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Licari, J.J. & Brands, E.R. (1970). Coatings for electronics. In C. A. Harper (Ed.), *Handbook of Materials and Processes for Electronics* (pp. 5-1 – 5-76). McGraw-Hill.

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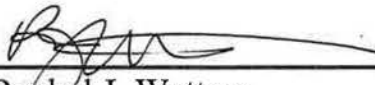
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EXHIBIT A

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HANDBOOK OF
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**Handbook of
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- TERMAN · Radio Engineers' Handbook
- TRUXAL · Control Engineers' Handbook

Handbook of Materials and Processes for Electronics

CHARLES A. HARPER *editor*

*Westinghouse Electric Corporation
Baltimore, Maryland*

McGRAW-HILL BOOK COMPANY

New York St. Louis San Francisco Düsseldorf London
Mexico Panama Sydney Toronto

HANDBOOK OF MATERIALS AND PROCESSES
FOR ELECTRONICS

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Library of Congress Catalog Card Number 76-95803

07-026673-5

1234567890 HDBP 7543210

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Preface

In recent years, the role of materials and processes has assumed a rapidly increasing degree of importance in the electronic and electrical industries. Necessity has indeed been the mother of invention, with the demands of more and more complex electronic and electrical systems requiring advances in materials and processing technologies. Based on these advances, the need has become acute for extending basic and practical knowledge of modern materials and processes. It is this need for more broadly communicating the vast new realms of knowledge which dictated the need for this *Handbook of Materials and Processes for Electronics*. The extensive data on materials and processes found in this Handbook, coupled with the extensive electromechanical data found in the companion *Handbook of Electronic Packaging*, should provide an invaluable data bank and reference library for the desktop of all persons with any degree of interest in these subjects, in both the electronic and electrical industries, and in those industries which supply components and materials to the electronic and electrical industries.

It might be well to expand briefly on the above statement regarding the applicability of the presentations in this Handbook to both the electronic and electrical industries. In some instances, these two industrial areas are clearly distinct. In others they are not. In any event, however, the progression of materials and processing technologies very often begins in advanced electronics and aerospace systems, and with time, extends to broad usefulness in the commercial and consumer electrical industries. Many current materials and processes used by the

electrical industries have their origin in the advanced electronic and aerospace industries. This progression is becoming more rapid.

The successful progression of materials and processing technologies also requires improvements in bridging the knowledge gap between chemical and electrical scientists—a gap which has long been a problem. It is hoped that this *Handbook of Materials and Processes for Electronics* will help bridge this gap. Certainly a key guideline in the preparation of this Handbook has been to present information in a manner which allows an easy understanding of chemical concepts by those who are not chemical specialists, and an easy understanding of electrical concepts by those who are not electrical specialists. Therefore, this Handbook should be helpful to those in the chemical and material industries who have interests in the electronic and electrical industries, as well as to those in the electronic and electrical industries. Again, the practical presentation plan used in this Handbook parallels that of the earlier mentioned companion *Handbook of Electronic Packaging*.

The chapter content of this Handbook illustrates the breadth of coverage which has been developed. An attempt has been made to conveniently group the chapters. The first five chapters cover important organic based materials, such as plastics, laminates, composites, adhesives, elastomers, coatings, and wire and cable systems. Next come presentations on other nonconductors such as ceramics, glasses, and micas, and on increasingly important semiconductors. Following these come chapters on ferrous and nonferrous metals, and metallic and chemical finishes on metals and nonconductors. The last group of chapters concern what might be considered the more advanced subjects of thin films, thick films, metals joining of electronic circuitry, and photofabrication. Finally, one chapter is devoted to the important subject of materials for the space environment. Each chapter might well be considered the equivalent of a book in itself.

In addition to the broad presentation of data and guidelines, several other features of this Handbook should be noted. First, considerable coverage is given to definitions and basic explanations, which will be an invaluable asset to broad, ready understanding of the material presented. Next, tradeoff guidance is a key element. Such guidance will be very useful in making decisions among various possible approaches to given problem areas. Last, every attempt has been made to provide a very complete and thoroughly cross-referenced index, again, for maximum reader convenience.

Length and coverage of a Handbook of this magnitude are necessarily measured compromises. Inevitably, varying degrees of shortages and excesses will exist, depending on the needs of each individual reader. Then too, the time required to complete such a major work as this necessarily demands that some most recent data may not be fully

covered. Further, in spite of the tremendous efforts involved, some errors or omissions may exist. While every effort has been made to minimize such shortcomings, it is my greatest desire to improve each successive edition. Toward this end, any and all reader comments will be welcomed and appreciated.

Charles A. Harper

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Chapter 5

Coatings for Electronics*

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* Adapted from J. J. Licari, "Plastic Coatings for Electronics," McGraw-Hill Book Company, New York, 1970.

FUNCTIONS OF COATINGS

Nature of Coatings

Most of the electrical properties data available for plastic molding and casting compounds apply also to coatings, because the majority of coatings are based on the same polymer resin systems. Other basic properties, such as resistance to chemicals, solvents, and environmental conditions, will also be similar for coatings as for the bulk plastics. Basic information on the various classes of polymeric (plastic) materials can be found in Chap. 1, and will therefore not be repeated here for coatings. Likewise, many basic properties will not be covered where bulk plastic properties suffice for coatings. Many electrical and electronics-related properties are defined and discussed in Chap. 2, to which the reader is also referred. However, additional formulating is necessary to obtain properties such as adhesion, low viscosity, good application properties in thin films, cohesive strength, flexibility, low moisture-vapor transmission, and high dielectric properties. Other resins or functional chemicals are often added in order to modify polymer basic properties. For instance, more active curing agents may be necessary in thermosetting coatings than are used in bulkier sections of resin (such as potting compounds) wherein exothermic heat can accumulate to speed the reaction.

Other problems, directly related to thinness, are the need for low porosity, and freedom from pinholes and foreign inclusions. Most coatings are applied as solutions of the resins in suitable solvents. This enables the application of uniformly thin coatings (and often limits the possible thickness), but causes other problems. Freeing the films of the last vestiges of these solvents is sometimes difficult, but necessary in order to develop the full polymer properties.

The following is a discussion of function and end use of coatings for electronics, specific test methods, properties for coatings, and application technology, including surface preparation and applicable specifications.

Property—Function—End Use. The following definitions of property, function, and end use are those used in the discussion of coatings.

PROPERTY: A property is that single characteristic which can be separated and measured in terms of established units. Examples are dielectric breakdown voltage, hardness, and moisture-vapor transmission.

The significant properties of coatings are, of course, directly related to the desired end use, or functions, of the coating. As mentioned, a given end-use coating must fulfill a number of different functions and, hence, often possess a myriad of different properties. There presently exists no perfect coating, since there are no combinations of perfect properties. All coatings, therefore, will exhibit advantages and disadvantages for a given end use. Presumably, those coatings having a preponderance of advantages are being or have been employed for the given end use. A listing of end uses and recommended coatings is to be found in Table 1.

FUNCTION: A function is defined as a general area of performance such as electrical insulation or environmental protection and consists of a collection of "properties." For instance, electrical insulation depends upon properties such as dielectric strength, volume resistivity, surface resistivity, and dielectric constant. The different conditions present during performance of the function will determine which of the required properties are most important. For example, in a high-humidity environment, properties such as moisture absorption and freedom from electrolytes (purity) would be major factors. In a high-temperature environment, the softening temperature and chemical stability would be influential. Environmental protection would depend upon some integrations of properties such as moisture absorption, moisture transmission, adhesion, hardness, and toughness.

END USE: End use is the actual service to which a coating is put. Typically, a given end-use coating must fulfill a number of different functions. An example might be conformal coatings for circuitry. Here, a minimum listing of required functions would include electrical insulation, environmental resistance, filleting and

bonding of smaller components, ruggedization to handling abuse, and vibration damping.

In order to choose a coating for a given end use, one must analyze and decide which of the many available coatings will best satisfy the functional requirements for the desired end use. Data are provided here as an aid to making such selections.

End-use Coatings

Printed circuit-board coatings *Coating Types.* The most commonly used coatings for circuit boards are the polyurethanes, epoxies, silicones, polystyrenes, and polyvinyl fluoride. Their choice depends largely on the operating and storage requirements of the circuit boards. For high-temperature applications, for example, only silicones should be used; whereas for resolderability, polyurethanes are outstanding; and for adhesion and moisture resistance, epoxies are preferred. The most widely used circuit-board coatings are covered by MIL-I-46058, according to which three classes of coatings are defined as follows:

Class A. General-purpose coating:

Type ER—epoxy

Type PUR—polyurethane

Class B. Heat-resistant coating:

Type SR—silicone

Class C. Low-loss dielectric coating:

Type PO—Polystyrene

Reliability. Printed-circuit boards are usually coated as the last step in their fabrication to improve the reliability of the entire assembly. This is particularly important for boards used in military electronics and astronautics, where the value of a completed board may easily be in the \$3,000 to \$5,000 range and where storage and operational time may be as long as eight years. It has been demonstrated numerous times and by many firms that without a protective coating, these assemblies will fail owing to such mechanisms as moisture degradation, large decreases in electrical insulation resistance, electric short circuiting and corrosion. Even for commercial applications such as television and radio, organically coated circuit boards prolong service life.¹

After six months in a 95 percent relative-humidity environment, a board coated with 1.5 mils (0.0015 in.) of polyurethane showed no signs of corrosion and passed all electrical functional tests. A similar unprotected board showed excessive corrosion on components, solder, and conductor lines after only two days of the same exposure. To ensure maximum reliability of circuit boards and other electronic assemblies, defense contracts require hardware to meet stringent environmental tests called out in specifications such as MIL-E-5272, MIL-E-5400, MIL-E-16400E, and MIL-STD-202. These specifications call for resistance to humidity and temperature exposure (Fig. 1), salt spray, abrasion, impact, fungus, and other tests. Table 2 gives a list of tests defined in MIL-STD-202. Many of these are applicable to coatings either per se or in combination with a component. Thus, to meet these requirements, the need for a coating or some type of encapsulant protection becomes mandatory. Figure 2 shows the corrosive effects of 50-hr salt spray on an uncoated circuit board and the protection afforded by a 1-mil polyurethane coating under the same conditions. An insulation resistance drop of 10^6 to 10^7 ohms is often experienced with printed circuitry on uncoated epoxy or phenolic laminates when exposed to warm, humid environments, compared to 10^2 - to 10^3 -ohm drops for coated boards (Fig. 3 and Table 3).

In addition to minimizing electrical degradation of laminates, coatings also minimize or prevent some discoloration effects caused by moisture and processing conditions. With some laminates, including epoxy-glass, whitening (also referred to as "measling") occurs when the board, which has gone through various processing steps, is subjected to a warm, humid environment. Although structurally not serious, this effect has been the cause for rejection of many completed assembled boards because of the poor aesthetics. A coating possessing good humidity-resistance prop-

TABLE 1 Properties of Coatings by Polymer Type

Coating type	Electrical properties				Physical characteristics				
	Volume resistivity, ohm-cm (ASTM D 257)	Dielectric strength, volts/mil	Dielectric constant	Dissipation factor	Maximum continuous service temperature, °F	Adhesion to metals	Flexibility	Approximate Sward hardness (higher number is harder)	Abrasion resistance
Acrylic	10 ¹⁴ -10 ¹⁵	450-550	2.7-3.5	0.02-0.06	180	Good	Good	12-24	Fair
Alkyd	10 ¹⁴	300-350	4.5-5.0	0.003-0.06	200 250 T.S.	Excellent	Fair to good Low temperature—poor	3-13 (air dry) 10-24 (bake)	Fair
Cellulosic (nitrate butyrate)		250-400	3.2-6.2		180	Good	Good Low temperature—poor	10-15	
Chlorinated poly-ether (Penton*)	10 ¹⁵	400	3.0	0.01	250	Excellent	Good		
Epoxy-amine cure	10 ¹⁴ at 30°C 10 ¹⁰ at 105°C	400-550	3.5-5.0	0.02-0.03 at 30°C	350	Excellent	Fair to good Low temperature—poor	26-36	Good to excellent
Epoxy-anhydride, Dicy		650-730	3.4-3.8	0.01-0.03	400	Excellent	Good to excellent Low temperature—poor	20	Good to excellent
Epoxy-polyamide	10 ¹⁴ at 30°C 10 ¹⁰ at 105°C	400-500	2.5-3.0	0.008-0.02	350	Excellent	Good to excellent Low temperature—poor	20	Fair to good
Epoxy-phenolic	10 ¹² -10 ¹³	300-450			400	Excellent	Good Low temperature—fair		Good to excellent
Fluorocarbon TFE	10 ¹⁸	430	2.0-2.1	0.0002	500	Can be excellent; primers required.	Excellent		
FEP CTFE	10 ¹⁸ 10 ¹⁸	480 500-600	2.1 2.3-2.8	0.0003-0.0007 0.003-0.004	400 400	Can be excellent; primers required	Excellent		
Parylene (polyxylylenes)	10 ¹⁶ -10 ¹⁷	700	2.6-3.1	0.0002-0.02	240°F (air) 510°F (inert atm.)	Good	Good		

Phenolics	10 ⁹ -10 ¹²	100-300	4-8	0.005-0.5	350	Excellent	Poor to good Low temperature—poor	30-38	Fair
Phenolic-oil varnish					250	Excellent	Good Low temperature—fair		Poor to fair
Phenoxy	10 ¹² -10 ¹⁴	500	3.7-4.0	0.001	180	Excellent	Excellent		
Polyamide (nylon)	10 ¹² -10 ¹⁵	400-500	2.8-3.6	0.01-0.1	225-250	Excellent			
Polyester	10 ¹² -10 ¹⁴	500	3.3-8.1	0.008-0.04	200	Good on rough surfaces; poor to polished metals.	Fair to excellent	25-30	Good
Chlorosulfonated (polyethylene (Hypalon)†			6-10	0.03-0.07	250	Good	Elastomeric	Less than 10	
Polyimide	10 ¹⁶ -10 ¹⁸	400 3,000 (10 mil)	3.4-3.8	0.003	500	Good	Fair to excellent		Good
Polystyrene	10 ¹⁸ -10 ¹⁹	500-700	2.4-2.6	0.0001-0.0005	140-180		Poor to fair		
Polyurethane	10 ¹² -10 ¹³	450-500 3,800 (1 mil)	6.8 (1 kHz) 4.4 (1 MHz)	0.02-0.08	250	Often poor to metals. (Excellent to most non-metals.)	Good to excellent. Low temperature—poor	10-17 (castor oil) 50-60 (polyester)	
Silicone	10 ¹⁴ -10 ¹⁶	550	3.0-4.2	0.001-0.008	500	Varies, but usually needs primer for good adhe- sion.	Excellent Low temperature—ex- cellent	12-16	Fair to ex- cellent
Vinyl chloride (poly-)	10 ¹¹ -10 ¹⁵	300-800	3-9	0.04-0.14	150	Excellent, if so formu- lated.	Excellent Low temperature—fair to good	5-10	
Vinyl chloride (plastisol, organi- sol)	10 ⁹ -10 ¹⁶	400	2.3-9	0.10-0.15	150	Requires adhesive primer.	Excellent Low temperature—fair to good	3-6	
Vinyl fluoride	10 ¹² -10 ¹⁴	260 1,200 (8 mil)	6.4-8.4	0.05-0.15	300	Excellent, if fused on surface.	Excellent Low temperature—ex- cellent		
Vinyl formal (Formvar‡)	10 ¹² -10 ¹⁵	850-1,000	3.7	0.007-0.2	200	Excellent			

* Trademark of Hercules Powder Co., Inc., Wilmington, Del.

† Trademark of E. I. du Pont de Nemours & Co., Wilmington, Del.

‡ Trademark of Monsanto Co., St. Louis, Mo.

TABLE 1 Properties of Coatings by Polymer Type (Continued)

Coating type	Resistance to environmental effects				Flammability	Repairability	Film formation		Application method	Typical uses
	Chemical and solvent resistance	Moisture and humidity resistance	Weatherability	Resistance to micro-organisms			Method of cure	Cure schedule		
Acrylic		Good	Excellent resistance to UV and weather	Good	Medium	Remove with solvent.	Solvent evaporation	Air dry or low-temperature bake	Spray, brush, dip	Coatings for circuit boards quick dry protection for markings and color coding.
Alkyd	Solvents—poor Alkalies—poor Dilute acids—poor to fair	Poor	Good to excellent	Poor	Medium	Poor	Oxidation or heat	Air dry or baking types	Most common methods	Painting of metal parts and hardware.
Cellulosic (nitrate butyrate)	Solvents—good Alkalies—good Acids—good	Fair		Poor to good	High	Remove with solvents.	Solvent evaporation	Air dry or low-temperature bake	Spray, dip	Lacquers for decoration and protection. Hot-melt coatings.
Chlorinate polyether (Penton*)		Good			Low		Powder or dispersion fuses	High temperature fusion	Spray, dip, fluid bed	Chemically resistant coatings.
Epoxy-amine cure	Solvents—good to excellent Alkalies—good Dilute acids—fair	Good	Pigmented—fair; clear—poor (chalks)	Good	Medium	No	Cured by catalyst reaction	Air dry to medium bake	Spray, dip, fluid bed	Coatings for circuit boards. Corrosion-protective coatings for metals.
Epoxy-anhydride, Dicy	Solvents—good Alkalies— Dilute acids—	Good		Good	Medium	No	Cured by chemical reaction	High bakes 300 to 400°F	Spray, dip, fluid bed, impreg.	High-bake, high-temperature-resistant dielectric and corrosion coatings.
Epoxy-polyamide	Solvents—fair Alkalies—good Dilute acids—poor	Good		Good	Medium	No	Cured by coreactant	Air dry or medium bake	Spray, dip	Coatings for circuit boards. Filletting coating.
Epoxy-phenolic	Solvents—excellent Alkalies—fair Dilute acids—good	Excellent	Pigmented—fair; clear—poor	Good	Medium	No	Cured by coreactant	High bakes 300 to 400°F	Spray, dip	High-bake solvent and chemical resistant coating.
Fluorocarbon TFE	Solvents—excellent Alkalies—good Dilute acids—excellent	Excellent		Good	None	No	Fusion from water or solvent dispersion	Approx. 750°F	Spray, dip	High-temperature-resistant insulation for wire.
FEP CTFE		Excellent		Good	None	No	Fusion from water or solvent dispersion	500-600°F	Spray, dip	High-temperature-resistant insulation. Extrudable.
Parylene (polyxylylenes)		Excellent			None		Vapor phase deposition and polymerization requiring special license from Union Carbide.			Very thin, pinhole-free coatings, possible semi-conductable coating.

Phenolics	Solvents—good to excellent Alkalies—poor Dilute acids—good	Excellent	Fair	Poor to good	Medium	No	Cured by heat	Bake 300–500°F	Spray, dip	High-bake chemical and solvent-resistant coatings.
Phenolic-oil varnish	Solvents—poor Alkalies—poor Dilute acids—good to excellent	Good	Good	Poor, unless toxic—additive	Medium	Poor	Oxidation or heat		Spray, brush, dip-impregnate	Impregnation of electronic modules, quick protective coating.
Phenoxy		Good		Good			Cured by heat			Chemical resistant coating.
Polyamide (nylon)		Fair				Fairly solderable				Wire coating.
Polyester	Solvents—poor Alkalies—poor to fair Dilute acids—good	Fair	Very good	Good	Medium	Poor	Cured by heat or catalyst	Air dry or bake 100–250°F	Spray, brush, dip	
Chlorosulfonated polyethylene (Hypalon†)		Good		Good	Low		Solvent evaporation	Air dry or low temperature bake	Spray, brush	Moisture and fungus proofing of materials.
Polyimide	Solvents—excellent Alkalies— Dilute acids—	Good	Good	Good	Low	Poor	Cured by heat	High bake	Dip, impregnate, wire coater	Very high temperature resistant wire insulation.
Polystyrene		Good		Good	High	Dissolve with solvents.	Solvent evaporation	Air dry or low bake	Spray, dip	Coil coating, low dielectric constant, low loss in radar uses.
Polyurethane	Solvents—good Dilute alkalies—fair Dilute acids—good	Good		Poor to good	Medium	Excellent; melts, solder-through properties	Coreactant or moisture cure	Air dry to medium bake	Spray, brush, dip	Conformal coating of circuitry, solderable wire insulation.
Silicone	Solvents—poor Alkalies—good (dilute) poor (concentrated) Dilute acids—good	Excellent	Excellent	Good	Very low (except in O ₂ atm.)	Fair to excellent. Cut and peel.	Cured by heat or catalyst	Air dry (RTV) to high bakes	Spray, brush, dip	Heat-resistant coating for electronic circuitry. Good moisture resistance.
Vinyl chloride (poly-)	Solvents—alcohol, good Alkalies—good	Good	Pigmented—fair to good Clear—poor	Poor to good (depends on plasticizer)	Very low	Dissolve with solvents.	Solvent evaporation	Air dry or elevated temperature for speed	Spray, dip, roller coat	Wire insulation. Metal protection (especially magnesium, aluminum).
Vinyl chloride (plastisol, organisol)		Good		Poor to good (depends on plasticizer)	Low	Poor	Fusion of liquid to gel	Bake 250–350°F	Spray, dip, reverse roll	Soft-to-hard thick coatings, electroplating racks, equipment.
Vinyl fluoride		Good	Excellent	Good	Very low	Poor	Fusion from water or solvent dispersion	Bake 400–500°F	Spray, roller coat	Coatings for circuitry. Long-life exterior finish.
Vinyl formal (Form-var†)		Good		Good	Medium	Poor	Cured by heat	Bake 350–500°F	Roller coat, wire coater	Wire insulation (thin coatings) coil impregnation.

