—	—		—
Flexural strength, 10^3 psi, $^1/_8$ in	ASTM D 790											
Lengthwise		25	15	13	14	12	14	16	12	16	17	20
Crosswise		22	14	12	12	10	12	13.2	10	13	15	16
Modulus of elasticity in flexure, 10^6 psi	ASTM D 229											
Lengthwise		1.8	1.4	1.3	1.2	1.0	0.9	1.0	1.0	1.2	1.0	1.3
Crosswise		1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.7	0.9	0.9	1.0
Shear strength, 10^3 psi	ASTM D 732	12	11	10	8	9.5	11	1.2	11	12	10.8	11
Izod impact strength, ft·lb/in of notch	ASTM D 256											
Flatwise		4.0	1.3	1.0	—	—	—	—	—	—	—	—
Edgewise		0.5	0.35	0.35	—	—	—	—	—	—	—	—
Rockwell hardness, M scale	ASTM D 785	110	105	110	95	75	100	100	95	95	97	100
Bond strength, lb	ASTM D 229	700	800	950	1,100	1,400	—	1,100	1,000	1,200	1,200	950
Coeff. of thermal expansion, cm/cm/°C × 10^{-5}, x-axis	IPC-TM 650-2.4.24	1.3	—	1.5	1.3	1.5	—	1.6	1.7	1.6	1.6	2
Water absorption, % 24 h, $^1/_{16}$ in	ASTM D 229	6	2	1.4	3.6	5.5	1.8	—	0.75	—	0.75	0.65
Dielectric strength, volts/mil, short time, $^1/_{16}$ in	ASTM D 229	700	700	650	650	625	700	650	650	650	650	600
Dissipation factor, 10^6 cycles	ASTM D 150	0.06	0.05	0.04	0.06	0.06	0.04	0.04	0.04	0.065	0.035	0.035
Thermal Class, electrical, $^1/_{16}$ in and over		130	130	130	130	130	130	130	130	105	105	130
Flammability	UL 94	HB	HB	HB	HB	HB	HB	HB	HB	V-0	V-0	V-0

TABLE 9-1 (*Continued*)

	TEST METHOD	GRADE									
NEMA/ASTM Grade		FR-4 FR-5	FR-6	CE	LE	N-1	G-7	G-9	G-10 G-11	CEM-1	CEM-3
MIL-P Grade		–4 GEE	—	FBG	FBE	NPG	GSG	GME	GEE	—	—
Federal L-P-509/513 Grade		–5 GEB	—	CE	LE	N-1	—	—	GEB	—	—
PROPERTY											
Tensile strength, 10^3 psi	ASTM D 638										
Lengthwise		40	9	12	12	8.5	23	37	40	45	—
Crosswise		35	9	9	8.5	8	18.5	30	35	34	—
Compressive strength, 10^3 psi	ASTM D 695										
Flatwise		60	29	39	37	20	45	70	60	50	—
Edgewise		35	29	24.5	25	—	14	25	35	—	—
Flexural strength, 10^3 psi, $^1/_8$ in	ASTM D 790										
Lengthwise		55	20	17	15	10	23	55	55	35	40
Crosswise		45	20	14	13	9	20	35	45	28	32
Modulus of elasticity in flexure, 10^6 psi	ASTM D 229										
Lengthwise		2.7	0.7	0.9	1.0	0.6	1.4	2.5	2.7	2.5	—
Crosswise		2.2	0.7	0.8	0.9	0.5	1.2	2.0	2.2	2.1	—
Shear strength, 10^3 psi	ASTM D 732	19	14	11	11	14	17	20	19	15	14
Izod impact strength, ft-lb/in of notch	ASTM D 256										
Flatwise		7.0	3.5	2.3	1.8	4.0	8.5	12.0	7.0	1.6	1.6
Edgewise		5.5	3.5	1.4	1.0	3.5	1.5	8.0	5.5	1.2	1.4
Rockwell hardness, M scale	ASTM D 785	111	114	105	105	105	100	120	111	102	—
Bond strength, lb	ASTM D 229	—	—	1,800	1,600	1,000	650	1,700	2,200	1,400	—
Coeff. of thermal expansion, cm/cm/°C × 10^{-5}, x-axis	IPC-TM 650-2.4.24	0.9	1.0	2.0	2.0	8.0	1.0	1.0	0.9	1.3	—
Water absorption, % 24 h, $^1/_{16}$ in	ASTM D 229	0.25	0.18	2.2	1.95	0.6	0.3	0.8	0.25	0.3	0.25
Dielectric strength, volts/mil, short time, $^1/_{16}$ in	ASTM D 229	500	500	500	500	600	400	400	500	675	—
Dissipation factor, 10^6 cycles	ASTM D 150	0.025	0.017	0.055	0.055	0.038	0.003	0.017	0.015	0.035	0.025
Thermal Class, electrical, $^1/_{16}$ in and over		130	130	130	130	105	180	—	130	130	—
Flammability	UL 94	V-0	V-0	HB	HB	HB	V-0	V-0	HB	V-0	

resistance to radiation, outstanding dimensional stability, chemical inertness, and are inherently nonflammable.
- Nylon-reinforced laminates which retain high insulation resistance under humid conditions. They have exceptionally low dielectric constant and dissipation factor, making them preferred for high-frequency electronic applications.
- Composite laminates which are easy to punch and are suitable for substrates for printed circuits.

Use of high-price silicone, fluorocarbon, and polyimide resin laminates is limited to those applications where their superior properties are required.

Table 9-1 shows key property values for NEMA grade high-pressure thermoset laminates.

Polyester Glass Mat Laminates

These materials, some of which are made to NEMA standards, may also easily be formulated to meet individual customer specifications at relatively low cost compared with other types of reinforced resins. Major suppliers are Cincinnati Development, Glastic, and Haysite Reinforced Plastics.

Chemistry

Unsaturated thermosetting polyesters used with reinforcing substrates are condensation polymers formed by reacting an anhydride or dibasic acid with a dihydroxy alcohol. At least one of the acidic components must contain an olefinic bond. Saturated acids may be included to control unsaturation and improve physical properties. A reactive monomer, such as styrene or vinyl toluene, is added to control viscosity and to promote crosslinking. A small amount of inhibitor, for example hydroquinone, is added to retard the reaction prior to use. Thus, a wide range of resin properties is obtainable by varying the ratio of ingredients. For a general purpose resin, a typical mole ratio would be:

RAW MATERIAL	MOLES
Propylene glycol	2.1
Phthalic anhydride	1.0
Maleic anhydride	1.0
Styrene	1.8

See also the "Unsaturated Polyesters" (p. 248) in Chapter 8, *Insulating Coatings and Impregnants*.

Federal Specifications for Polyester Glass Mat Laminates

The following Federal specifications have been developed for polyester glass mat laminates: