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.