* Trademark of Hercules Powder Co., Inc., Wilmington, Del.

† Trademark of E. I. du Pont de Nemours & Co., Wilmington, Del.

‡ Trademark of Monsanto Co., St. Louis, Mo.

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erties can minimize or eliminate this defect. The curing schedule for the coating also has a significant effect on its moisture-barrier properties, with an extended cure at an elevated temperature enhancing the performance of the coating. Improvement is probably due to elimination of residual solvent in the coating film and further crosslinking.

The use of conformal coatings for printed circuits also allows design engineers greater freedom in achieving narrower conductor lines and closer spacings. Without coatings, impurities, moisture, and other contaminants will easily bridge the conductors, resulting in decreases in insulation resistance and even arcing between conductors. The dielectric breakdown voltage across a clean, dry surface is very good, but maintaining the surface in this condition is extremely difficult. The increased insulation protection afforded by an epoxy coating on a G-10 laminate board with $\frac{1}{16}$ -in. conductor spacings was shown by McGuiness.³ The flashover voltage for

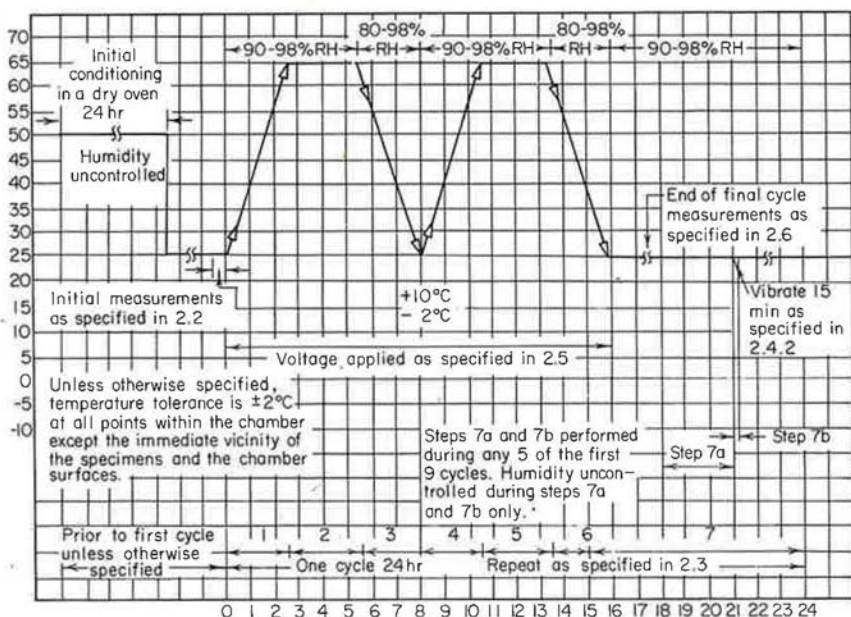


Fig. 1 Graphical representation of moisture-resistance test per MIL-STD-202B, Method 106.

the coated board was 5,000 volts as compared with 1,600 volts for an uncoated board when run at 80°F in 50 percent relative humidity. Allowable spacings between conductors for various applied voltages are given in Table 4. The reduction in spacing made possible by the use of conformal coatings is also apparent from this table. These data are specified in MIL-STD-275B, Printed Wiring for Electronic Equipment.

Coatings also serve other functions which contribute to the overall assembly reliability. These include the rigidity imparted to thin leads, solder joints, and components, thus preventing breakage or lifting during normal handling and especially during vibration.

Coating Thickness. Theoretically, the thicker the coating, the better the humidity barrier since moisture permeability is inversely related to thickness. This holds true fairly well for the 100 percent solids coatings. However, it is not always true for solvent-based coatings since the probability of entrapment of solvent volatiles in the cured coating is greater, the thicker the coating. With trapped solvent mole-

cules, a more porous structure results in which water can be more readily absorbed and transmitted, thereby causing blistering, corrosion, and large decreases in insulation-resistance values. Solvent-based coatings, however, may be formulated that contain various additives, permitting rapid release of solvents on curing; and cure cycles can be optimized also to achieve the same results. Thus, with proper techniques, both 100 percent solids and solvent-based coatings will afford better humidity protection by increasing their thickness.

Most circuit-board manufacturers use 0.3- to 3-mil-thick coatings. Excessive thicknesses have been reported to cause cracking of components such as glass

TABLE 2 MIL-STD-202 Test Methods and Numbers

Test method	Method No.
<i>Environment tests (100 class):</i>	
Salt spray (corrosion).....	101C
Temperature cycling.....	102A
Humidity (steady state).....	103B
Immersion.....	104A
Barometric pressure.....	105C
Moisture resistance.....	106B
Thermal shock.....	107B
Life (at elevated ambient temperature).....	108A
Explosion.....	109A
Sand and dust.....	110
Flammability (external flame).....	111
Seal.....	112A
<i>Physical-characteristics tests (200 class):</i>	
Vibration.....	201A
Shock (specimens weighing not more than 4 lb).....	202B
Shock (specified pulse).....	213
Random drop.....	203A
Vibration, high frequency.....	204A
Vibration, random.....	214
Shock, medium impact.....	205C
Life (rotational).....	206
High-impact shock.....	207A
Solderability.....	208B
Resistance to solvents.....	215
<i>Electrical-characteristics tests (300 class):</i>	
Dielectric withstanding voltage.....	301
Insulation resistance.....	302
Dc resistance.....	303
Resistance-temperature characteristic.....	304
Capacitance.....	305
Q factor.....	306
Contact resistance.....	307
Current-noise test for fixed resistors.....	308
Voltage coefficient of resistance.....	309
Contact-chatter monitoring.....	310

diodes or glass-sealed resistors. Cracking is variously attributed to (1) stresses resulting from shrinkage of the plastic coating when the solvent evaporates; (2) high shrinkage from polymerization during curing; or (3) large differences in coefficients of expansion between the glass and the plastic coating. The cracking may be manifest soon after drying, after curing, or much later during testing or rework operations where additional stresses are imposed. For stress-sensitive components, it is therefore important to avoid very thick coatings; and if filleting is used, to avoid bridging between components.

Inspection. Many manufacturers are providing dyed or fluorescent coatings to allow visual or ultraviolet-light inspection, assuring that all areas have been coated

adequately. Bare spots, pinholes, and other discontinuities are easily detected, thus facilitating quality control. Fluorescent indicators are also being used to determine whether particles of coating are migrating and contaminating other portions of a system, because particulate matter is especially critical to the functioning of parts in the immediate vicinity of the circuit board, such as gyros, accelerometers, bearings, and rotating memory disks.

Reworkability of Coated Assemblies. Many commercial electronic modules are designed as throw-away items, so that no coating or, at most, a relatively inexpensive varnish or polyester is employed. For more complex and expensive electronic gear, speciality coatings are needed to achieve long-term reliability. Because of the

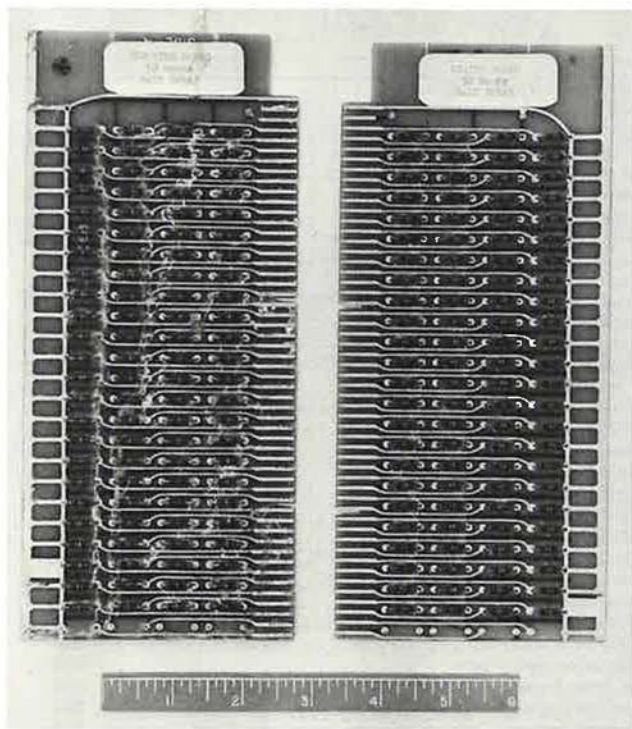


Fig. 2 Effects of salt spray on coated and uncoated circuit boards (board on right was coated).

probability that one or more defective components or solder joints will have to be repaired, it is imperative that the module be reworkable. Hence, the coating selected, in addition to meeting the numerous engineering and manufacturing requirements, must be amenable to being removed so that defective components may be separated and replaced. The removal technique must be one that does little or no damage to good adjacent components, surfaces, and markings. Combining all these desirable features in one material is, of course, a very difficult problem. Where service temperatures are lower than 275°F, polyurethanes have been popular because, being thermoplastic, they can be melted in localized areas by a hot solder-iron tip (Fig. 4), and indeed behave as a partial solder flux. Epoxy-polyamides and epoxy-amines also may be softened and removed by a hot solder iron; however, with much more difficulty. Heat may decompose and carbonize the epoxy polymer, resulting in poor solderability and darkened areas.

Silicone elastomeric coatings are easily removed by cutting into them with a knife blade because of their softness. Being thermosetting, they will not soften or melt with heat, but will eventually decompose. Silicones and other thermosetting plastics may also be swelled by prolonged contact with chlorinated or fluorinated solvents such as methylene chloride or trichloroethylene, and then removed mechanically.⁴ However, there are four problems encountered with solvent-removal techniques: (1) the process is slow, requiring immersion for one or two days; (2) solvents do not really dissolve the plastic, but only swell it; (3) the solvent cannot be localized, and so there is the probability of the other areas being damaged; (4) swelling of the plastic can generate large stresses which then induce failure modes in other devices.

Addition of 3 to 10 percent of an additive, such as silica aerogel, will convert the solvent to a paste which will not flow under normal conditions. This method is also extremely slow and subject to solvent evaporation.

Solder resists and maskants In the assembly and processing of electronic components, resists or maskants may be needed to "stop off" certain areas from conformal coating or solder. For example, in the conformal coating of printed-circuit boards, the edge connector strip should be left uncoated to allow electric contact with an edge connector.

In soldering, of course, solder splatter is undesirable, especially where bridging and short-circuiting of closely spaced conductors can occur. To prevent solder wetting of

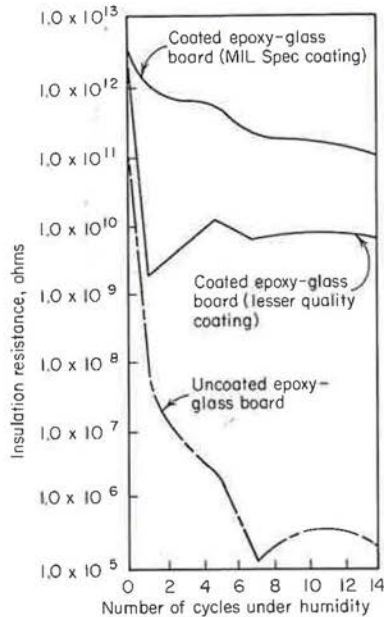


Fig. 3 Insulation resistance of coated and uncoated boards as a function of humidity cycling (MIL-I-46058).²

TABLE 3 Humidity Effects on Insulation Resistance of Circuit Boards²

Sample	Insulation resistance, ohms		
	Initial	5th cycle	10th cycle
A Uncoated.....	1.5×10^{12}	3×10^7	5×10^4
Coated.....	1×10^{12}	3×10^9	2×10^9
B Uncoated.....	3×10^{12}	5×10^7	5×10^3
Coated.....	3.1×10^{12}	5×10^{11}	4×10^{11}
C Uncoated.....	3×10^{12}	5.5×10^7	1.5×10^6
Coated.....	3×10^{12}	3×10^{11}	4.1×10^{10}

such areas, solder maskants, also referred to as solder stop-offs, are employed. They are usually epoxy formulations because of the need to withstand exposure to solder temperatures of 475°F and higher without degrading. Most nonepoxy types are reported to blister, lift, outgas, or decompose in some other way. Solder maskants are normally applied by screening, although spraying through a stencil and brushing have also been used. The main limitation in the use of epoxy solder maskants is

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that once they have been applied and cured, repair is virtually impossible. A fully cured epoxy coating is strongly adherent, and all methods required to remove it will invariably result in damage to the substrate or the circuitry.⁴

**TABLE 4 Minimum Allowable Spacings
between Conductors on Printed-circuit Boards
for Conformance to MIL-STD-275B**

Voltage between conductors (dc or ac peak)	Minimum spacing, in.
<i>Uncoated boards:</i>	
Sea level to 10,000 ft:	
0-150	0.025
151-300	0.050
301-500	0.100
Greater than 500	0.002*
Over 10,000 ft:	
0-50	0.025
51-100	0.060
101-170	0.125
171-250	0.250
251-500	0.500
Greater than 500	0.001*
<i>Coated boards:</i>	
All altitudes:	
0-30	0.010
31-50	0.015
51-150	0.020
151-300	0.030
311-500	0.060
Greater than 500	0.00012*

* Inch per volt.



Fig. 4 Soldering through a polyurethane conformal coating on a ceramic printed-circuit assembly.

The maskants described above as useful for stopping off either conformal coatings or solder may take a number of forms, as follows:

1. Screenable coatings
2. Strippable dip or spray coatings
3. Tapes, adhesive-backed
4. Molded rubber pressed into close contact by means of a clamp fixture

A list of representative examples is given in Table 5.

Coatings for thin-film circuits Coatings, either alone or in conjunction with encapsulants, are being used more and more as the method of packaging of both thin- and thick-film circuits. Large cost savings can be achieved over the normal packaging methods involving hermetically sealed metal cans. However, because of the close value tolerances to which thin- or thick-film elements such as resistors must be held, and because of the sensitivity of these elements to changes, hermetically sealed packages with an inert gas must still be used in many cases. Where organic coatings are to be used, they should be checked for compatibility with the various circuit elements (resistors, capacitors, conductors, etc.) before use. Compatibility is commonly determined by (1) assessing changes in electrical values before and after coating and after environmental testing such as thermal cycling

TABLE 5 Typical Resist Coatings and Maskants Used in Assembly of Printed Circuits

Type	Name	Manufacturer	Characteristic feature
Strippable coatings.....	Spraylat 1071	Spraylat	Vinyl solution, brush, dip, or spray. Air dry, good toughness. Heat resistance 200-250°F.
Adhesive tapes.....	No. 35	Minnesota Mining & Mfg. Co.	Vinyl tape, acrylic adhesive.
	No. 63		Teflon tape, acrylic adhesive.
	EE 6379	Permacel	Polyimide tape, silicone adhesive.
Screenable solder resists	No. 470	Minnesota Mining & Mfg. Co.	Vinyl tape, synthetic rubber adhesive.
	DSM 727	Dynachem Corp.	A thermosetting, screenable, one-component coating, available in a number of colors. An elevated-temperature cure is recommended. Stable for 1 min at 525°F.
	184 Series	Wornow Process Paint Co.	Reinforced alkyd-based transparent green. Heat curing from 200 to 300°F required for permanent resist. Stable at 500°F for 15 sec.
	PRH-403 Lonco PC33R PC 535	Permacel London Chemical	Two-component epoxy. Melamine-polyester. Silicone-polyester.

and humidity exposure; (2) determining degree of adhesion of the coating to the various substrates and surfaces comprising the circuit; and (3) checking for corrosivity to metallic surfaces by long-term or accelerated testing.

Because many thin-film resistors must maintain close tolerances (± 0.1 percent) and most coatings effect changes greater than this, it is a common practice to passivate the resistors using special composition glasses or silicon monoxide. After such glassification, the circuit chip can be plastic-packaged by coating, transfer molding, or other methods.

Coatings for thick-film circuits So-called thick-film circuits are formed by the deposition of conductive, resistive, dielectric, and insulative coatings on ceramic or plastic substrates. The coatings, often in the form of screenable inks or pastes, are applied as circuitry lines, resistors, or capacitors.

Most of the criteria previously described as applicable to the selection of conformal

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coatings for etched printed-circuit boards also apply to thick-film circuit protection. Hence, moisture resistance, stability of electrical insulation properties, adhesion, solder-through properties, and transparency are usually required. Many coatings used for the protection of epoxy circuit boards cannot be used for ceramic circuits because of differences in adhesion to the substrate. Adhesion of organic coatings to ceramics is generally poorer than to an epoxy substrate. Primers may have to be used to achieve both adhesion and other desirable properties.

TABLE 6 NEMA Standards and Manufacturers' Trade Names for Wire Insulation

Manufacturer	Plain enamel	Polyvinyl formal	Polyvinyl formal modified	Polyvinyl formal with nylon overcoat	Polyvinyl formal with butyral overcoat	Polyamide	Acrylic	Epoxy
Thermal class	105°C	105°C	105°C	105°C	105°C	105°C	105°C	130°C
NEMA Standard ⁶	MW 1	MW 15	MW 27	MW 17	MW 19	MW 6	MW 4	MW 9
Anaconda Wire & Cable Co.	Plain enamel	Formvar	Hermetic Formvar	Nyform	Cement coated Formvar			Epoxy epoxy-cement coated
Asco Wire & Cable Co.	Enamel	Formvar		Nyform	Formbond	Nylon	Acrylic	Epoxy
Belden Manufacturing Co. ...	Beld-enamel	Formvar		Nyclad				Epoxy
Bridgeport Insulated Wire Co.		Formvar			Quickbond	Quick-Sol		
Chicago Magnet Wire Corp.	Plain enamel	Formvar		Nyform	Bondable Formvar	Nylon	Acrylic	Epoxy
Essex Wire Corp.	Plain enamel	Formvar	Formetex	Nyform	Bondex		Ensorex/ESX	Epoxy
General Cable Corp.	Plain enamel	Formvar	Formetic	Formlon	Formeze		Solderable acrylic	Epoxy
General Electric Co.		Formex				Nylon		
Haveg-Super Temp Div.								
Hitemp Wires Co. Division								
Simplex Wire & Cable Co.								
Hudson Wire Co.	Plain enamel	Formvar		Nyform	Formvar AVC	Ezsol		
New Haven Wire & Cable, Inc.	Plain enamel							
Phelps Dodge Magnet Wire Corp.	Enamel	Formvar	Hermetex	Nyform	Bondeze			
Rea Magnet Wire Co., Inc. ...	Plain enamel	Formvar	Hermetic Formvar special	Nyform	Koilset	Nylon		Epoxy
Viking Wire Co., Inc.	Enamel	Formvar		Nyform	F-Bondall	Nylon		

Courtesy of Rea Magnet Wire Co., Inc.

Polymer coatings or encapsulants used over thick-film circuits should be carefully chosen for purity and stability. Outgassing or contaminants of a reducing nature such as hydrogen gas evolving from the polymer will degrade resistance values, especially of palladium-palladium oxide-silver composition inks. This is due to the reduction of the oxides in such compositions to free metal which increases conductivity. Hence, plastic overcoatings may have a very damaging effect rather than the intended beneficial effect. It is reported that the platinum composition resistors are unaffected by hydrogen and are less sensitive to impurities.⁵

Wire and coil coatings and varnishes In general, wire coatings consist of high-molecular-weight polymers, either of the thermoplastic (linear) or thermosetting (crosslinked) types. The thermoplastic types have definite softening or melting points, above which the materials are not usable especially if a stress is applied in a localized area. Examples include Teflon* and nylon. The thermosetting coatings are more resistant to *cut-through*—required in all wire-wound devices—and have improved solvent resistance. Examples include silicones, polyester, and poly-

TABLE 6 NEMA Standards and Manufacturer's Trade Names for Wire Insulation (Continued)

Teflon	Polyurethane	Polyurethane with friction surface	Polyurethane with nylon overcoat	Polyurethane with butyral overcoat	Polyurethane with nylon and butyral overcoat	Polyester	Polyester with overcoat	Polyimide	Polyester polyimide	Ceramic, ceramic-Teflon, ceramic-silicon
200°C MW 10	105°C MW 2	105°C	130°C MW 28	105°C MW 3 (PROP)	130°C MW 29 (PROP)	155°C MW 5	155°C MW 5	220°C MW 16	180°C	180°C+ MW 7
.....	Analac	.....	Nylac	Cement-coated analac	Cement-coated nylac	.....	Anatherm D, Anatherm 200	Al 220 M.L.	Anatherm N Anamid M (amide-imide) Ascomid	
.....	Poly	.....	Nypol	Asco bond-P	Asco bond	Ascotherm	Isotherm 200 Polythermaleze	M.L.		
.....	Beldure	.....	Beldsol	.....	.....	Isonel		M.L.		
.....	Polyurethane Soderbrite	Uniwind	Poly-nylon Nysod	Polybond	.....	Isonel 200				
.....	Soderex	.....	Soderon	Bondable polyurethane Soderbond	Soderbond N	Polyester 155				
.....	Enamel "G"	.....	Genlon	.....	.....	Thermalax F	Polythermalex/ PTX 200	Allex		
.....		.....		.....	.....	Gentherm	Polythermaleze 200			
Teflon Temprite	.....	.....	.....	.....	.....	Alkanex Isonel				
.....	Hudsol	Gripon	Nypoly	Hudsol AVC	Nypoly AVC	Isonel 200	Isonel 200-A Imp-200	M.L.	Isomid	
.....	Impsol	.....	Impsolon	.....	.....	.....				
.....	Soderex	Gripeze	Nyleze	.....	S-Y Bondeze	.....	Polythermaleze 200 II	M.L.		
.....	Solvar	.....	Nylon solvar	Solvar coilset	.....	Isonel 200	Polythermaleze 200	Pyre M.L.	Isomid	Ceroc
.....	Polyurethane	.....	Poly-nylon	P-Bondall	.....	Isonel 200	Iso-poly	M.L.	Isomid Isomid-P	

vinyl formal. A list of some wire coating types, trade names, and manufacturers is given in Table 6.

As described in Table 6, many wire coatings consist of a combination of polymers. Polyvinyl formal may be coated with nylon to attain the lubricating properties of nylon which improves winding properties. Polyvinyl formal is frequently overcoated with polyvinyl butyral to form a coating that is self-bonding by either heat or solvent action to make formed coils.

* Trademark of E. I. du Pont de Nemours & Co., Wilmington, Del.

A description of wire coating types and their properties follows. A summary of properties is found in Table 7.

Coil Coatings. Wire that is to be wound in coils around forms, cores, or the like to form inductors, transformers, fields and armatures, or solenoids, of course, requires primary insulation on the wire. In addition, these coils are usually further treated to encapsulate or fix the wires in place. Furthermore, such inductive devices may have to withstand severe environments, as in military or aerospace equipment, or even in household washing machines. These are usually encapsulated, potted in plastic cups, or molded or cast in synthetic resins designed to meet the severe conditions. These treatments are largely described in Chap. 1.

TABLE 7 Summary of Properties of Various Coated Wires

Coating	Thermal rating, °C	Advantages	Limitations
Formvar.....	105	Tough, high dielectric strength, compatibility, heat shock	Crazes in polar solvents*
Polyesters.....	155	Toughness, dielectric strength, chemical resistance, cut-through	Hydrolyzes in moist, sealed atmosphere
Polyurethane.....	105	Dielectric strength, chemical resistance, compatibility, solderable without stripping, moisture and corona resistance	Reduced abrasion resistance
Nylon.....	105	Dielectric strength, solvent resistance, solderability, toughness, windability	Moisture absorption, high electrical loss at all frequencies
Polytetrafluoroethylene (Teflon)	180	Thermal stability, chemical stability, dielectric strength, low dielectric constant, low friction	Gas permeability, cold flow, adhesion
Formvar-nylon.....	105	Solvent resistance, toughness, windability, heat shock	Nylon portion subject to same limitation as nylon above
Formvar-Butvar†....	105	Bondable, dielectric strength, heat shock	Vibration, high mechanical stress
Polyurethane-nylon	105	Solderability, solvent resistance	Moisture absorption, high-frequency losses
Polyimide.....	220	Thermal resistance, chemical stability, radiation resistance	Stripping difficulty, solvent crazes*

*A prebake at 125°C for 2 to 4 hr after winding relieves film stress so that crazing does not subsequently occur during varnish or resin encapsulation.

† Trade name of Shawinigan Resins Co., division of Monsanto Chemical Co.

Wire Coating Types. OLEORESINOUS COATINGS: These coatings are essentially varnishes derived from natural drying oils such as linseed or tung oil containing numerous carbon-to-carbon double bonds and polymerizing by oxidative reaction of the double bonds. The varnishes may be "beefed up" by "cooking in" fossil or synthetic resins to improve their hardness and solvent resistance. Because of the dark color of the finished wire, they are commonly referred to as *black enamels*.

POLYURETHANE COATINGS: Polyurethane coatings used in wire enamels are generally the reaction products of hydroxylated polyesters, and hydroxylated polyesters which have been reacted with an excess of tolylene diisocyanate.

If two such materials are mixed, the reaction proceeds too rapidly for application. For this reason, for wire coating, the polyester containing the excess isocyanate groups is reacted with phenol, which forms a moderately stable compound and gives the total mixture sufficient stability for application. After application of the material to the wire, the phenol is released during the bake; and the resulting isocyanate can

then react with the hydroxyl groups of the other polyester forming the urethane linkages necessary for polymerization.

POLYAMIDES: Polyamides are the result of the reaction of a dicarboxylic acid and an aliphatic diamine. The best-known example is nylon.

POLYVINYL FORMAL: Coatings based on polyvinyl formal, commonly referred to as Formvar, are probably the most widely used of all wire coatings. The base polymer is prepared by partial hydrolysis of polyvinyl acetate followed by condensation with formaldehyde. Polyvinyl formal used alone is deficient in solvent resistance and hardness; but these properties are greatly improved by the addition of reactants such as phenol-formaldehyde and cresol-formaldehyde resins. These resins condense with the hydroxyl groups of the polyvinyl formal, producing a coating that is exceedingly tough and flexible, yet possessing good resistance to abrasion and solvents. Strong solvents are used in formulating these.

POLYESTER COATINGS: Polyester resins are produced by the condensation of a dibasic acid, such as fumaric, phthalic, or maleic; a glycol; and perhaps an unsaturated monomer such as styrene. When mixed and cooked in the proper proportions, partial polymerization occurs, leaving the product soluble in solvents. After application to the wire and during the cure, condensation occurs with release of water to produce a crosslinked network. Polyester wire coatings derive their excellent thermal properties from the stability of the ester linkages and the symmetry of the para substitution on the benzene ring.

POLYIMIDE COATING: Varnish suitable for application as a wire coating consists of polyamide acid resins soluble in strong solvents such as dimethyl formamide. Removal of water from the polyamide-acid during the coating cure results in formation of the polyimide.

POLYFLUORO COATING: These coatings differ from previously discussed coatings in that polymerization does not occur during application of the coatings. The coatings are applied as water dispersions of the polymer and then heat-fused or sintered during application. Examples would be Teflons TFE and FEP, polyvinyl fluoride, and CTFE.

Testing of Coated Wire. Coated wire testing is conducted most often according to procedures described in NEMA (National Electrical Manufacturers Association) Publication MW 1000, "Magnet Wire"; or in Military Specification MIL-W-583C, Wire, Magnet, Electrical,¹ in the case of government procurement. Considerable duplication exists between these two standards since many tests are identical. In the following discussion, some of the more commonly used tests are described.

FILM THICKNESS: Film thickness is measured by micrometer readings of the coated wire, removal of the coating in a manner nondestructive to the wire, and determining the wire diameter after removal of the coating. Half the difference between these diameters gives the thickness of the coating. One method of removing the coating from the copper wire is to burn off the coating by heating, followed by quick immersion of the hot wire in ethyl alcohol to reduce any copper oxide formed.

ADHESION: Adhesion is measured by elongating a 10-in. length of wire at 12 in./min for sizes 13 AWG (American Wire Gauge) and larger or by sudden pull for sizes 14 and finer. Examination of the wire for separation or cracking at specified magnification for different wire sizes determines failure.

FLEXIBILITY: Flexibility is determined by winding the wire around a mandrel of specified size followed by examination at magnification dependent on the size of the wire. Flexibility is frequently expressed as 1X, 2X, 3X, etc., signifying that the particular wire coating will withstand winding around a mandrel 1, 2, or 3 times the AWG size of the wire involved.

Adhesion and flexibility tests are frequently followed by elongation and by a mandrel-wind test similar to the above.

HEAT SHOCK: Heat is determined by elongation or stretching, winding around a mandrel of specified size, dependent on wire size, followed by exposure to oven heat. The specimen is then examined for cracking or separation from the metal under specified magnification.

SCRAPE RESISTANCE: Scrape resistance is measured in two ways: repeated scrape and unidirectional scrape. The repeated-scrape test is conducted using a machine that rubs a 0.016-in.-diameter needle or wire, oriented at 90° to the wire, but rubbed in a direction parallel to the axis of the wire under test with provision for a specified load at a rate of 60 strokes/min. Each stroke consists of a 360° rotation of an eccentric drive. The machine is equipped with an electric circuit which stops the action, and a counter which records the strokes at the time of break-through of the film.

The unidirectional-scrape resistance test consists of a scraping action in one direction only. The machine employed provides for a 0.009 in.-diameter needle rubbing in one direction on the coated wire at 16 in./min at right angles to the wire with constantly increasing load. The machine is equipped with an electric circuit for detecting the time to failure. Failure is recorded as "grams to fail."

THERMOPLASTIC FLOW: This property is frequently referred to as *cut-through*. Two pieces of 18 AWG wire are placed at right angles to each other and pressed together by a load of 2,000 g. The conductors of the wires are connected to a 110-volt power supply with an indicating device in the circuit such as an argon lamp. The unit is placed in an oven and the temperature raised at a rate of less than 5°C per min. When the indicating device shows short circuiting, the temperature of the plate supporting the wires is measured and recorded.

DIELECTRIC STRENGTH: Dielectric strength of most wire coatings used in electronic equipment is determined by means of "twisted pairs." The specimens used consist of two wires twisted under a specified tension and total number of twists, dependent on wire size, for a length of approximately 4.75 in. The conductors of each pair are connected to a 60 Hz ac power source, and the voltage is increased at a rate of 500 volts/sec until breakdown occurs.

CONTINUITY: Continuity is measured by passage of 100 ft of wire through a mercury bath at 100 ft/min. A discontinuity-indicating circuit operates at voltages from 20 to 75 volts direct current dependent on wire size. The discontinuity device operates when the resistance between the bath and conductor is less than 5,000 ohms but not more than 10,000 ohms. The test circuit is arranged so as to record the number of dielectric breaks. Results are reported as number of breaks per 100 ft of wire.

High-voltage continuity is measured by passage of 100 ft of wire between grooved metal rollers with the wire grounded to the take-off drum. The test circuit is arranged so as to impose a 60-Hz voltage between the take-off drum and the roller, and has a sensitivity of 1 megohm at the test voltage to indicate dielectric breaks during test. The test voltages to be used are dependent on the thickness of the coating and the size of wire.

SOLVENT RESISTANCE AND COMPLETENESS OF CURE: Degradation of wire coatings due to solvent exposure may be determined by an accelerated test in which the wire specimens are exposed to various solvents and their scrape resistance is measured. The scrape-resistance value may then be compared with that of a control unexposed wire. Weight loss of insulating coating after extraction with solvents is another method of assessing solvent resistance as well as the degree of cure of the coating. Solvent extractables are usually determined by Soxhlet methods using toluene followed by methanol; or, in the case of polyvinyl formal-urethane, using boiling methanol. Extractables are calculated from the original weight of coated wire, the weight of the extracted solution after stripping off the solvent, or the weight of wire after all the coating has been removed. For most wires, the extractable content provides a good index of degree of cure, particularly where the wire is later to be exposed to the action of various liquids such as in oil- or fluid-filled transformers.

Still a third method involves microscopic examination of the coated wire after it has been exposed to solvent. In the case of polyvinyl formal wire, the wire is exposed for 5 min to a mixture of 30 percent toluene, 70 percent denatured alcohol (by volume). Removal of self-bonding resin from the polyvinyl formal or swelling within 0.5 in. from the end is considered a failure. For other insulations such as

polyimide, the completeness of cure may be determined by dissipation factor measurements.

SOLDERABILITY: The solderability of wire (principally nylon- and polyurethane-insulated) is tested by immersion in rosin-alcohol flux followed by molten 50:50 tin-lead solder at temperatures dependent on size of wire followed by visual examination. The sample is prepared by twisting the ends of a 12-in. length of wire for a distance of $\frac{3}{4}$ to 1 in. and cutting off the end of the twist, leaving 5 to 10 turns.

BOND STRENGTH OF SELF-BONDING WIRE: Twisted pairs are prepared similar to those used for dielectric strength tests and bonded by heating for $\frac{1}{2}$ hr at 125°C. The bond strength is then measured by using a tensile testing machine with one end of one wire clamped in one jaw of the machine and the opposite end clamped in the other jaw. The rate of pull is 12 in./min, and the load causing one wire to slide along the other is recorded.

THERMAL RATING AND THERMAL STABILITY: Thermal ratings are based on heating tests of twisted-pair specimens of 18 AWG wire with a heavy film coating in accordance with ASTM D 2307. According to this rather complex test, sets of 10 or more twisted-pair specimens are exposed to temperatures at least 20°C apart for cycle periods specified, followed by proof-voltage tests dependent on coating thickness. The proof voltages (60 Hz alternating current) are selected to produce a voltage stress of approximately 300 volts/mil. Using statistical procedures outlined in ASTM D 2307, the results are extrapolated for a predicted life of 20,000 hr. This method is the basis for the thermal ratings presented in Tables 6 and 7.

The thermal stability of wire coatings may also be determined by differential thermal analysis (DTA)⁸ and by thermal gravimetric analysis (TGA)⁹. According to the DTA procedure, all endothermic and exothermic reactions that the material undergoes in being exposed to a programmed temperature sweep are recorded. These heat changes correspond to phase changes occurring at the indicated temperatures; for example, they may consist of glass transitions, softening or melting, oxidation, sublimation, or decomposition. Differential thermal analysis, however, does not indicate weight changes since phase changes may occur without weight loss or gain. For exact weight changes, thermal gravimetric analysis may be used. According to TGA, weight loss is plotted dynamically (again during a programmed temperature rise), using a very sensitive electrobalance. By running both a DTA curve (known as a thermogram) and a TGA curve (known as a pyrogram), an almost complete thermal profile of the material may be obtained. Both methods are being used to study the thermal and oxidative stability of other polymeric coatings and for plastics in general. The reader is referred to other books and articles for further details and applications.⁸⁻¹² With reference to wire coatings, the thermograms for polyethylene, polyvinyl chloride, Kel F, Teflon, Formex, Nylon-Formex, Alkenex, polyurethane, and polyimide coatings have been reported by Murphy and Hill.⁸

Coatings used in packaging electronic devices Organic coatings, used alone or in combination with transfer-molded or cast resins, provide an extremely important and economical approach for packaging and protecting electronic components. Plastic encapsulated devices are rapidly replacing hermetically sealed canned devices in many applications. Resistors, capacitors, transistors, diodes, and integrated circuits are all now available in plastic packages. So great has been the impact of plastics that production of encapsulated transistors alone now numbers in the tens of millions of devices per month. Indeed, the sealing of devices in plastics appears to be the dominant trend, especially in the semiconductor industry.

The popularity of using plastics stems from the simplicity and rapidity with which they can be processed and applied, resulting in substantial cost savings.¹⁴ Dramatic cost reductions have been achieved, especially in the case of transistors and integrated circuits. Devices that previously sold for as high as \$3 to \$5 in metal cans have been reduced to 50 cents to \$1 per unit by transfer-molding them in either epoxy or silicone resins. Plastics may also be molded in an almost

infinite variety of configurations; however, most of them are designed to be interchangeable with their metal-can counterparts (Fig. 5).

Functions of Plastic Packaging Materials. Both coatings and transfer-molding compounds are generally employed as a complete system.

The combination of a coating and a molding plastic provides greater rigidity, dimensional stability, impact resistance, and moisture protection over the use of a coating alone. The main functions of the coating, also referred to as the "inner coating," "barrier coating," or "junction coating," may be listed as follows:

1. To hold delicate components and fine interconnection wires together, allowing them to be handled, dropped, vibrated, etc., without electrical or mechanical damage. This function is sometimes referred to as "ruggedization."
2. To impart stress relief. Stresses arising from the transfer-molding operation, resin shrinkage, differences in coefficients of expansion between the plastic and substrates, thermal cycling, and thermal shock may be equalized and dissipated by using the proper barrier coating.
3. To provide some degree of moisture, gas, and dust protection, preventing corrosion and electrical malfunctioning.
4. To provide an insulation barrier, thus preventing electric short circuiting.

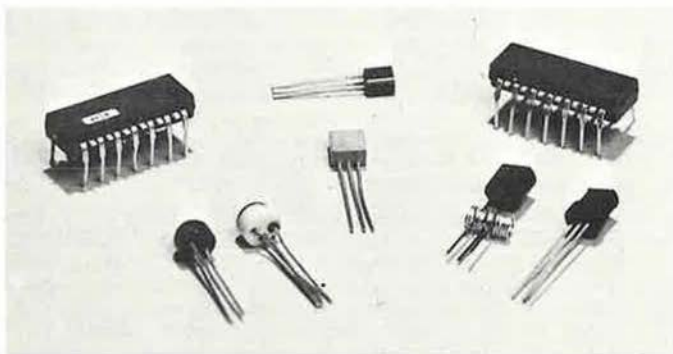


Fig. 5 Plastic-encapsulated semiconductor devices.

Among the functions of the transfer-molding or casting compounds are the following:

1. To provide a well-defined structure with exact dimensional tolerances comparable to those for hermetic cans. This permits standardization and interchangeability of parts.
2. To provide high impact and mechanical shock resistance.
3. To provide a longer path for moisture, thus reducing moisture penetration. The use of the coating alone does not afford a sufficient moisture seal.

Application of Coatings Used in Plastic Packaging of Electronic Devices. Barrier coatings may be applied to components by dipping, spraying, fluidized bed, or eye dropping. These methods are applicable to resistors and capacitors, but the coating of uncased semiconductor devices and microcircuits is limited to the eye-dropping method. Barrier or stress-relief coatings applied to semiconductor devices must be localized so that they cover only the active surface, metallization, and a portion of the internal flying leads. The coating should not be allowed to spread to the edges of the device or onto the external leads where it could affect the adhesion and moisture permeability of the subsequently applied molding compound or the solderability of the leads. Because of these restrictions, the only practical method of applying the coating is by dispensing it in small drops from a microsyringe or from an eyedropper.

The structural plastic is subsequently applied by transfer molding, casting, or

dipping, and is successfully being used for the encapsulation of thin-film resistors, wire-wound resistors, diodes, bipolar and MOS-FET transistors, integrated circuits, coils, and many other components. The relative position of the barrier coating with respect to the molding compound is shown in Fig. 6 for a commonly used 14-lead integrated-circuit package.

Plastic Parameters Affecting Device Reliability. The main plastic parameters that can affect the reliability of a device are moisture penetration, purity, corrosivity, stresses, and adhesion. Some of these parameters will be treated separately in the following discussion. However, it should be emphasized that they are all closely interrelated. For example, lack of adhesion will increase moisture penetration; impurities will cause corrosion; and corrosion in turn can affect both adhesion and moisture penetration.

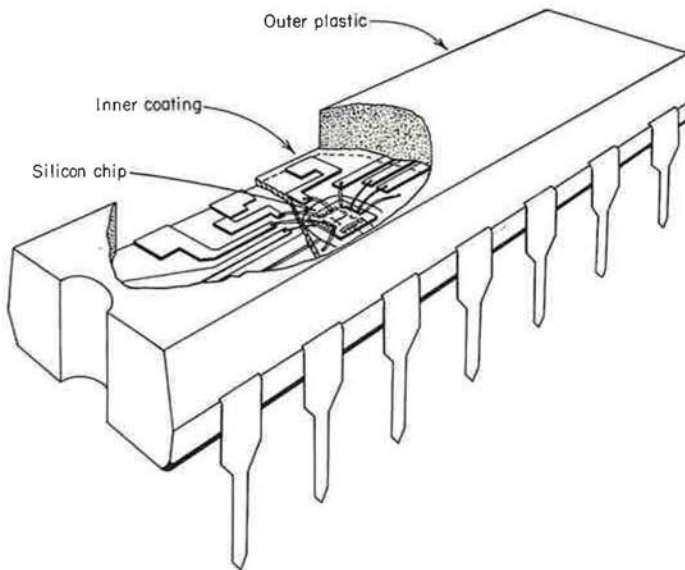


Fig. 6 Cross section of plastic-packaged integrated circuit.

MOISTURE RESISTANCE: All plastics absorb and transmit moisture to a finite extent. When used to package devices, they should not therefore be considered hermetic in the same sense that metal cans or metal-to-glass seals are; nor do the same hermeticity and leakage tests apply. In spite of this, plastic-packaged devices have been found to pass the moisture requirements for many military specifications, and devices have been shown to be operational after limited exposures to high humidity and elevated temperatures. Their long-term resistance to humidity and warm, humid environments is, however, questionable. In many cases, the key to the success of plastic-packaged transistors and integrated circuits has been not the plastic itself but the reliability and hermeticity of the passivation layer used over the device surface. Significant improvements in passivation layers such as the development of silicon nitride and silicon nitride-silicon dioxide composites and the deposition of certain low-melting glasses have greatly reduced the criticality of plastic properties.

PURITY: The degree of purity of coatings and plastics is an extremely critical factor when these materials are used on any electronic assembly, but more so when used directly on active microelectronic devices. However, if the active devices are well passivated, plastic purity is not as critical a factor. Indeed, the success

of many plastic-packaged devices has been due primarily to improvements in the reliability of inorganic passivation layers such as glass and silicon nitride.^{15,16} Silicon nitride, in particular, has been shown to be one of the best barriers to sodium ions even at elevated temperatures and with an applied bias.¹⁷ Sodium, potassium, and lithium ions cause inversion layers, high leakage currents, and low breakdown voltages in diodes and transistors.¹⁸⁻²⁰ These effects and the degradation of electrical insulating properties of coatings are enhanced by an increase in mobility of the charged carriers, brought about by moisture, electrical stress, or elevated temperature. Ionic impurities are present in most commercially available coatings.

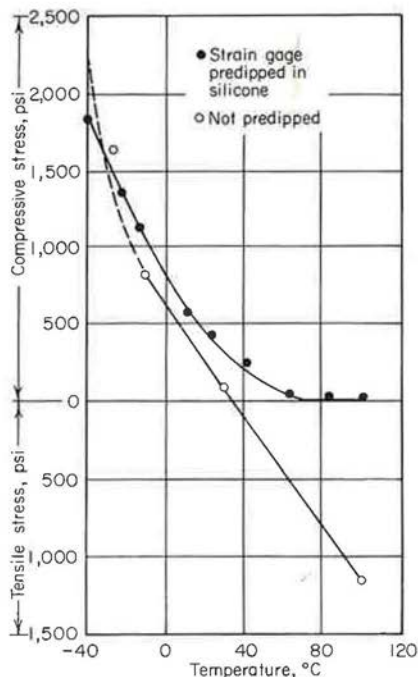


Fig. 7 Effect of flexible precoat on stress of DGEBA-polyamide cured system.²¹

in component packaging. For example, in the packaging of transistors, one firm coats components with 10 to 20 mils of silicone, and then encapsulates them with a *m*-phenylenediamine-cured epoxy. Other semiconductor manufacturers employ small amounts of silicone barrier coatings, and then transfer-mold with silicone or epoxy.

The validity of using flexible dip coatings to relieve stresses is apparent from data presented in Fig. 7. In other work, total stresses of 5,000 psi at -40°C on components embedded in a silica-filled epoxy resin have been reported; but when the components were precoated with RTV elastomeric silicone, the total stress imposed and stress concentrations were reduced. A 1-mil silicone coating at -40°C reduced the total pressure to 3,500 psi, and an 8-mil-thick coating further reduced this pressure to below 400 psi.^{21,22}

The use of plastic systems involving more than one coating or plastic may present

CORROSIVITY: The immediate or long-term effect of moisture may be the corrosion of metal portions of a device. Most susceptible to corrosion are the external leads, internal flying leads, interconnection bonds, and metallized conductors. Besides moisture, ionic and other impurities on the device surface or within the plastic play a key role in initiating and accelerating corrosion. Chloride ion contamination, for example, chemically corrodes aluminum through the formation of aluminum chloride. Other ions, both cationic and anionic, contribute to electrolytic corrosion between external leads or between closely spaced internal conductors. Again, this type of corrosion can be minimized or avoided by employing extremely pure plastics.

In many instances, catalysts used for curing resins, have been known to induce corrosion of metal surfaces.

STRESSES AND STRESS RELIEVING: Barrier coatings can be used to minimize or eliminate stresses imposed by subsequently used transfer-molding or casting compounds and to protect electronic components from vibration and shock. The stress-relief coatings selected must, however, be flexible and possess a low modulus of elasticity. Silicones, both the Silastic[®] and RTV[†] types, meet these requirements and have found many applications.

[®] Trademark of Dow Corning Corporation, Midland, Mich.

[†] Trademark of General Electric Co., Schenectady, N.Y.

problems if the inner coating has a higher coefficient of expansion than the outer plastic. An increase in temperature will obviously cause the inner coating to exert pressure against the confining outer plastic. An example of this is the use of an inner unfilled silicone coating and an outer epoxy shell in some resistor and semiconductor devices. Stress problems can be avoided by either minimizing the amount of inner silicone coating or by providing an empty volume between the inner coating and the outer shell into which the silicone can expand.

ADHESION: Good adhesion of plastics to components is essential for two basic reasons: (1) to effect a satisfactory seal against moisture and contaminants; and (2) to allow the encapsulating plastic to dissipate mechanical stresses to the leads during handling, installation, and service. Adhesion can be improved by coatings.

Several factors affecting adhesion may be itemized as follows:

1. Type of substrate material (metal or nonmetal)
2. Surface treatment prior to encapsulation
3. Surface roughness or porosity
4. Intrinsic adhesive properties of the polymer coating
5. Presence of internal release agents in transfer-molding plastics

The nature and preparation of the substrate are the strongest factors affecting adhesion. For example, the ease of bonding (bondability) varies greatly among metals, with the noble metals being more difficult to bond to. Examples of metals known to be difficult to bond to are gold, Kovar,* nickel alloys, solder, solder plating, and cadmium.

A clean surface is essential for good adhesion. Methods for cleaning vary from solvent cleaning to etching of surfaces. For difficult-to-bond metals, primers are sometimes used. For example, epoxy primers are used over gold before coating with polyurethane. Special primers are frequently used to enhance the adhesion of silicones, particularly the RTV types.

The intrinsic bondability of polymers varies from type to type. Epoxies and phenolics, for example, are known for their inherently good adhesive properties. Polyurethanes exhibit fair to excellent bonds, while silicones exhibit adhesive properties that vary from very poor to good.

With reactive metals, other critical adhesion factors are the type and mechanical strength of the oxide which forms rapidly on the surface under normal ambient conditions. This oxide layer may actually assist in improving adhesion.

Coatings for Semiconductors. Early experimental work on coatings for the protection of semiconductor junctions was performed between 1955 and 1960. Many of these early compositions consisted of waxes combined with plastics.^{22,21} Later, silicone resins filled with lead tetroxide or mercuric oxide were used to coat transistors and germanium rectifying diodes.²² In 1962, the first epoxy-packaged transistors were mass-produced for the consumer and automotive markets.²³ Finally, in 1964 plastic-packaged devices were introduced for industrial and computer applications and in 1966 and 1967 for some military applications.

Presently, several types of coatings and molding compounds are employed in plastic-packaged semiconductor devices and other electronic components. These types are predominantly epoxies and silicones, with phenolics and polyesters being used to a lesser extent. A list of some commonly used barrier and junction coatings and their characteristics is given in Table 8.

Commercial versus Military Uses of Plastic Packages. For the most part, plastic-packaged devices are used for consumer and industrial applications such as for television, radios, computers, and in-house test equipment. There is no question about their cost savings and performance for the applications. Greater precautions and proof of long-term reliability are, however, necessary for military systems because of the often more severe environments that these systems will encounter. The main drawback to the more extensive use of plastics for military electronics has been their inability to act as sufficient moisture barriers to meet stringent requirements such as those defined in MIL-E-5272, MIL-E-5400, MIL-E-16400 E, MIL-STD-202,

* Trademark of Westinghouse Electric Corporation, Pittsburgh, Pa.

TABLE 8 Barrier and Junction Coatings

Commercial designation	Supplier	Type	Characteristics
DC 643	Dow Corning	One-part unfilled silicone solution coating	A high-purity coating compatible with transistors and n-p-n junctions. Cures in 12 hr at 200°C, or 4 hr at 250°C. Does not cure at 150°C.
DC 644	Dow Corning	One-part unfilled silicone solution coating	Used for diode, transistor, and rectifier junctions. Cures in 12 hr at 200°C, or 4 hr at 250°C.
DC 645	Dow Corning	One-part silicone solution coating	Used for diode, transistor, and rectifier junctions. Cures in 12 hr at 200°C, or 4 hr at 250°C.
DC 646	Dow Corning	One-part unfilled silicone solution coating	A high-purity coating compatible with diodes, controlled rectifiers, p-n-p, and p-n-p+ type junctions. Cures in 12 hr at 200°C, or 4 hr at 250°C.
DC 51	Dow Corning	A silicone dielectric gel	A very soft, high-purity material used to coat devices in hermetically sealed metal cases. Stabilizes life character of devices by reducing junction temperatures and cushioning the junction against shock.
R-60087	Dow Corning	Two-part clear, unfilled, solventless silicone	Provides physical protection and support of small interconnecting wires plus protection against contamination of junction surfaces. Cures in 2 hr at 200°C.
R-60093	Dow Corning	Two-part black, filled, solventless silicone	High-purity silicone resin designed for use on semiconductor junction surfaces. Cures in 2 hr at 200°C.
R-62044	Dow Corning	One-part clear, unfilled silicone solution coating	Contaminant-free silicone resin which contains no catalysts or driers. Cures in 24 hr at 200°C.
XR-60092	Dow Corning	Two-part clear silicone	Same as R-60093 except does not contain filler.
R-90703	Dow Corning	Black-filled two-part solventless silicone	A high-purity coating for semiconductor junction protection. Cures in 4 hr at 65°C or 2 hr at 150°C.
XR-60095	Dow Corning	Two-part solventless silicone	A high-purity coating designed for protecting active semiconductor surfaces and to support delicate interconnecting wires. Cures in 4 hr at 65°C.
SR-98	General Electric	One-part silicone varnish	Very hard film over wide temperature range with excellent stability at high temperatures. Cures in 8 hr at 200°C.
R-620	Union Carbide	One-part silicone varnish	A high-temperature coating which retains electrical properties under adverse conditions. Cures in about 12 hr at 200°C.

and more recently, MIL-STD-883. In attempting to meet these requirements, some device manufacturers have resorted either to the use of multiple coats of silicones or epoxies, with high-temperature bakes after each application, or to alternating several different coating types, e.g., a silicone followed by an epoxy. In active devices and integrated circuits, improved passivation layers such as silicon nitride or special glasses can serve as the primary barriers for moisture and ionic contaminants. Less reliance therefore needs to be placed on the plastic to achieve these functions. Some firms report a very high level of reliability with plastic-packaged devices primarily because of the improved passivation layers which they have developed.

PROPERTIES OF ELECTRONIC COATINGS

Coatings for electronics may serve numerous functions; but, in general, the two most important ones are (1) to provide high electrical insulation between conductors, interconnections, components, and other electrical parts, and (2) to provide protection from environmental damage. Protection from one or more of a number of severe environments may be necessary. Examples include moisture, heat, salt spray, oxygen, radiation, microorganisms, chemicals, and solvents. In addition, for rather fragile microelectronic assemblies, coatings are used to protect from abrasion, handling, shock, and vibration damage. Specially synthesized or formulated coatings may also serve a number of functional requirements such as to provide electric conductivity for radio-frequency interference (RFI) and for ohmic contacts, or to provide either thermal insulation or thermal conductance. Hence, coatings play a very vital part in the successful operation of electronic assemblies; and indeed, if it had not been for the development of superior electrical coatings, many of the highly dense and intricate windings, coils, and microelectronic assemblies would not have been possible.

Electrical Protection

One of the most important functions of organic coatings is to provide high electrical insulation and dielectric isolation for active or passive electronic components. Their effectiveness in this respect is expressed in terms of insulation resistance, volume resistivity, surface resistivity, and dielectric strength. Other functions include the storage of electric current and the conductance of current. These are expressed in terms of dielectric constant, capacitance, dissipation factor, and conductivity. A knowledge of exact electrical values and how these vary with changes in composition, purity, structure, or environment is important in selecting the most reliable coating for electronic equipment. The following will define these electrical parameters; show how they change with temperature, frequency, and other variables; and present tables of values for the more commonly used coatings. More theoretical discussions of electrical parameters may be found in other books.²⁸⁻³⁰

Insulation resistance and resistivity Insulation resistance is simply the ohmic relationship of the ratio of applied voltage to the total current between two electrodes in contact with a specific material. It is directly proportional to the length of a specimen and inversely proportional to the cross-sectional area according to the equation

$$R = \frac{\rho l}{A}$$

where R is insulation resistance in ohms, l is length, A is area, and ρ is a proportionality constant called the specific resistance or resistivity. When dimensions are in centimeters, the units are ohm-centimeters; when in inches, the units are ohm-inches.

Resistivity and other properties of plastics in general are treated in Chap. 3.

Resistivity is an important value because it reduces resistance measurements to a common denominator and permits comparisons between different materials. Volume resistivity, for example, is the ohmic resistance of a cube of bulk dielectric

TABLE 9 Volume Resistivities of Polymer Coatings

Material	Volume resistivity at 25°C, ohm-cm	Source of information
Acrylics.....	10^{14} – 10^{15} $>10^{14}$ 7.6×10^{14} – 1.0×10^{15}	^a ^b Columbia Technical Corp., Humiseal
Alkyds.....	10^{14}	^a
Chlorinated polyether.....	10^{15}	^b
Chlorosulfonated polyethylene.....	10^{14}	^b
Depolymerized rubber.....	1.3×10^{13}	H. V. Hardman, DPR Subsidiary
Diallyl phthalate.....	10^8 – 2.5×10^{10}	^a
Epoxy (cured with DETA).....	2×10^{16}	^{c,d}
Epoxy polyamide.....	1.1 – 1.5×10^{14}	
Phenolics.....	6×10^{12} – 10^{13}	^a
Polyamides.....	10^{13}	
Polyamide-imide.....	7.7×10^{16}	^e
Polyethylene.....	$>10^{16}$	
Polyimide.....	10^{16} – 10^{18}	^f
Polypropylene.....	10^{10} – $>10^{16}$	^a
Polystyrene.....	$>10^{16}$	^b
Polysulfide.....	2.4×10^{11}	^g
Polyurethane (single component).....	5.5×10^{12}	^h
Polyurethane (single component).....	2.0×10^{12}	^h
Polyurethane (single component).....	4×10^{13}	
Polyurethane (two components).....	1×10^{13} 5×10^9 (300°F)	Columbia Technical Corp. Products Research & Chemical Corp. (PR-1538)
Polyvinyl chloride.....	10^{11} – 10^{15}	^b
Polyvinylidene chloride.....	10^{14} – 10^{16}	^a
Polyvinylidene fluoride.....	2×10^{14}	^h
Polyxylylenes (parlylenes).....	10^{16} – 10^{17}	
Silicone (RTV).....	6×10^{14} – 3×10^{15}	Union Carbide Corp. Stauffer Chemical Co., Si-O-Flex SS 831, 832, & 833
Silicone, flexible dielectric gel.....	1×10^{15}	Dow Corning Corp.
Silicone, flexible, clear.....	2×10^{15}	Dow Corning Corp.
Silicone.....	3.3×10^{14}	Columbia Technical Corp. Humiseal 1H34
Teflon TFE.....	$>10^{18}$	^b
Teflon FEP.....	$>2 \times 10^{18}$	^b

^a Mater. Eng., Materials Selector Issue, vol. 66, no. 5, Chapman-Reinhold Publication, mid-October, 1967–1968.

^b Insulation, Directory Encyclopedia Issue, no. 7, June-July, 1968.

^c Lee, H., and K. Neville: "Epoxy Resins," McGraw-Hill Book Company, New York, 1966.

^d Tucker, Cooperman, and Franklin: Dielectric Properties of Casting Resins, *Electron. Ezutp.*, July, 1956.

^e Freeman, J. H.: A New Concept in Flat Cable Systems, *5th Ann. Symp. on Advan. Tech. for Aircraft Elec. Syst.*, Washington, D.C., October, 1964.

^f Milek, J. T.: Polyimide Plastics: A State of the Art Report *Hughes Aircraft Rep. S-8*, October, 1965.

^g Hockenberger, L.: *Chem.-Ing. Tech.*, vol. 36, 1964.

^h *Hughson Chemical Co. Tech. Bull.* 7030A; *Pennsalt Chemicals Corp. Prod. Sheet* KI-66a, Kynar Vinylidene Fluoride Resin, 1967.

material, one unit on a side, and is expressed as ohm-centimeters or ohm-inches. Surface resistivity is the resistance between two electrodes on the surface of an insulating material in ohms per square centimeter. All materials may be roughly classified according to their ability to conduct or impede the flow of electricity. They range from metals, which are extremely good conductors, to plastics, which are very good insulators. A rough classification of types may be made as follows:

Class	Volume resistivity, ohm-cm
Good conductors.....	10^{-6} – 10^0
Semiconductors.....	10^0 – 10^8
Good insulators (poor conductors).....	10^8 – 10^{12}

Organic coatings are, in general, good electrical insulators and as such are useful for electronic hardware (see Table 9). Although the resistivity of plastics is quite high (usually greater than 10^{12} ohm-cm), and the current which they conduct is considered negligible for most power equipment, still for some electronic assemblies even this small current flow can be a critical factor. Therefore, a knowledge of the electrical tolerances that a circuit or device must meet is important before a coating selection is made. A comparison of volume resistivities of some of the more familiar materials is presented in Fig. 8. The wide difference (up to 24 orders of magnitude) between the most conductive materials such as copper or silver and the least conductive such as polytetrafluoroethylene or polystyrene should be noted.

Effect of Variables on Resistivity: As was pointed out above, resistivity is a constant characteristic of a material. There are, however, many variables which can affect it. First of all, changes in the chemical composition or formulation may have pronounced effects. Besides gross compositional changes, minor amounts of impurities will affect resistivity values. Ionic impurities in plastics coupled with the presence of moisture are known to degrade resistivity values by as much as 6 to 11 orders of magnitude. The degree of cure or advancement in the state of polymerization will affect resistivity values, which increase as the cure of the resin advances.

Variation of resistivity of coatings with temperature is also important. Large decreases in values can occur at elevated temperatures. Hence a coating that is an adequate insulator at room temperature may be completely unsatisfactory when the equipment is operating at higher temperatures. Examples of temperature-resistivity curves for some polymer coating types are given in Fig. 9. Finally, volume- and surface-resistivity values also depend on frequency, voltage, pressure, light (photoconductivity of some organic crystals and polymers), and on the conditioning of the sample.

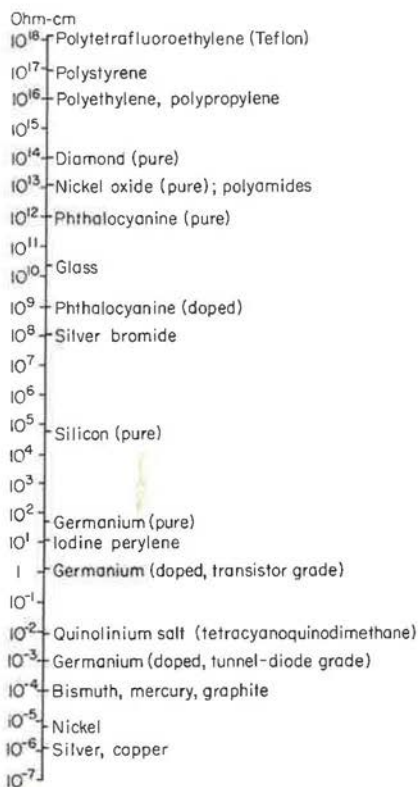


Fig. 8 Comparative electrical resistivities of materials.

Surface Resistivity: Moisture and contaminants have a more pronounced effect on surface resistivity than on volume resistivity. Whereas it may take several days or weeks for volume resistivity to change when subjected to humid or contaminating

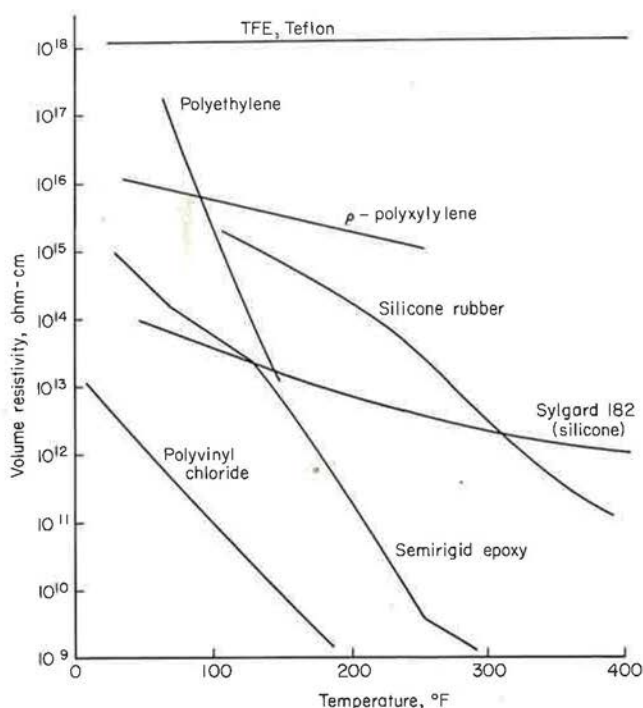


Fig. 9 Electrical resistivity-temperature curves of polymer coating types.

TABLE 10 Effects of Contaminants on Surface Resistivity³¹

Material	Surface resistivity, ohms/sq	
	At 50 % RH	At 96 % RH
Polyethylene (as received).....	$>10^{18}$	2.4×10^9
Polyethylene (contaminated with fingers).....	.....	4.6×10^7
Polyethylene (freshly shaved surface).....	.....	2.2×10^{11}
Polystyrene (as received).....	$\sim 10^{18}$	1.8×10^{11}
Polystyrene (contaminated with fingers).....	.....	5.5×10^9
Polymethyl methacrylate (as received).....	$\sim 10^{18}$	2.0×10^{14}
Polymethyl methacrylate (contaminated with fingers).....	.....	1.2×10^{12}
Clean silica glass.....	10^{16}	5.0×10^8

environments, surface effects are almost immediate. Drastic reductions in surface resistivity occur through contamination, even for coatings that have very high initial values. Table 10 lists some examples.

Conductance and conductivity The reciprocal of resistance is called conductance (expressed in ohms^{-1} or mhos), and the reciprocal of resistivity is the specific

conductance (expressed in $\text{ohms}^{-1}\text{cm}^{-1}$ or mhos/cm). Coatings may be formulated with metal or conductive fillers to render them electrically semiconducting or conducting. These coatings are useful in applications such as providing ohmic contact for circuits and bridging of conductors, providing radio-frequency interference protection, and for the dissipation or bleeding off of electrostatic charges. Silver, gold, copper, and carbon blacks are the most commonly used fillers; whereas epoxies, polyurethanes, silicones, vinyls, and acrylics are typical resin binders. Compositions are available or may be formulated in all viscosities ranging from thick pastes to sprayable types.³²

TABLE 11 Conductivity Data for Metal-filled Plastics
(mhos/cm)

Composition	Cure	Initial	After 40 days humidity cycling	After 50 hr 20 % salt spray
Silver-filled epoxy	6 hr at 350°F	3,000	1,250	1,400
Silver-filled epoxy	Air dry at 36 hr	100	700	
Gold-filled epoxy	6 hr at 120°F	200-700		

Conductivity values vary widely, depending on the conductivity of the filler chosen, the cleaning and processing of the filler particles, and the percentage (loading) of the filler. Except for the noble metals (gold, platinum, etc.), meticulous cleaning of the filler metal is necessary to remove high-resistance surface oxide layers. Even after removal, metal oxides may again slowly form; and over long periods of time or under accelerated conditions, conductivity will decrease. The degree of cure of the resin binder also affects conductivity values and, in general, better values are obtained with the baking-type formulations than with the air-drying varieties (see Table 11).

TABLE 12 Conductive Compositions Analysis

Metal filler	Advantages	Disadvantages
Silver	Very high conductivity	High cost; silver migration can occur under certain conditions; tarnishing and corrosion.
Gold	Very high conductivity, very inert and stable	Cost higher than that of silver. Subject to government controls and audit.
Copper	Low cost, high conductivity	Requires extra steps for cleaning to remove oxides; conductivity values usually decrease on aging.
Carbon blacks (lampblack, acetylene black)	Low cost	Very low conductivity.

For very high conductance, silver or gold fillers are employed; and with optimum formulation and cure, conductivity values of the order of 10^3 mhos/cm may be obtained. A comparison of several conductive compositions is shown in Table 12.

Dielectric constant, dissipation factor, power factor *Dielectric Constant of Materials.* The significance of dielectric constant is described in Chap. 3. As can be seen from the tables, the dielectric constants of gases are low and only slightly greater than one, but values up to 100 are common for many organic compounds, especially the very polar types, and values up to 1,000 are known for some inorganic materials such as barium titanate.

TABLE 13 Dielectric Constants of Polymer Coatings (at 25°C)

Coating	60-100 Hz	10 ⁶ Hz	>10 ⁸ Hz	Reference source
Acrylic.....		2.7-3.2		a
Alkyd.....			3.8 (10 ¹⁰ Hz)	b
Asphalt and tars.....			3.5 (10 ¹⁰ Hz)	b
Cellulose acetate butyrate.....		3.2-6.2		a
Cellulose nitrate.....		6.4		a
Chlorinated polyether.....	3.1	2.92		a
Chlorosulfonated polyethylene (Hypalon).....	6.19	~5		E. I. du Pont
Depolymerized rubber (DPR).....	7-10 (10 ³ Hz)			de Nemours & Co.
	4.1-4.2	3.9-4.0		H. V. Hardman, DPR Subsidiary
Diallyl isophthalate.....	3.5	3.2	3 (10 ⁸ Hz)	a,c
Diallyl phthalate.....	3-3.6	3.3-4.5		a,c
Epoxy-anhydride—castor oil adduct.....	3.4	3.1	2.9 (10 ⁷ Hz)	Autonetics, Division of North American Rockwell
Epoxy (one component).....	3.8	3.7		Conap Inc.
Epoxy (two components).....	3.7			Conap Inc.
Epoxy cured with methyl nadic anhydride (100:84 pbw).....	3.31			d
Epoxy cured with dodecenylsuccinic anhydride (100:132 pbw).....	2.82			d
Epoxy cured with DETA.....	4.1	4.2	4.1	e
Epoxy cured with m-phenylenediamine.....	4.6	3.8	3.25 (10 ¹⁰ Hz)	e
Epoxy dip coating (two components).....	3.3	3.1		Conap Inc.
Epoxy (one component).....	3.8	3.5		Conap Inc.
Epoxy-polyamide (40 % Versamid* 125, 60 % epoxy).....	3.37	3.08		e
Epoxy-polyamide (50 % Versamid 125, 50 % epoxy).....	3.20	3.01		e
Fluorocarbon (TFE, Teflon).....	2.0-2.08	2.0-2.08		E. I. du Pont de Nemours & Co.
Phenolic.....		4-11		a
Phenolic.....	5-6.5	4.5-5.0		c
Polyamide.....	2.8-3.9	2.7-2.96		
Polyamide-imide.....	3.09	3.07		
Polyesters.....	3.3-8.1	3.2-5.9		e
Polyethylene.....		2.3		a
Polyethylenes.....	2.3	2.3		e
Polyimide-Pyre-M.L.† enamel.....	3.8	3.8		f
Polyimide—Du Pont RK-692 varnish.....	3.8			g
Polyimide—Du Pont RC-B-24951.....	3.0 (10 ³ Hz)			g
Polyimide—Du Pont RC-5060.....	2.8 (10 ³ Hz)			g
Polypropylene.....		2.1		a
Polypropylene.....	2.22-2.28	2.22-2.28		c
Polystyrene.....	2.45-2.65	2.4-2.65	2.5 (10 ¹⁰ Hz)	b
Polysulfides.....	6.9			h
Polyurethane (one component).....	4.10	3.8		Conap Inc.
Polyurethane (two components—castor oil cured).....		2.98-3.28		i
Polyurethane (two components).....	6.8 (10 ³ Hz)	4.4		Products Research & Chemical Corp. (PR-1538)
Polyvinyl butyral.....	3.6	3.33		a
Polyvinyl chloride.....	3.3-6.7	2.3-3.5		a
Polyvinyl chloride-vinyl acetate copolymer.....	3-10			a
Polyvinyl formal.....	3.7	3.0		a
Polyvinylidene chloride.....		3-5		a
Polyvinylidene fluoride.....	8.1	6.6		f
Polyvinylidene fluoride.....	8.4	6.43	2.98 (10 ⁸ Hz)	k

TABLE 13 Dielectric Constants of Polymer Coatings (Continued)

Coating	60-100 Hz	10 ⁶ Hz	>10 ⁶ Hz	Reference source
p-Polyxylylene:				
Parylene N.....	2.65	2.65	.....	Union Carbide Corp.
Parylene C.....	3.10	2.90	.....	Union Carbide Corp.
Parylene D.....	2.84	2.80	.....	Union Carbide Corp.
Shellac (natural, dewaxed).....	3.6	3.3	2.75(10 ³ Hz)	†
Silicone (RTV types).....	3.3-4.2	3.1-4.0	.....	General Electric and Stauffer Chemical Cos.
Silicone (Sylgard I type).....	2.88	2.88	.....	Dow Corning Corp.
Silicone, flexible dielectric gel	3.0	.....	.....	Dow Corning Corp.
FEP dispersion coating.....	2.1(10 ³ Hz)	.....	.....	E. I. du Pont de Nemours & Co.
TFE dispersion coating.....	2.0-2.2(10 ³ Hz)	.....	.....	E. I. du Pont de Nemours & Co.
Wax (paraffinic).....	2.25	2.25	2.22(10 ¹⁰ Hz)	†

* Trademark of General Mills, Inc., Kankakee, Ill.

† Trademark of E. I. du Pont de Nemours & Co., Wilmington, Del.

‡ Trademark of Dow Corning Corporation, Midland, Mich.

* Mater. Eng., Materials Selector Issue, vol. 66, no. 5, Chapman-Reinhold Publication, mid-October 1967-1968.

* Volk, M. C., J. W. Lefforge, and R. Stetson: "Electrical Encapsulation," Reinhold Publishing Corporation, New York, 1962.

* Insulation, Directory Encyclopedia Issue, no. 7, June-July, 1968.

* Coombs, C. F. (ed.): "Printed Circuits Handbook," McGraw-Hill Book Company, New York, 1967.

* Lee, H., and K. Neville: "Handbook of Epoxy Resins," McGraw-Hill Book Company, New York, 1967.

* Learn, J. R., and M. P. Seegers: Teflon-Pyre-M.L. Wire Insulation System, 13th Symp. of Tech. Progr. in Commun. Wire and Cable, Atlantic City, N.J., Dec. 2-4, 1964.

* Du Pont Bull. H65-4, Experimental Polyimide Insulating Varnishes, RC-B-24951 and RC-5060, January, 1965.

* Hockenberger, L.: Chem.-Ing. Tech. vol. 36, 1964.

* Spencer-Kellogg (division of Tectron, Inc.) Bull. TS-6593.

* Barnhart, W. S., R. A. Ferren, and H. Iserson: 17th ANTEC of SPE, January, 1961.

* Pennsalt Chemicals Corp. Prod. Sheet KI-66a, Kynar Vinylidene Fluoride Resin, 1967.

* Von Hippel, A. R. (ed.): "Dielectric Materials and Applications," Technology Press of MIT and John Wiley & Sons, Inc., New York, 1961.

Dielectric constants for polymers used for insulating and protective coatings range from 2 to 8. Those coatings that have low dielectric constants and low dissipation factors and are able to maintain these low values over a wide temperature and humidity range are preferred as electrical insulating materials. On the other hand, those combining high dielectric constants and low dissipation factors are useful as capacitors, since they can store and hold large amounts of electric energy.

Dielectric constants of 4.5 maximum at 1,000 Hz and 77°F are normally considered satisfactory for insulating materials used for electronic and electrical assemblies. This is the minimum requirement specified in MIL-I-16923. However, for microelectronic and miniaturized circuitry operating at high frequencies, capacitance effects must be minimized, and materials with lower dielectric constants are necessary. A knowledge of dielectric constants at high frequencies is therefore important to the engineer designing such circuits. Values of dielectric constants at 60 Hz and at 10⁶ (or 1 MHz) are to be found in Table 13.

Dissipation Factor and Power Factor. The dissipation factor D is the ratio of the resistive (loss) component of current I_r to capacitive component of current I_c and equals the tan of the dielectric loss angle δ as follows:

$$D = \frac{I_r}{I_c} = \tan \delta$$

For dielectric materials, the power factor and dissipation factor are essentially equal; and these terms are used interchangeably in the literature. Military specifications call for values no greater than 0.020 at 1,000 Hz and 77°F (MIL-I-16923).

Loss factor is the product of the power factor and dielectric constant and is a measure of signal absorption according to the following equation:

$$\text{Loss factor} \cong \text{watts loss} \cong K \tan \delta \cong KD$$

For all these parameters, low values are desirable, especially for high-speed high-frequency circuitry operating in the 10^1 - to 10^{10} -Hz range.

A low value indicates low conversion of electric energy to heat energy and reduced power loss for the network. The dissipation factor as well as other electrical parameters is dependent upon frequency, temperature, humidity, and purity of the sample. A compilation of dissipation factors is given in Table 14.

DIELECTRIC CONSTANT AND DISSIPATION FACTOR VARIATION WITH TEMPERATURE: At constant frequency, both dielectric constant and dissipation factor for insulating coatings will, in general, increase with increasing temperature. Because coating formulations are not homogeneous but consist of many ingredients that will volatilize or change on heating, electrical values may decrease initially and then increase, or with some materials, may be quite erratic so that no simple straight-line curve can be drawn.

Dielectric strength and breakdown voltage Still another important electrical property is dielectric strength or the ability of a coating to withstand applied voltage without breakdown. It is the maximum voltage (usually reported per mil thickness) at or below which no breakdown occurs. Some prefer to speak about dielectric breakdown, that is, the voltage threshold at or above which actual failure occurs. This is also reported in volts per mil thickness. The two terms are often used interchangeably. The physical breakdown of coatings at a critical voltage is believed to be due to a large increase in electrons (electron avalanche effect) within the insulation.²³ In even the best insulation, a small number of ions and free electrons exist owing to thermal agitation or molecular imperfections. Here a very high voltage will be necessary to cause breakdown. Other less perfect insulation, containing impurities, voids, and moisture, will have lower breakdown voltages.²⁴

Accurate dielectric strength data are important in designing reliable electrical parts of high circuit or component density intended for operating at high voltages. For both low- and high-voltage operating parts, organic coatings are widely used since they have sufficiently high dielectric strength values and are used in sufficient thicknesses so that a very high margin of safety exists. In fact, dielectric strengths for organic coatings are, in general, much higher than for inorganic or ceramic materials.

Dielectric strength values must be carefully obtained under specified conditions to obtain reproducible results and to allow reliable comparisons. A large number of test conditions are known to affect the dielectric strength values. As an example, it is always important to standardize on the electrode configuration and on the thickness of the specimen. Although values are all ultimately reduced to volts per mil thickness, differences in values are obtained, depending on the thickness of the sample used (Figure 10). In general, thin specimens give higher per unit thickness values than thicker ones. In most cases, the thickness specified in the ASTM procedure of 17 mils is too thick to be applicable to coatings. Therefore, this procedure is followed but at lower thicknesses of 2 to 5 mils. Other variables that affect readings are the manner in which the voltage is applied, whether continuously or stepwise; the rate of voltage increase; the frequency of the applied power; the integrity of the coating film (lack of pinholes and air voids); and the purity of the sample. With respect to the last named, the dielectric strength will decrease with an increase in sample imperfections or impurities.

TABLE 14 Dissipation Factors of Polymer Coatings (at 25° C)

Coating	60-100 Hz	10 ⁶ Hz	>10 ⁶ Hz	Reference source
Acrylics.....	0.04-0.06	0.02-0.03	.....	^a
Alkyds.....	0.003-0.06	.....	.....	^a
Chlorinated polyether.....	0.01	0.01	.....	^a
Chlorosulfonated polyethylene.....	0.03	0.07(10 ³ Hz)	.....	^b
Depolymerized rubber (DPR)	0.007-0.013	0.0073-0.016	.....	H. V. Hardman, DPR Subsidiary
Diallyl phthalate.....	0.010	0.011	0.011	^b
Diallyl isophthalate.....	0.008	0.009	0.014(10 ¹⁰ Hz)	^b
Epoxy dip coating (two components)	0.027	0.018	.....	Conap Inc.
Epoxy (one component).....	0.011	0.004	.....	Conap Inc.
Epoxy (one component).....	0.008	0.006	.....	Conap Inc.
Epoxy polyamide (40 % Versamid 125, 60 % epoxy)	0.0085	0.0213	.....	^c
Epoxy polyamide (50 % Versamid 115, 50 % epoxy)	0.009	0.0170	.....	^c
Epoxy cured with anhydride-castor oil adduct	0.0084	0.0165	0.0240	Autonetics, North American Rockwell
Phenolics.....	0.005-0.5	0.022	.....	^a
Polyamide.....	0.015	0.022-0.097	.....	^a
Polyesters.....	0.008-0.041	.....	.....	^a
Polyethylene (linear).....	0.00015	0.00015	0.0004(10 ¹⁰ Hz)	^d
Polymethyl methacrylate.....	0.06	0.02	0.009(10 ¹⁰ Hz)	^d
Polystyrene.....	0.0001-0.0005	0.0001-0.0004	.....	^d
Polyurethane (two component, castor oil cure).....	.....	0.016-0.036	.....	^e
Polyurethane (one component)	0.038-0.039	0.068-0.074	.....	Conap Inc.
Polyurethane (one component)	0.02	.....	.....	Conap Inc.
Polyvinyl butyral.....	0.007	0.0065	.....	^a
Polyvinyl chloride.....	0.08-0.15	0.04-0.14	.....	^a
Polyvinyl chloride, plasticized	0.10	0.15	0.01(10 ¹⁰ Hz)	^d
Polyvinyl chloride-vinyl acetate copolymer.....	0.6-0.10	.....	.....	^f
Polyvinyl formal.....	0.007	0.02	.....	^g
Polyvinylidene fluoride.....	0.049	0.17	.....	^g
Polyxylylenes:	.....	.....	.....	
Parylene N.....	0.0002	0.0006	.....	Union Carbide Corp.
Parylene C.....	0.02	0.0128	.....	Union Carbide Corp.
Parylene D.....	0.004	0.0020	.....	Union Carbide Corp.
Silicone (Sylgard 182).....	0.001	0.001	.....	Dow Corning Corp.
Silicone, flexible dielectric gel	0.0005	.....	.....	Dow Corning Corp.
Silicone, flexible, clear.....	0.001	.....	.....	Dow Corning Corp.
Silicone (RTV types).....	0.011-0.02	0.003-0.006	.....	General Electric
Teflon FEP dispersion coating	0.0002-0.0007	.....	.....	E. I. du Pont de Nemours & Co.
Teflon FEP.....	<0.0003	<0.0003	.....	^a
Teflon TFE.....	<0.0003	.....	.....	^a
Teflon TFE.....	0.00012	0.00005	.....	Union Carbide Corp.
Other materials:	.....	.....	.....	
Alumina (99.5 %).....	.....	0.0001	.....	^h
Beryllia (99.5 %).....	.....	0.0003	.....	^h
Glass silica.....	0.0006	0.0001	0.00017(10 ¹⁰ Hz)	^d
Glass, borosilicate.....	.....	0.013-0.016	.....	Corning Glass Works
Glass, 96 % silica.....	.....	0.0015-0.0019	.....	Corning Glass Works

^a Mach. Des., Plastics Reference Issue, vol. 38, no. 14, Penton Publishing Co., 1966.^b Insulation, Directory, Encyclopedia Issue, no. 7, June-July, 1968.^c Lee, H. and K. Neville: "Handbook of Epoxy Resins," McGraw-Hill Book Company, New York, 1967.^d Mathes, K.: Electrical Insulation Conference, 1967.^e Spencer-Kellogg (Division of Textron, Inc.) Tech. Bull. TS-6593.^f Barnhart, W. S., R. A. Ferren, and H. Iserson: 17th ANTEC of SPE, January, 1961.^g Pennsalt Chemicals Corp. Prod. Sheet KI-66a, Kynar Vinylidene Fluoride Resin, 1967.^h Mach. Des., Design Guide, Sept. 28, 1967.

Atmospheric conditions, such as temperature and humidity, under which the test is carried out are also important variables. A plot of the variation of dielectric strength with temperature shows the same general shaped curve for all polymers. There is fairly little change at low temperature, but a rapid decline occurs above a critical temperature, characteristic of the coating being tested³⁵ (Fig. 11).

Although temperature and moisture exposure have pronounced degrading effects in some cases, final values may still be sufficiently high to be of little concern. As an example, the dielectric breakdown voltage of an 8-mil silicone coating DC630 with an initial 1,000-volt/mil value, dropped to 400 volts/mil after 24 hr immersion in distilled water and to 500 volts/mil after 24 hr exposure at 500°F.³⁶

Several standardized procedures for measuring dielectric strength are available, such as ASTM D 149. A list of dielectric strength values for the commonly used organic coatings and for some ceramic and nonorganic materials is given in Table 15.

Arc resistance Arc resistance is the time in seconds that an arc may play across the surface of a material without rendering it conductive or the time before electrical breakdown occurs along the surface. An arc of high voltage and low current is usually used to simulate service conditions such as those existing in ac circuits operating at high voltages with currents limited to the order of milliamperes. The ASTM D 495 test method,

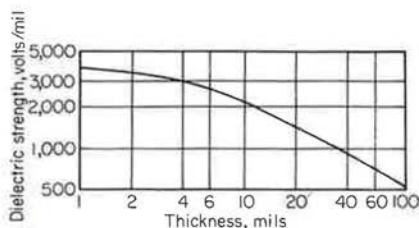


Fig. 10 Effect of coating thickness on dielectric strength of Teflon TFE.

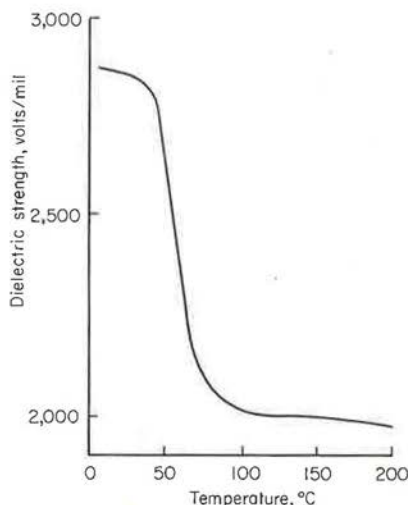


Fig. 11 Temperature dependence of the dielectric strength of polytetrafluoroethylene³⁵ (5-mil film, 1/4-in. electrode).

normally used, calls for exposure of 300 sec or more without failure. There are three modes by which failures due to arcing can occur in organic coatings:

1. By tracking, that is, by the formation of a thin wiry line between the electrodes.
2. By carbonization of the surface due to heating. A conductive path is formed because of the formation of carbonaceous material which has less resistance to the flow of current.
3. The coating may burst into flame without the formation of any visible conducting path.

Not all coatings may be defined in terms of precise arc-resistance values. Some may melt, gum up, or mechanically degrade by cracking. Where precise values are obtained, they will be a function of the inherent stability of the material, the purity of the material, and its surface cleanliness. With regard to the last mentioned, arc resistance may be improved by maintaining the surface dry and free from contaminants. Simply handling the surface with the fingers will reduce the arc resistance because of moisture, salts, and grease contamination transferred from the fingers. Typical arc-resistance values of some polymeric compounds are found in Table 16.

TABLE 15 Dielectric Strengths of Polymer Coatings

Material	Dielectric strength, volts/mil	Comments*	Source of information
<i>Polymer coatings:</i>			
Acrylics.....	450-550	Short-time method	a
	350-400	Step-by-step method	a
	400-530	.....	b
	1,700-2,500	2-mil-thick samples	Columbia Technical Corp., Humiseal Coatings
Alkyds.....	300-350	.....	b
Chlorinated polyether	400	Short-time method	a
Chlorosulfonated polyethylene.....	500	Short-time method	a
Diallyl phthalate.....	275-450	.....	b
	450	Step-by-step method	a
Diallyl isophthalate...	422	Step-by-step method	a
Depolymerized rubber (DPR)	360-380	.....	H. V. Hardman Co., DPR Subsidiary
Epoxy.....	650-730	Cured with anhydride-castor oil adduct	Autonetics, Div. of North American Rockwell
Epoxy.....	1,300	10-mil-thick dip coating	
Epoxies, modified.....	1,200-2,000	2-mil-thick sample	Columbia Technical Corp., Humiseal Coatings
Neoprene.....	150-600	Short-time method	a
Phenolic.....	300-450	.....	b
Polyamide.....	780	106 mils thick	
Polyamide-imide.....	2,700	.....	
Polyesters.....	250-400	Short-time method	a
	170	Step-by-step method	a
Polyethylene.....	480	.....	b
	300	60-mil-thick sample	c
	500	Short-time method	a
Polyimide.....	3,000	Pyre-M.L., 10 mils thick	d
	4,500-5,000	Pyre-M.L. (RC-675)	e
	560	Short-time method, 80 mils thick	a
Polypropylene.....	750-800	Short-time method	a
Polystyrene.....	500-700	Short-time method	a
	400-600	Step-by-step method	a
	450	60-mil-thick sample	c
Polysulfide.....	250-600	Short-time method	a
Polyurethane (single component).....	3,800	1-mil-thick sample	f
Polyurethane (two components)/castor oil cured.....	530-1,010	.....	g
Polyurethane (two components, 100 % solids)	275	125-mil-thick sample	Products Research & Chem. Corp. (PR-1538)
	750	25 mils thick sample	
Polyurethane (single component)	2,500	2-mil-thick sample	Columbia Technical Corp., Humiseal 1A27
Polyvinyl butyral.....	400	.....	
Polyvinyl chloride.....	300-1,000	Short-time method	
	275-900	Step-by-step method	
Polyvinyl formal.....	860-1,000	.....	b
Polyvinylidene fluoride	260	Short-time, 500-volt/sec, 1/4-in. sample	h
	1,280	Short-time, 500-volt/sec, 8-mil sample	h
	950	Step by step (1-kv steps)	h

TABLE 15 Dielectric Strengths of Polymer Coatings (Continued)

Material	Dielectric strength, volts/mil	Comments*	Source of information
Polyxylylenes:			
Parylene N.....	6,000	Step by step	Union Carbide Corp.
	6,500	Short time	Union Carbide Corp.
Parylene C.....	3,700	Short time	Union Carbide Corp.
	1,200	Step by step	Union Carbide Corp.
Parylene D.....	5,500	Short time	Union Carbide Corp.
	4,500	Step by step	Union Carbide Corp.
Silicone.....	500	Sylgard 182	Dow Corning Corp.
Silicone.....	550-650	RTV types	General Electric & Stauffer Chemical Co. bulletins
Silicone.....	800	Flexible dielectric gel	Dow Corning Corp.
Silicone.....	1,500	2-mil-thick sample	Columbia Technical Corp., Humiseal 1H34
TFE fluorocarbons....	400	60-mil-thick sample	"
	480	Short-time method	"
	430	Step by step	"
Teflon TFE dispersion coating	3,000-4,500	1-4-mil-thick sample	E. I. du Pont de Nemours & Co.
Teflon FEP dispersion coating	4,000	1.5-mil-thick sample	E. I. du Pont de Nemours & Co.
<i>Other materials used in electronic assemblies:</i>			
Alumina ceramics.....	200-300	.....	"
Boron nitride.....	900-1,400	.....	"
Electrical ceramics....	55-300	.....	"
Forsterite.....	250	.....	"
Glass, borosilicate....	4,500	40-mil sample	"
Steatite.....	145-280	.....	"

* All samples are standard 125 mils thick unless otherwise specified.

^a *Insulation*, Directory Encyclopedia Issue, no. 7, June-July, 1968.

^b *Mater. Eng.*, Materials Selector Issue, vol. 66, no. 5, Chapman-Reinhold Publication, mid-October, 1967-1968.

^c Kohl, W. H.: "Handbook of Materials and Techniques for Vacuum Devices," p. 586, Reinhold Publishing Corporation, New York, 1967.

^d Learn, J. R., and M. P. Seegers: Teflon-Pyre-M. L. Wire Insulation System, 13th Symp. on Tech. Progr. in Commun. Wire and Cables, Atlantic City, N.J., Dec. 2-4, 1964.

^e Milek, J. T.: Polyimide Plastics: A State of the Art Report, *Hughes Aircraft Rep.* S-8, October, 1965.

^f *Hughson Chemical Co. Bull.* 7030A.

^g *Spencer-Kellogg* (Division of Textron, Inc.) *Bull.* TS-6593.

^h *Pennsalt Chemicals Corp. Prod. Sheet* KI-66a, Kynar Vinylidene Fluoride Resin, 1967.

Environmental Protection

Moisture protection Probably the most important function of coatings for printed circuits and indeed for all electronic assemblies is to act as moisture and gas barriers preventing corrosion and electrical insulation breakdown.

It should be understood that all present state-of-the-art coatings absorb water and are permeable to moisture and other gases to a greater or lesser extent and cannot be considered true hermetic seals in the sense that welded metal packages can. However, it is possible to select plastic coatings that will reduce the rate of moisture transmittance such that assemblies can pass long-term storage and operational requirements.

Failures due to penetration of moisture may be of two types. Moisture mobilizes ionic contaminants in the plastic or on the surface of the device. This results in the normally observed deterioration of electrical insulation or in the formation of inversion layers in semiconductor devices. Secondly, moisture, again in the presence of impurity ions, acts as a vehicle permitting electrolytic corrosion to take place. It is for these reasons that both active and passive devices such as

TABLE 16 Arc Resistances of Polymer Coatings

Material	Arc resistance, sec	Information source
Acrylic.....	35-55	^a
Diallyl phthalate.....	118	^b
Diallyl isophthalate.....	123-128	^b
Epoxy-polyamide (60 % epoxy, 40 % Versamid 125).....	82	^c
Epoxy-polyamide (50 % epoxy, 50 % Versamid 115).....	76	^c
Epoxies, modified.....	45-55	^a
Epoxies.....	45-120	^b
Epoxy (Epocast 202/D40) = A.....	64	^d
A + 100 % silica.....	124	^d
A + 100 % gypsum.....	102	^d
A + 75 % mica.....	79	^d
A + 100 % alumina.....	78	^d
Phenolic.....	Tracks	^b
Polyamide (nylon 6/6).....	140	^b
Polyamide (nylon 6/10).....	130	^b
Polyimide.....	183	^e
Polystyrene.....	60-80	^b
Polyurethanes (two components)—castor oil cured.....	88-140	^f
Polyurethane (one component—air drying).....	40	^a
Polyvinylidene fluoride.....	50-70	^g
Silicones.....	120-200	^h
Silicones (RTV types).....	90-130	^h
Silicone.....	60	^a
Teflon TFE.....	>300	ⁱ
Teflon FEP.....	>300	ⁱ

^a Columbia Technical Corp.: Humiseal Protective Coatings, technical data sheet.

^b *Insulation*, Directory Encyclopedia Issue, no. 7, June-July, 1968.

^c Lee, H. and K. Neville: "Handbook of Epoxy Resins," p. 10-8, McGraw-Hill Book Company, New York, 1967.

^d Delmonte, J.: *Plast. Technol.*, March, 1958.

^e Milek, J. T.: Polyimide Plastics, A State of the Art Report, *Hughes Aircraft Rep.* S-8, October, 1965.

^f Spencer-Kellogg (Division of Textron, Inc.) *Bull.* TS-6593.

^g Pennsalt Chemicals Corp. *Prod. Sheet* KI-66a, Kynar Vinylidene Fluoride Resin, 1967.

^h Dow Corning Corp.: Technical bulletins.

ⁱ E. I. du Pont de Nemours & Co.: Teflon for Electrical and Electronic Systems, technical bulletin, 1964.

transistors, diodes, and resistors are hermetically sealed in metal packages and why entire electronic assemblies are sealed in an inert gas atmosphere. For most commercial applications, hermetic sealing is expensive and impractical. In these cases, organic coatings or plastic encapsulants may provide sufficient protection.

Since all organic coatings are permeable to moisture in varying degrees, quantitative values for their resistance to water are important. Water resistance may be defined in terms of three factors: (1) the percent absorption of water by the coating

at constant temperature over a period of time, (2) the rate of water-vapor transmission through the coating, and (3) survival of coated electronic assembly after simulated or accelerated humidity cycling tests.

Water Absorption. The percentage of water absorption eventually becomes constant at constant temperature for each material. In many cases, however, equilibrium is only achieved after several months of immersion. Unfortunately, most of the reported data are for a 24-hr water immersion and do not give the true

TABLE 17 Water Absorption Data for Polymer Coatings

Material	% absorption in 24 hr*	Source of information
Chlorinated polyether (Penton).....	Negligible	Hercules Powder Co.
Depolymerized rubber.....	0.5	H. V. Hardman, DPR Subsidiary
Diallyl phthalate.....	0.09	^a
Epoxy.....	0.04	^a
Epoxies.....	0.11-1.84	^b
Epoxy cured with DETA.....	0.11-0.12	^c
Fluorocarbon (Teflon).....	0.01	^a
Fluorocarbon (Teflon TFE dispersion coating)	<0.1	Du Pont
Fluorocarbon (Teflon FEP dispersion coating)	<0.01	Du Pont
	0.3-0.4	
Phenolic.....	0.9	^e
Phenoxyl.....	0.13	^d
Polyesters (copolymerized with styrene).....	0.17-0.28	^e
Polyethylene.....	0.01	^a
Polyimide.....	0.7	Union Carbide
Polyimide-amide.....	0.5-1.9 (in boiling water)	
Polystyrene.....	0.04	^a
Polyvinyl fluoride.....	0.04	Product Techniques, Inc., PT-207 Coating
Polyvinyl formal (Formvar).....	0.75-1.1	
Polyvinylidene chloride-polyvinyl chloride (Saran).....	0.05	
Polyvinylidene fluoride.....	0.04	^f
Polyxylylene (Parylene C).....	0.06	Union Carbide
Polyxylylene (Parylene N).....	0.01	Union Carbide
Silicone.....	0.15	^a

* At room temperature, unless otherwise specified.

^a Piser, J.: *Electron. Des.* vol. 17, Aug. 16, 1967.

^b Celanese Corp. *Tech. Bull.* 1164.

^c Lee, H., and K. Neville: "Epoxy Resins," McGraw-Hill Book Company, New York, 1966.

^d Lee, H., D. Stoffey, and K. Neville: "New Linear Polymers," McGraw-Hill Book Company, New York, 1967.

^e Parker, E. E., and E. W. Moffett: *Ind. Eng. Chem.*, vol. 46, p. 1615, 1954.

^f Barnhart, W. S., R. A. Ferren, and H. Iserson: *17th ANTEC of SPE*, January, 1961.

^g "Modern Plastics Encyclopedia" (annual), McGraw-Hill, Inc., New York.

equilibrium values, which are often considerably higher. Twenty-four-hour data will be meaningful and can serve as a means of comparison for applications where they are equal to or more severe than the part will see in actual operation. For the most part, the percent of water absorption is not in itself a very meaningful value. For some coatings, electrical properties are adversely affected, even though only a small amount of water has been absorbed, and conversely, others with very large water absorptions may be quite stable electrically.³⁷ In general, however, surface resistivity and volume resistivity decrease and dissipation factor increases

with increase in percent of water absorbed, and therefore water absorbed or permeating a coating is undesirable and should be avoided.³⁵ It is in this light that comparative water-absorption values should be studied and used (Table 17).

Water-vapor Permeability. Moisture may seep through a coating by one or both of two mechanisms. One involves passage through microcracks, channels, or pinholes arising from imperfections in the coating. Pinholes and pores can be reduced considerably by applying a number of consecutive coats, each one further reducing the pinhole probability. The second mechanism is one inherent with the molecular structure of polymer molecules and within polymers.

This water-vapor permeability or moisture-vapor transmission rate (MVTR) is more significant than water absorption in defining water resistance. It is expressed according to the equation

$$\text{MVTR} = \frac{Ql}{a \Delta p}$$

where MVTR = g/(hr)(cm²)(cm/cm Hg)

Q = water vapor permeating the film, g

l = film thickness, cm

a = film area, cm²

t = time, hr

Δp = vapor-pressure difference, cm Hg

Organic coating polymers differ widely in permeability rates because of differences in their molecular structures. An example of this is polyvinylidene chloride (Saran),^{*} a material which because of its polar chloro groups, is an excellent moisture barrier.

Permeability is also a function of the nature and amount of pigment or filler used. Coatings have decreasingly lower permeabilities as pigment is increased up to a critical pigment-volume ratio, after which the permeability rises sharply. Pigments in flake form such as aluminum will considerably improve resistance to moisture penetration. Several other factors that affect permeability are as follows:

Factor	Usual effect on permeability
1. Solvent entrapment.....	Increase
2. Plasticizers.....	Increase
3. Structure of film:	
Polar.....	Increase
Nonpolar.....	Decrease
4. Degree of crosslinking.....	Decrease

A list of permeabilities may thus serve as a preliminary selection guide (Table 18). The list should not be used as the sole basis for selection because these values are usually obtained by testing carefully fabricated films for the test. In actual usage, a sprayed or dipped coating may contain many imperfections such as pinholes, solvent entrapment, and contaminants, all of which increase its porosity.

Humidity Testing. Both water-absorption and water-permeability values may serve as preliminary data for selecting coatings for further evaluation. As was pointed out above, to ensure long-term reliability, electronic assemblies should be subjected to long-term or accelerated environmental testing. A humidity test such as that called out in MIL-E-5272 or MIL-STD-202B is one of the most severe and critical. Generally, the test requires a 10-day exposure to moisture in both the vapor and condensate forms with temperature cycling from 25 to 65°C. A 100-volt dc applied stress is also required according to MIL-STD-202B. The test is an accelerated one but does give an indication of the long-term reliability of the assembly under outdoor and operating conditions. Because of the variety of

* Trademark of Dow Chemical Company, Midland, Mich.

substrates, metal combinations, and sensitive components, very few pieces of uncoated hardware will pass this test without serious physical or electrical degradation. Even when a protective coating is employed, care should be taken in selecting one that will not only shield the assembly but also will not itself degrade by blistering, lifting, whitening, softening, or absorbing excessive amounts of water. Unfortunately, since coating formulations vary widely, it is impossible to give a list of good coatings and poor ones from which to select. It is imperative that humidity testing of some sort be performed in each case before recommendation and use.

TABLE 18 Moisture-vapor Transmission Rates (MVTR) of Plastic Coatings and Film (in g/(mil)(in.²)(24 hr)

Coating or film	MVTR	Information source
Epoxy-anhydride.....	2.38	Autonetics data (25°C)
Epoxy-aromatic amine.....	1.79	Autonetics data (25°C)
Neoprene.....	15.5	Baer ²⁹ (39°C)
Polyurethane (Magna X-500).....	2.4	Autonetics data (25°C)
Polyurethane (isocyanate-polyester)	8.72	Autonetics data (25°C)
Olefane,* polypropylene.....	0.70	Avisun data
Cellophane (type PVD uncoated film)	134	Du Pont
Cellulose acetate (film).....	219	Du Pont
Polycarbonate.....	10	FMC data
Mylar†.....	1.9	Baer ²⁹ (39°C)
	1.8	Du Pont data
Polystyrene.....	8.6	Baer ²⁹ (39°C)
	9.0	Dow data
Polyethylene film.....	0.97	Dow data (1-mil film)
Saran resin (F120).....	0.097 to 0.45	Baer ²⁹ (39°C)
Polyvinylidene chloride.....	0.15	Baer ²⁹ (2-mil sample, 40°C)
Polytetrafluoroethylene (PTFE).....	0.32	Baer ²⁹ (2-mil sample 40°C)
PTFE, dispersion cast.....	0.2	Du Pont data
Fluorinated ethylene propylene (FEP)	0.46	Baer ²⁹ (40°C)
Polyvinyl fluoride.....	2.97	Baer ²⁹ (40°C)
Teslar.....	2.7	Du Pont data
Parylene N.....	14	Union Carbide data (2-mil sample)
Parylene C.....	1	Union Carbide data (2-mil sample)
Silicone (RTV 521).....	120.78	Autonetics data
Methyl phenyl silicone.....	38.31	Autonetics data
Polyurethane (AB0130-002).....	4.33	Autonetics data
Phenoxy.....	3.5	Lee, Stoffey, and Neville ⁴⁰
Alkyd-silicone (DC-1377).....	6.47	Autonetics data
Alkyd-silicone (DC-1400).....	4.45	Autonetics data
Alkyd-silicone.....	6.16-7.9	Autonetics data
Polyvinyl fluoride (PT-207).....	0.7	Product Techniques Incorp.

* Trademark of Avisun Corporation, Philadelphia, Pa.

† Trademark of E. I. du Pont de Nemours & Co., Wilmington, Del.

Corrosion protection Coatings are applied to metal surfaces where protection from the corrosive effects of the surrounding medium is necessary. The most commonly encountered corrosive environments are listed in Table 19. In most cases, elevated temperature will accelerate the degradation effects due to these environments.

Metals corrode in different ways depending on their nature and the environment to which they are exposed. A partial list of the various modes of failure for the metals and alloys commonly employed in electronic assemblies is given in Table 20.

In general, corrosion occurs by either a chemical or an electrochemical process. In either process, moisture is invariably necessary. Hence the moisture barrier and

TABLE 19 Environments and Their Corrosive Constituents

Environment	Corrosive constituents
1. Normal air ambient.....	Moisture, oxygen, sulfur dioxide, carbon dioxide
2. Water immersion.....	Calcium salts and other metal salts
3. Salt-water immersion or salt spray	Sodium and chloride ions, marine organisms
4. Chemicals and solvents.....	Numerous acids, bases, oxidizing or reducing agents, solvents strippers, etc. which may come into contact with the part during processing or operation.
5. Soil.....	Moisture, fungus, other microorganisms

resistance of a coating become a key factor in corrosion prevention. For many metals, oxide inorganic films will normally form on storage in air. These films are quite passive and will arrest the further degradation of the metal. In other cases, artificially produced inorganic coatings may be formed; and these will also provide

TABLE 20 Corrosion Modes for Metals and Alloys Commonly Used in Electronic Assemblies

Metal/Alloy	Type of corrosion
Copper.....	Thermal-air exposure results in black oxidation product. Forms green copper carbonate (verdigris) which inhibits further corrosion except as accelerated by galvanic coupling. Exposure to salt environment produces high electrical resistance due to formation of copper salts.
Copper-nickel alloys.....	Tarnishes in sulfur-containing ambients.
Copper-beryllium alloys.....	Tarnishing in sulfur-containing ambients and in moist air.
Aluminum (pure or 5052, 6061, 1100, 3003)	White oxide formations, normally superficial with no structural damage.
Aluminum high-strength alloys: 2024, 2014.....	Susceptible to tunneling, exfoliation, and stress corrosion.
7075, 7079.....	Susceptible to stress corrosion.
Aluminum alloys, general.....	Galvanic corrosion from dissimilar metal couples.
Magnesium AZ31B.....	Rapid local dissolving occurs at breaks in metallic coatings or at points of coupling with nobler metals. Oxidizes slowly in moist air.
Magnesium-lithium alloy.....	Interaction of moisture with the lithium portion of the alloy results in rapid evolution of hydrogen and formation of white lithium hydroxide. Organic protective coatings used are permeable to moisture and become blistered and lift owing to hydrogen generation. This alloy also reacts with carbon dioxide from the ambient to give white lithium carbonate.
Magnesium-thorium alloy.....	Very susceptible to moist ambient.
Beryllium.....	Stable in air. On heating in air, forms a metal oxide protective layer. Will react rapidly with methyl alcohol. Attacked by alkalies with evolution of hydrogen.
Nickel.....	Little corrosion problem except for galvanic couples. Very stable in air and water owing to presence of nickel oxide layer.
Solder (lead-tin).....	Little corrosion problem except for galvanic couple, such as with copper. Tin salts produced.
Silver.....	Black silver sulfide "tarnish" on exposure to ambient due to interaction with SO ₂ and H ₂ S contaminants in air.
Gold.....	Extremely inert, no corrosion products.

the same protection. These films, called chemical conversion coatings, are formed by the reaction of the metal surface with oxygen, phosphates, chromates, or other chemicals. Other passive films are electrochemically formed, such as the anodized films. For very harsh environments or for very long-term exposure, organic coatings are applied over these conversion coatings and provide a very effective barrier system. Lacquers, baking enamels, and highly resistant epoxies, vinyls, polyurethanes, or silicone coatings are often used.

Wide differences in the effectiveness of these coatings are possible because of differences in surface preparation and cleanliness of the substrate and in thickness of the coating. In general, the thicker the coating, the better corrosion protection is afforded. Thickness affords protection by reducing the probability of imperfections in the coating, by increasing protection from abrasion and mechanical damage during use, and by increasing the moisture resistance of the film.

Magnesium. Because of its high strength-to-weight ratio, good fatigue strength, and good dimensional stability, magnesium has become a very popular metal for electronic applications, especially those intended for flight hardware. Heat sinks, housings, coolant tubes, and frames are but a few examples of the use of magnesium. For benign environments such as indoor exposure or a black box containing inert gas, a protective finishing system is usually not necessary. Even for normal weathering or short-term intermittent outdoor exposure, an electrochemical conversion coating alone or a single coating of clear lacquer may provide sufficient protection.

Other chemical treatments, useful as protective coatings in themselves or as bases for primers and topcoats, are Dow Chemical Treatments No. 1 (chrome pickle); No. 7 (dichromate); and No. 19 (dilute chromic acid).⁴¹ The treatments most commonly used for electronic hardware are Dow 17, HAE, or fluoride anodizing, which are excellent paint bases for long-term exposure to humid and salt environments; Dow 7, used for a corrosion-protective paint base; and Dow 19, used as a touch-up applied by brush, spray, or swab for rework on Dow 7 or Dow 17 surfaces. The various treatments are compared in Table 21.

These surface treatments are all acid types in order to either neutralize or acidify the normally alkaline magnesium surface. Suppression of alkali formation is essential in improving the durability and adhesion of paints and coatings. To be effective, primers for magnesium should be based on alkali-resistant vehicles such as polyvinyl butyral (as contained in wash primers), acrylic, polyurethane, vinyl, epoxy, or baked phenolic. Zinc chromate, strontium chromate, and basic zinc chromate are often employed as further corrosion inhibitors.^{41,42}

For severe or extensive exposure as encountered in ground-support, ground-operating equipment, or marine equipment, the best finish system will usually consist of three parts: a conversion coating, a primer, and finally an organic topcoat.

Magnesium-Lithium Alloys. Magnesium-lithium alloys such as LA141 are attractive to designers of airborne electronic equipment because of their stiffness and high strength-to-weight ratio. By using these alloys, a 20 to 25 percent weight savings over magnesium or other magnesium alloys may be achieved. However, the high reactivity of magnesium-lithium with moisture and carbon dioxide limits their use to hermetically sealed boxes with inert gas ambients. Often, even in an enclosed box, an incompatible situation may arise owing to the evolution of moisture from plastics or from electronic components contained in the box. Moisture reacts with the lithium portion of the alloy, forming hydrogen gas and lithium hydroxide. In the presence of carbon dioxide, white lithium carbonate is formed on the alloy surface. In addition to the formation of these chemical corrosion products and deterioration of the alloy, a secondary, perhaps even more harmful effect may result by the evolution and reaction of hydrogen gas with active devices, chemically sensitive thick- or thin-film resistors and other components. Although there are reported to be several coatings which will protect magnesium-lithium in normal environments, no organic coating or coating system is currently known to provide adequate protection to pass military environmental specifications such as MIL-E-5272, temperature and humidity cycling, or MIL-STD-151, salt-spray test.⁴³

TABLE 21 Chemical and Anodic Treatments Used in Finishing of Magnesium¹¹

Name	Type	Military specification	Appearance	Alloys used on	Uses	Remarks
Dow 1.....	Chrome pickle	MIL-M-3171A —type 1	Matte gray to yellow-red	All	For protection during shipment and storage.	Simple dip treatment, slight dimensional loss, good paint base.
Dow 7.....	Dichromate	MIL-M-3171A —Type 3	Brassy to dark brown	All except Th-containing alloys	Good combination of paint base and protective qualities.	Does not materially affect dimensions.
Dow 9.....	Galvanic anodize	MIL-M-3171A —Type 4	Dark brown to black	All	Used on alloys that will not take No. 7 or where a black coat is needed.	Requires galvanic couple between work and steel cathode. No external current required.
Dow 10....	Sealed chrome pickle	MIL-M-3171A —Type 2	Matte gray to yellow-red-brown	All	Corrosion resistance equal to No. 7.	Chrome pickle plus dichromate boil. Improved protection over No. 1. Slight dimensional loss.
Dow 17....	Anodize thin	MIL-M-45202	Light gray to light green	All	Excellent protective and decorative finish.	Thin: 0.0001 to 0.0003 in.
Dow 17....	Heavy	MIL-M-45202	Dark green	All	Excellent protective and decorative finish.	Full: 0.001 to 0.0015 in.
Dow 23....	Stannate immersion	None	Medium to dark gray	All	Good paint base and protective finish. Used with dissimilar metal inserts (except aluminum or in assemblies).	Coating is stable above melting point of metal. Best abrasion resistance, best paint base, and most consistent of all Dow treatments for magnesium. License required.
HAE.....	Anodize	MIL-M-45202 MIL-C-13335 AMA 2476	Tan to brown	All	Excellent protective and decorative finish. Good paint base.	Must be neutralized if painted. Retards galvanic corrosion. License required.
Fluoride....	Anodize	Proprietary	Light gray	All	Good base for resin impregnation or painting. Very clean surface.	H. A. Evangelides, at Pitman-Dunn Lab, Frankford Arsenal. Dr. W. F. Higgins, Magnesium Elektron, Ltd.

Tin-Lead. For maximum protection of solder joints and solder-plated surfaces, conformal coatings should be used.⁴⁴ However, as with other metals, corrosion can be prevented or minimized by employing certain design principles. For example, bimetallic combinations of tin-lead solder with either copper or aluminum should be avoided in high-humidity or salt-water environments where corrosion is known to occur.⁴⁵ The coating of such bimetallic combinations will only provide temporary protection. Other difficulties associated with corrosion of solder joints or solder

TABLE 22 Resistance of Coating Resins to Microorganisms⁴⁶

Coating type	Resistance to attack
Acrylic.....	G
Alkyd.....	P
Cellulosics:	
Cellulose acetate.....	G to P
Cellulose acetate butyrate.....	G
Cellulose nitrate.....	P
Ethylcellulose.....	G
Chlorinated rubber.....	G
Chlorosulfonated polyethylene.....	G
Epoxy-amine.....	G
Epoxy-polyamide.....	G
Epoxy-phenol-formaldehyde.....	G
Epoxy-urea-formaldehyde.....	G
Melamine-formaldehyde.....	G to P
Phenol-formaldehyde.....	G to P
Phenoxy.....	G
Polyester.....	G
Polyethylene:	
Low molecular weight.....	P
High molecular weight.....	G
Polychlorofluoroethylene.....	G
Polyisobutylene.....	G
Polystyrene.....	G
Polyurethane.....	P
Polyvinyl acetate.....	P
Polyvinyl butyrate.....	P
Polyvinyl chloride.....	G*
Polyvinyl chloride-acetate.....	G
Polyvinylidene chloride.....	G to P
Polyvinylidene fluoride.....	G
Silicone.....	G
Silicone-alkyds.....	G to P
TFE fluorocarbon.....	G
Urea formaldehyde.....	G

* Except when plasticized.

G Good

P Poor

plate are caused by the incomplete removal of corrosive fluxes during cleaning operations. Conformal coatings will not provide protection unless these contaminants are adequately removed. A discussion of cleaning procedures for flux residues is given in another section.

Aluminum. Like magnesium, aluminum is also widely used because of its low weight. It, too, must be protected from corrosion, although the normal oxide film which forms on its surface on exposure to air is protective and prevents deterioration of the bulk of the metal. A number of oxide coatings (anodize) may be purposely formed, as are chemical surface treatments such as chromates, to function

as protective coatings or to improve the adhesion of subsequent organic coatings.

Microorganism Protection. As with moisture and salt spray, microorganisms also cause millions of dollars of loss per year due to material deterioration.

Microbial growth may cause corrosion of metals and bimetallic combinations, may deteriorate a coating or substrate mechanically or electrically, or may roughen a surface, causing an increase in friction and drag; the latter property being especially critical for underwater vehicles. The resistance of coatings to biological attack from microorganisms such as fungi, bacteria, etc., is particularly important for electronic hardware that will be stored or operated in humid, tropical, or semitropical environments, or contact of moist soil. Table 22 gives some coating resins and the resistance to attack.

As a rule, the newer synthetic coatings such as epoxies, silicones, and polyurethanes possess excellent fungus-resistance properties. Some formulations may not be as good as others because of plasticizers or other nutrient additives used in the formulation.

Thermal protection One of the more destructive influences on most organic materials is heat and high temperature. The heat transfer (conductivity) of organic materials compared to that of air spaces is excellent, but compared to metals, or even some ceramics, it is very poor.

Heat Resistance. Heat degradation is an effect of time and temperature. Hence, one usually refers to temperatures that can be resisted for short, intermittent times (minutes or hours) or to temperatures for the long term or "service life" (months or years). A rough value for representative type coatings can be found in Table 1.

Thermal Conductivity. The total heat conducted through a material is directly proportional to the surface area, time of contact, and temperature gradient, and inversely proportional to the thickness of the sample according to Eq. (1),

$$Q \propto \frac{(T_2 - T_1)At}{d} \quad (1)$$

where Q = total heat flow

A = surface area, cm^2

d = thickness of sample, cm

T_2 = temperature of the hot surface, $^{\circ}\text{C}$

T_1 = temperature of the cold surface, $^{\circ}\text{C}$

t = time, in seconds

When a proportionality constant k is introduced, the equation becomes

$$Q = \frac{k(T_2 - T_1)At}{d} \quad (2)$$

The constant k is a material constant called the *coefficient of thermal conductivity*. It is the time rate of heat flow under steady-state conditions, through a unit area and unit thickness, per unit temperature gradient.

Organic coatings, as a rule, are seldom used for the prime purpose of conducting heat away. Unfilled coatings and plastics have rather low k values and are very good thermal barriers or insulators. Furthermore, there is very little difference in thermal conductivity among the different polymer types; the order of magnitude is about 10^{-4} $\text{cal}/(\text{sec})(\text{cm}^2)(^{\circ}\text{C}/\text{cm})$. This value is to be compared with those for metals or metal oxides which are thousands of times higher. Table 23 gives some representative thermal conductivities for coatings and other electronic materials.

From a design standpoint, the low thermal conductivity of organic coatings may be desirable as in the case of ablative and thermal protective materials, or undesirable as in the case of high heat-dissipating electronic assemblies.

For the most part, plastics used in intimate contact with electronics such as spacers, filleting compounds, substrates, heavy coatings, and encapsulants require high thermal conductance. Assemblies or modules having a high density of electronic components require the dissipation of large amounts of heat. Properly insulated metal heat sinks or beryllium oxide spacers are commonly employed. No plastic yet exists

TABLE 23 Thermal Conductivity Data for Polymer Coatings

Material	k value,* cal/(sec)(cm ²) (°C/cm) × 10 ⁴	Source of information
<i>Unfilled plastics:</i>		
Acrylic.....	4-5	^a
Alkyd.....	8.3	^a
Depolymerized rubber.....	3.2	H. V. Hardman, DPR Sub- sidiary
Epoxy.....	3-6	^b
Epoxy (electrostatic spray coating).....	6.6	Hysol Corp., DK-4
Epoxy (electrostatic spray coating).....	2.9	Minnesota Mining & Mfg., No. 5133
Epoxy (Epon† 828, 71.4 % DEA, 10.7 %)	5.2	^c
Epoxy (cured with diethylenetriamine)	4.8	
Fluorocarbon (Teflon TFE).....	7.0	Du Pont
Fluorocarbon (Teflon FEP).....	5.8	Du Pont
Nylon.....	10	^d
Polyester.....	4-5	^a
Polyethylenes.....	8	^a
Polyimide (Pyre-M.L. enamel).....	3.5	^e
Polyimide (Pyre-M.L. varnish).....	7.2	^f
Polystyrene.....	1.73-2.76	^g
Polystyrene.....	2.5-3.3	^a
Polyurethane.....	4-5	ⁿ
Polyvinyl chloride.....	3-4	^a
Polyvinyl formal.....	3.7	^a
Polyvinylidene chloride.....	2.0	^a
Polyvinylidene fluoride.....	3.6	^h
Polyxylylene (Parylene N).....	3	Union Carbide
Silicones (RTV types).....	5-7.5	Dow Corning Corp.
Silicones (Sylgard types).....	3.5-7.5	Dow Corning Corp.
Silicones (Sylgard varnishes and coat- ings).....	3.5-3.6	Dow Corning Corp.
Silicone (gel coating).....	3.7	Dow Corning Corp.
Silicone (gel coating).....	7 (150°C)	Dow Corning Corp.
<i>Filled plastics:</i>		
Epon 828/diethylenetriamine = A.....	4	^b
A + 50 % silica.....	10	^b
A + 50 % alumina.....	11	^b
A + 50 % beryllium oxide.....	12.5	^b
A + 70 % silica.....	12	^b
A + 70 % alumina.....	13	^b
A + 70 % beryllium oxide.....	17.8	^b
Epoxy, flexibilized = B.....	5.4	ⁱ
B + 66 % by weight tabular alumina	18.0	ⁱ
B + 64 % by volume tabular alumina	50.0	ⁱ
Epoxy, filled.....	20.2	Emerson & Cuming, 2651 ft Wakefield Engineering Co. International Electronic Research Co.
Epoxy (highly filled).....	15-20	
Polyurethane (highly filled).....	8-11	
<i>Other materials used in electronic assem- blies:</i>		
Alumina ceramic.....	256-442 (20-212°F)	^a
Aluminum.....	2767-5575	^a
Aluminum oxide (alumina), 96 %.....	840	ⁱ
Beryllium oxide, 99 %.....	5500	ⁱ
Copper.....	8095-9334	^a
Glass (Borosill, 7052).....	28	^k
Glass (pot-soda-lead, 0120).....	18	^k

TABLE 23 Thermal Conductivity Data for Polymer Coatings (Continued)

Material	k value,* cal/(sec)(cm ²) (°C/cm) × 10 ⁴	Source of information
Glass (silica, 99.8 % SiO ₂)	40	<i>l</i>
Gold	7104 (20–212°F)	<i>a</i>
Kovar	395	<i>m</i>
Mica	8.3–16.5	<i>a</i>
Nichrome†	325	<i>m</i>
Silica	40	<i>k</i>
Silicon nitride	359	<i>m</i>
Silver	9995 (20–212°F)	<i>a</i>
Zircon	120–149	<i>a</i>

* All values are at room temperature unless otherwise specified.

† Trademark of Shell Chemical Co., New York, N.Y.

‡ Trademark of Driver-Harris Co., Harrison, N.J.

^a *Mater. Eng.*, Materials Selector Issue, vol. 66, no. 5, Chapman-Reinhold Publication, mid-October, 1967.

^b Wolf, D. C., *Proc. Nat. Electron. and Packag. Symp.*, New York, June, 1964.

^c Lee, H., and K. Neville: "Handbook of Epoxy Resins," McGraw-Hill Book Company, New York, 1966.

^d Davis, R.: *Reinf. Plast.*, October, 1962.

^e *Du Pont Tech. Bull.* 19, Pyre-M.L. Wire Enamel, August, 1967.

^f *Du Pont Tech. Bull.* 1, Pyre-M.L. Varnish RK-692, April, 1966.

^g Teach, W. C., and G. C. Kiessling: *Polystyrene*, Reinhold Publishing Corporation, New York, 1960.

^h Barnhart, W. S., R. A. Ferren, and H. Iserson: 17th ANTEC of SPE, January, 1961.

ⁱ Gershman, A. J., and J. R. Andreotti: *Insulation*, September, 1967.

^j *American Lava Corp. Chart 651.*

^k Shand, E. B., "Glass Engineering Handbook," McGraw-Hill Book Company, 1958.

^l Kingery, W. D.: *Oxides for High Temperature Applications*, *Proc. Int. Symp.*, Asilomar, Calif., October, 1959, McGraw-Hill Book Company, New York, 1960.

^m Kohl, W. H.: "Handbook of Materials and Techniques for Vacuum Devices," Reinhold Publishing Company, New York, 1967.

ⁿ "Modern Plastics Encyclopedia," McGraw-Hill, Inc., New York, 1968.

combining the high thermal conductivity and low electric conductivity of beryllia, which is unique among materials in this respect.

Where some degree of thermal conduction in organic coatings is required, one or both of two approaches may be used: (1) employing a coating that is formulated with a high, thermally conductive filler and/or (2) employing as thin a coating layer as possible, since thermal conduction is inversely related to thickness. In practice, it is found that what is gained in filling a coating is lost in that the coating may be more difficult to apply in thin layers. Except for those cases where electrical conductivity is not a problem, fillers used should be good electrical insulators. Commonly used fillers meeting these requirements are aluminum oxide (Al₂O₃) also known as alumina, silicon dioxide (SiO₂) also known as silica, mica, and beryllium oxide (BeO), known as beryllia. The improvement in the thermal conductivity of an Epon 828-diethylenetriamine (DEA) formulation by filling it with silica, aluminum, or beryllium, oxide is about three-to-fourfold but still far below the thermal conductivity of the filler alone. There is a scarcity of thermal conductivity data for coatings, probably due to the difficulty in preparing thick enough samples to run the thermal conductance. Many of these materials reported are molding or casting types where thick enough samples can be formed (see Table 23).

Test Methods. Several methods for measuring thermal conductivity are available, of which the Cenco-Fitch and the Guarded Hot Plate methods are the most widely

used. The most accurate method for plastic samples having thermal conductivities of 3.4×10^{-3} or less (most filled or unfilled plastics will fall in this category) is the guarded hot-plate method described in ASTM C 177.⁴⁷ A discussion of this and other methods is given by Anderson.⁴⁸

The Cenco-Fitch method is based on the calorimeter principle, in which the sample to be measured is placed between a constant-temperature heat source and a heat drain (an insulated copper plug), and the heat transfer over a period of time is accurately measured. The procedure is given in ASTM D 1674 and MIL-I-16923.

For fairly accurate results, this method requires a uniform pinhole-free, air-free sample of 0.125 in. thickness.

TABLE 24 Abrasion Resistance of Organic Coatings

Coating	Taber wear index, mg/kHz
Polyurethane Type 1.....	55-67
Polyurethane Type 2 (clear).....	8-24
Polyurethane Type 2 (pigmented).....	31-35
Polyurethane Type 5.....	60
Urethane oil varnish.....	155
Alkyd.....	147
Vinyl.....	85-106
Epoxy-amine-cured varnish.....	38
Epoxy-polyamide enamel.....	95
Epoxy-ester enamel.....	196
Epoxy-polyamide coating (1:1).....	50
Phenolic spar varnish.....	172
Clear nitrocellulose lacquer.....	96
Chlorinated rubber.....	200-220
Silicone, white enamel.....	113
Catalyzed epoxy, air-cured (PT-401).....	208
Catalyzed epoxy, Teflon-filled (PT-401).....	122
Catalyzed epoxy, bake-Teflon-filled (PT-201).....	136
Parylene N.....	9.7
Parylene C.....	44
Parylene D.....	305
Polyamide.....	290-310
Polyethylene.....	360
Alkyd TT-E-508 enamel (cured for 45 min at 250°F).....	51
Alkyd TT-E-508 (cured for 24 hr at room temperature).....	70

The buildup of such thick coatings presents a problem with many solvent-based coatings but can be achieved by multiple coating and baking operations. As with the guarded hot-plate method, thinner coatings or coatings on a metal substrate may be used but with less accuracy.

Mechanical Protection

Abrasion and frictional resistance For applications involving excessive handling, rubbing, or other contact with objects, a high degree of abrasion resistance will be required. For other applications where repeated sliding or insertions must take place as in some electronic drawers or consoles, surfaces with a low coefficient of friction will render the insertions easier and will minimize surface abrasion and deterioration of the coating.

Abrasion Resistance. Abrasion resistance may be determined by periodic examinations performed while the coating is in actual use. However, several accelerated and quantitative test methods are available that may be correlated with actual service performance or used to compare the relative abrasion resistances of coatings. These include projection of a controlled stream of abrasive such as Carborundum^o

^o Trademark of The Carborundum Co., Niagara Falls, N.Y.

(ASTM D 658-44) or sand (ASTM D 968-51) against the sample and recording the amount of abrasive required to wear through a unit thickness of coating, use of abrasive tape (Armstrong test, ASTM D 1242), controlled scraping with a metal tool until the coating is penetrated,⁴⁹ or use of rotating abrasive wheels. The last mentioned (referred to as the Taber Abrasion Test) is the most widely used for plastic coatings and is described in Federal Test Methods 141 No. 6192 and ASTM Methods D 412 and D 1044. According to the last-mentioned test, abrasion is effected through the action of two standardized abrading wheels made to rotate against the coating sample. The sample consists of a 4- by 4-in.-square coated metal panel having a center spindle hole. The panel is preweighed to the nearest milligram and placed on a turntable operating at a constant speed while two abrad-

TABLE 25 Coefficients of Friction of Typical Coatings

Coating	Coefficient of friction, μ	Information source
Polyvinyl chloride.....	0.4-0.5	a
Polystyrene.....	0.4-0.5	a
Polymethyl methacrylate.....	0.4-0.5	a
Nylon.....	0.3	a
Polyethylene.....	0.6-0.8	a
Polytetrafluoroethylene (Teflon).....	0.05-0.1	a
Catalyzed epoxy air-dry coating with Teflon filler.....	0.15	b
Parylene N.....	0.25	c
Parylene C.....	0.29	c
Parylene D.....	0.31-0.33	c
Polyimide (Pyre-M.L.).....	0.17	d
Graphite.....	0.18	d
Graphite-molybdenum sulfide:		
Dry-film lubricant.....	0.02-0.06	e
Steel on steel.....	0.45-0.60	e
Brass on steel.....	0.44	e
Babbitt on mild steel.....	0.33	e
Glass on glass.....	0.4	e
Steel on steel with SAE no. 20 oil.....	0.044	e
Polymethyl methacrylate to self.....	0.8 (static)	e
Polymethyl methacrylate to steel.....	0.4-0.5 (static)	e

^a Bowder, F. P., *Endeavor*, vol. 16, no. 61, p. 5, 1957.

^b Product Techniques Incorporated: Bulletin on PT-401 TE, Oct. 17, 1961.

^c Union Carbide data.

^d *Du Pont Tech. Bull.* 19, Pyre-M.L. Wire Enamel, August, 1967.

^e Electrofilm, Inc. data.

ing wheels each ½-in. wide are fixed on each side of the spindle and in direct contact with the coating.

A load up to 1,000 g may be placed on the wheels in addition to their own weight. A built-in tachometer records the number of turntable revolutions, and a vacuum attachment removes plastic particles as they are abraded from the surface. The instrument is operated for a specific number of cycles or until a portion of the substrate becomes exposed. Results are reported as weight loss in milligrams for a specified number of cycles ranging from 100 to 1,000, referred to as Taber Wear Index, or may be reported as the number of cycles to failure per mil thickness of coating. Quantitative data for a number of coatings may be found in Table 24.

Coefficient of Friction. The coefficients of friction of plastics, with exceptions such as some fluorocarbons, are of the same order of magnitude as metals. With plastics, however, values are more dependent on test conditions such as temperature, humidity, loading, operating speed, and on material conditions such as degree of

cure and moisture content. As an example, the coefficient of friction of nylon will vary from 0.91 to 1.19, with a variation of moisture content from 0.2 to 10 percent, respectively.⁵⁰ The surface against which the sample is tested is also an important variable. A highly polished steel surface is often used, but polished glass or wood have also been employed. In any event, the nature of this surface should be specified.

Teflon appears to be unique among both plastics and metals in possessing one of the lowest friction coefficients. The coefficients of friction of nylon and of some specially formulated epoxies and polyurethanes containing Teflon fillers, although not as low as for Teflon, are still considered satisfactory for many sliding or insertion applications. The use of Teflon as a filler for epoxy coatings can reduce the coefficient of friction and the Taber Wear Index (Tables 24 and 25).

TABLE 26 Sward Hardness Values for Coatings
(Polished Glass = 100)

Coating	Value	Information source
Two-component polyurethane (polyester cure).....	68	a
Two-component polyurethane (castor oil cure).....	46	a
Chlorinated rubber.....	12	a
Epoxy.....	22	a
Polyvinyl.....	6	a
Polyurethane clear coating (TDI-castor oil).....	10	b
Polyurethane clear coating (MDI-castor oil).....	17	b
Polyurethane (moisture cure) ASTM, Type 2.....	48	c
Acrylics.....	~20	d
Epoxy-amine paint (PT-401)*.....	18-22	e
TT-E-489B, Class A*.....	13	e
TT-E-489, Class A*.....	5-8	e
MIL-E-7729, Type I*.....	8	e
TT-E-529, Class A*.....	7	e
Kemaacryl M49WC15 (Sherwin-Williams), acrylic*.....	12	e
Aero Cati-Coat F55W-P-20 (Sherwin-Williams), epoxy*.....	26	e
TT-E-527, alkyd*.....	3-4	e
MIL-E-15090, Type III, alkyd, Class I*.....	5-7	e
MIL-E-7729, Type III, alkyd (baked 15 min at 320°F).....	8-9	e
MIL-L-7178, nitrocellulose*.....	11-12	e

* Cure 7 days at room temperature.

^a Chem. Eng., Feb. 9, 1959, pp. 144-148.

^b Dombrow, B. A.: "Polyurethanes," Reinhold Publishing Corporation, New York, 1965.

^c Patton, T. C.: *J. Paint Technol.*, vol. 39, no. 512, September, 1967.

^d Teach, W. C., and G. C. Kiessling, "Polystyrene," Reinhold Publishing Corporation, New York, 1960.

^e Autonetics Materials and Processes Laboratories data.

Hardness Hardness values are also valuable in establishing how resistant a coating may be to erosion, scratching, or other mechanical abuse. One of the more popular methods for determining hardness makes use of the Sward hardness tester. Values obtained are relative to polished plate glass which is taken as 100. Although the Sward hardness test is nondestructive, it often cannot be used on an actual part because the tester will accommodate only a flat (about 0.032-in.) surface from 3 by 6 in. to about 4 by 12 in. Sward hardness values for some coatings and paints are presented in Table 26.

The pencil hardness test employs the use of a series of pencils of varying hardness to scratch through the coating to the substrate. It is simple but highly subjective and destructive in nature. Numerous other hardness and scratch tests have been developed.⁵¹

APPLICATION TECHNOLOGY

Cleaning and Cleaning Methods

The efficient cleaning of an assembly prior to coating is critical to the performance of the coating and the assembly. Surface contaminants cause poor adhesion, resulting in peeling, or leave water-soluble materials that cause blistering and corrosion, especially after humidity exposure. Therefore, proved cleaning procedures should always be specified. A discussion of cleaners, methods, and equipment follows.

Potential contaminants Contamination, always a serious problem, has become critical for high-density microelectronics, where the active portions of the device may be of the same size as the contaminant particle. Ultraclean areas, such as Class 100 clean rooms,³² laminar-flow work stations, spray booths, and ovens, should always be employed for these highly sensitive operations. Some of the commonest contaminants to be found on electronic hardware are categorized in Table 27.

TABLE 27 Typical Contaminants and Their Sources

Contaminant	Possible source
Fibers (nylon, cellulose, etc.)	Clothes of personnel in assembly areas, cleaning papers
Silicates, fly ash	Rocks, sand, soil
Oxides and scale	Oxidation products from some metals
Oils and greases	From machining, fingerprints, handling, hair sprays, tonics, and ointments
Silicones	Hair sprays, shaving cream, aftershave lotions, hand lotions, and soap
Metals	Grinding, machining, and fabricating metal parts, storage cans, metal containers
Ionic residues	Perspiration, fingerprints (sodium chloride), residues from cleaning solutions containing ionic detergents, certain fluxes such as the glutamic acid hydrochloride types, residues from previous chemical steps such as etching or plating
Nonionic residues	Rosin fluxes, nonionic detergents, organic processing material
Solvent residues	Cleaning solvents

The incomplete removal and entrapment of these contaminants under a coating may result in electric short circuits, corrosion, deterioration of the coating, and increased penetration of moisture and contaminants through the degraded coating. Several dramatic examples of the seriousness of leaving fingerprint contaminants may be cited. In thin-film circuits the entire disappearance of Nichrome resistors has been observed when tested with applied voltage in a humid environment. In another instance fingerprints left under the coating become visible after humidity exposure through blistering of the coating over the fingerprints.

To establish a scientific basis for the selection of a cleaning method, the coatings specialist should answer the following questions:

1. What contaminants are on the surface?
2. How damaging are they?
3. How can they be removed?
4. What tests can be used to assure complete removal of contaminants?

These are all difficult questions to answer.

An empirical approach is often used to establish the cleaning method. A number of cleaning solutions and methods may be tried, and the one found to be most convenient or least expensive is selected. If no trouble is encountered, no further work is performed.

A number of cleaning techniques which have been employed are described below. To evaluate the method, the contaminants must first be detected and monitored in some fashion to assure the effectiveness of the cleaning procedures. Examples

are by magnification, by rendering the particles fluorescent or radioactive, or by determining the wettability or the water break-free surface properties.

Solvents and Solutions Used for Cleaning. Cleaning solvents and solutions may be classified in three groups, according to Table 28. The hydrophobic types are those that will effectively remove water-insoluble contaminants such as greases, oil, or organic material. The hydrophilic types will easily remove water-soluble contaminants such as ionic salts. Since both types of contaminants are normally present on electronic assemblies, a safe practice is to use both types of cleaners in a two-step process or to use a combination cleaner-of the hydrophobic-hydrophilic type. A dramatic example of what can happen if only the hydrophobic solvent is used is shown in Fig. 12. In example *a*, where only the hydrophobic solvent was used, considerable blistering of the coating occurred after humidity whereas in example *b* where both hydrophobic and hydrophilic (aqueous solution) solvents were used, no blistering occurred.

TABLE 28 Cleaning Solution Types

-
- | |
|---|
| I. Hydrophobic |
| Organic solvents—methyl ethyl ketone |
| Freons* |
| Chlorinated solvents, such as trichloroethylene |
| II. Hydrophilic |
| A. Alkaline, acid, detergent-water solutions |
| B. Nonionic, detergent-water |
| C. Water deionized or distilled |
| D. Alcohols such as isopropanol or ethanol |
| III. Hydrophobic-hydrophilic |
| A. Alcohol-naphtha (50:50) |
| B. TWD-602 (a Freon-water emulsion-containing surfactant) |
-

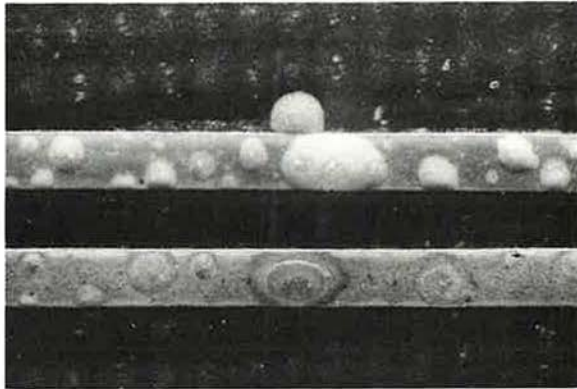
* Trademark of E. I. du Pont de Nemours & Co., Wilmington, Del.

Solvent Purity. Solvents used in cleaning may contain varying amounts of particulate contaminants and nonvolatile residues. Though amounts may be extremely small, such residues may be critical to the performance of the electronics. The purity of the cleaning media may be determined by residue from evaporation, by conductivity of water extract for ionizable matter, and particle-count analysis after filtering through standard-size membranes.²³

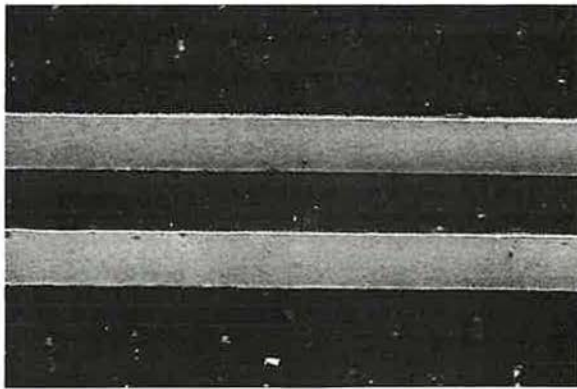
Nature of Particles. In interpreting particle-analysis results, not only the amount but also the nature of the particles is important. The identification of particles after they have been separated requires considerable skill and experience. A widely used procedure involves microscopic examination and comparison with standards. Descriptions and photographs of hundreds of particles may be found in "The Particle Atlas."²⁴ Metal particles, even in small quantities, are serious. For example, even a single metal particle, wedged between two closely spaced conductors can be catastrophic. An electric short circuit could occur immediately; or, in time, ionic corrosion could be produced. Metal particles have been detected in several commercial-grade cleaning solvents and have probably been introduced from storage cans or during the transfer of solvent from one container to another. Other particles such as fibers, greases, and soil minerals have been isolated and identified and could be detrimental, depending on the application. For space applications, some firms are specifying that deionized water and other solvents must contain no particles larger than 20 microns in size. The purest commercial solvents seldom meet this requirement; and if they do initially, they will quickly become contaminated through storage conditions and handling. It is a safe practice for all microelectronic fabrication processes to use solvents and cleaning solutions that have been filtered through

membrane filters just before use.⁵⁵ The two major suppliers of membrane filters in the United States are Millipore Corporation and Gelman Industries.

Many Federal and Military Specifications are available for the procurement of solvents and chemicals, but few are tight enough to provide control over the very small amounts of particulate contamination that has just been described. Hence, many firms have found it necessary to supplement these specifications with their own, calling out the tighter requirements.



(a)



(b)

Fig. 12 Effect of aqueous cleaning in preparing circuit boards for coating. (a) Test board D-D prepared without aqueous cleaning. (b) Test board Y-Y prepared with aqueous cleaning.

Cleaning methods There are essentially three mechanisms by which contaminants may be removed from a surface. These are:

1. By dissolving in the solvent or cleaning solution used. An example is the dissolving of salt in water.

2. By reacting chemically to give products that can be dissolved. Examples include the removal of metal oxides and scale by acid or alkaline treatments.

3. By being dislodged mechanically and then removed with liquids. Examples include metal and fiber particles removed by jet spray or ultrasonic energy. In practice, cleaning methods employ combinations of two or all three of these mechanisms to achieve most efficient cleaning.

A limited number of basic cleaning methods exist, but numerous modifications and combinations of these basic types are possible and are being used. The basic methods are:

1. Solvent spray
2. Solvent dip
3. Brush
4. Vapor degrease
5. Ultrasonic immersion
6. Pulsating spray

Vapor Degreasing. Vapor degreasing is a very widely used and efficient method for cleaning electronic parts. According to this method, the part is suspended in a specially designed chamber (commercially available) so that the vapors of a heated solvent condense on and flush the surface clean. The part is thus being washed repeatedly with fresh solvent as opposed to hand scrubbing or other manual cleaning methods where the solvent is stagnant and soon becomes contaminated. Combinations of vapor condensation and clean liquid spray are also used (Fig. 13). Detailed instructions for vapor degreasing are given in the literature.⁵⁶ The two most widely used vapor-degreasing solvents for removing greases and

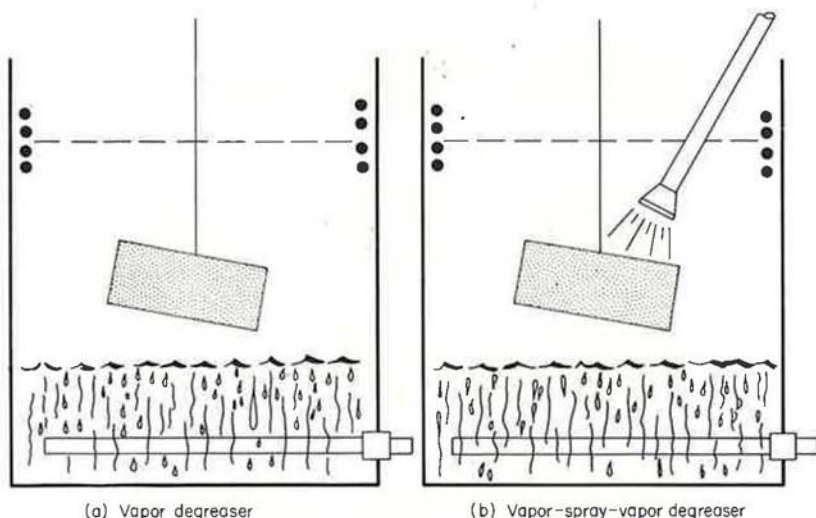


Fig. 13 Two types of commonly used vapor degreasers.

other hydrophobic contaminants are trichloroethylene and perchloroethylene. They may be purchased from a number of manufacturers under different trade names. Both are relatively nontoxic and stable. Trichloroethylene, will contain stabilizers to prevent hydrolytic breakdown, whereas perchloroethylene, because of its unreactive structure, requires little or no stabilization. As with other cleaning methods, the compatibility of these solvents with the substrates should be verified before they are specified for production parts. For example, it is reported that with some circuit-board laminates, cleaning with trichloroethylene causes leaching-out of resin, delamination, and discoloration effects.

Ultrasonic Cleaning. One of the best and most effective methods of cleaning employs an ultrasonically agitated solvent bath into which the part to be cleaned is immersed. Because of the high energy imparted to the solvent, contaminants are rapidly and easily removed, even from difficultly accessible areas. According to the method, sound vibrations at frequencies higher than 20,000 Hz (usually 20 to 40 kHz) are imparted to a liquid solvent or cleaning solution. This results

in what is called *cavitation* or the rapid formation and sudden collapse of thousands of microscopic bubbles in the liquid. The transfer of such energy to the part to be cleaned thus results in a very strong scrubbing action. Ultrasonic generators, and indeed complete ultrasonic cleaning systems, are available from a number of equipment manufacturers.

Ultrasonic cleaning is a very rapid process requiring only a few minutes per part and lends itself well to automated production lines. A large number and variety of off-the-shelf solvents and cleaning solutions are available, and many others have been formulated to achieve removal of very specific contaminants. The solvents used are limited only to the corrosion which they may impart to the tank, to their toxicity or flammability if any, and to their vibration dampening characteristics. Concentrated detergent solutions and acetone have high dampening effects and are not as effective as other solvents such as the Freons. The solvent is normally kept at room temperature, however. Water detergent or alkaline solutions are more effective at slightly elevated temperatures of 100 to 140°F. Ultrasonic agitation will itself heat the solution in time.²⁷

Although it is one of the most effective methods, ultrasonic cleaning has several limitations that should be recognized. For example, as the cleaning bath becomes contaminated, it will require frequent filtering or purification of the solvent or periodic replenishment with fresh solvent.

Secondly, mechanically fragile components such as glass diodes and other glass-sealed semiconductor devices have been known to fail catastrophically owing to the ultrasonic cracking of the glass or by lead separation. Where such failures do not immediately occur, there is always the question of the effect that ultrasonic stresses can have on the reliability and life expectancy of the device. Therefore, ultrasonic cleaning has found its greatest usefulness in the cleaning of bare substrates or of circuits prior to the attachment of sensitive devices.

Pulsating-spray Cleaning. The pulsating-spray method is unique in that the fresh solvent or cleaning solution used is pulsed at frequencies of 20,000 to 30,000 Hz at the time it is sprayed. The spray impinges upon the part at a pressure of about 500 psi. The main advantages of this high-energy method over ultrasonic cleaning are the avoidance of cavitation erosion of metal surfaces and the elimination of recontamination from drag-out or static dip-tank rinsing. A commercially available pulsating-spray unit is the Heinicke parts washer manufactured by the Heinicke Corporation. The equipment has been used successfully for cleaning printed-circuit boards, wiring, wire harnesses, and many other electronic and electrical parts. A completely automated cleaning cycle for such a washer consists of (1) a high-pressure wash combining pulsating jet stream of cleaning solution, (2) tap water rinse, and (3) final rinse using distilled or deionized water.

Pulsating-spray cleaning has been shown to be one of the most efficient methods for removing particulate contamination 5 microns or larger in size. Most of the work has employed aqueous detergent cleaners followed by hot tap water and filtered deionized water rinses. However, the equipment also lends itself to the use of organic solvents. Each operation is automatically timed to a predetermined cycle with a total cleaning time seldom exceeding 5 min. The number of parts that can be cleaned simultaneously is limited only by their size and orientation within the washer.

Application Methods

Because of the wide variety and complexity of electrical and electronic parts to be coated, there are presently in use numerous application methods. The coating of tiny semiconductor junctions on the one hand and thousands of feet of wire on the other, impregnation of all voids in huge motor rotors and stators, and applying ultrathin continuous dielectric layers on the thin-foil wrap of a capacitor require various and often ingenious deposition and polymerization techniques.

About a dozen major application methods exist. Some are amenable to rapid and even mechanized production, whereas others are very specialized, being suitable to the treatment of but one part at a time. A discussion of the coating processes

TABLE 29 Application Methods for Coatings

Method	Advantages	Limitations	Typical applications
Spray.....	Fast, adaptable to varied shapes and sizes. Equipment cost is low.	Difficult to completely coat complex parts and to obtain uniform thickness and reproducible coverage.	Motor frames and housings, electronic enclosures, circuit boards, electronic modules.
Dip.....	Provides thorough coverage, even on complex parts such as tubes and high-density electronic modules.	Viscosity and pot life of dip must be monitored. Speed of withdrawal must be regulated for consistent coating thickness.	Small- and medium-sized parts, castings, moisture and fungus proofing of modules, temporary protection of finished machined parts.
Brush.....	Brushing action provides good "wetting" of surface, resulting in good adhesion. Cost of equipment is lowest.	Poor thickness control; not for precise applications. High labor cost.	Coating of individual components, spot repairs, or maintenance.
Roller.....	High-speed continuous process; provides excellent control on thickness.	Large runs of flat sheets or coil stock required to justify equipment cost and setup time. Equipment cost is high.	Metal decorating of sheet to be used to fabricate cans, boxes.
Impregnation	Results in complete coverage of intricate and closely spaced parts. Seals fine leaks or pores.	Requires vacuum or pressure cycling or both. Special equipment usually required.	Coils, transformers, field and armature windings, metal castings, and sealing of porous structures.
Fluidized bed	Thick coatings can be applied in one dip. Uniform coating thickness on exposed surfaces. Dry materials are used, saving cost of solvents.	Requires preheating of part to above fusion temperature of coating. This temperature may be too high for some parts.	Motor stators; heavy-duty electrical insulation on castings, metal substrates for circuit boards, heat sinks.
Screen-on....	Deposits coating in selected areas through a mask. Provides good pattern deposition and controlled thickness.	Requires flat or smoothly curved surface. Preparation of screens is time-consuming.	Circuit boards, artwork, labels, masking against etching solution, spot insulation between circuitry layers or under heat sinks or components.
Electrocoating	Provides good control of thickness and uniformity. Parts wet from cleaning need not be dried before coating.	Limited number of coating types can be used; compounds must be specially formulated ionic polymers. Often porous, sometimes nonadherent.	Primers for frames and bodies, complex castings such as open work, motor end bells.
Vacuum deposition....	Ultrathin, pinhole-free films possible. Selective deposition can be made through masks.	Thermal instability of most plastics; decomposition occurs on products. Vacuum control needed.	Experimental at present. Potential use is in microelectronics, capacitor dielectrics.
Electrostatic spray	Highly efficient coverage and use of paint on complex parts. Successfully automated.	High equipment cost. Requires specially formulated coatings.	Heat dissipators, electronic enclosures, open-work grills and complex parts.

most commonly used in the electronics industry is given in the following sections. Ten of these processes, their advantages, disadvantages, and typical applications, are summarized in Table 29.

Spray coating The most widely used application method for electrical coatings is by spraying. Spraying in this case includes not only the common compressed-air vaporization, but also airless pressure spray, hot spray, hot vapor-impelled spray, electrostatic spray, dry-powder resin spray, electrostatic powder spray, and even the ubiquitous aerosol spray can.

Pressure Liquid Spray. Most liquid-spray methods employ the basic principle of atomizing the paint into a fine mist which is directed upon the surface to be coated. Atomization is accomplished by the use of compressed air, pressurized volatile solvents, or high-velocity jet stream. With the proper technique, a thin but continuous wet layer of lacquer or enamel may be deposited without rundown of drips or "sags" and without excessive "orange peel" or the unsightly "sandiness" of dry overspray. A skilled spray operator can apply a very uniform coating and can usually touch up defective areas during the process or later.

In applying coating to objects such as circuit boards having discrete components, the operator should build up the total desired thickness by spraying from four different directions so as to cover the top and all sides of components and to force coating underneath the components as well. Freedom from pinholes, skips, or voids should be a major consideration for such environmental protective coatings. Turntables, either hand- or power-rotated, are useful in orienting the work for directional spraying. Parts conveyers can be utilized to move parts past a spray painter or past automatic spray heads, as in the case of fully mechanized painting lines. Parts platforms or holders can be mounted on rotating spindles to make all surfaces accessible to the paint spray.

All paint spraying should, of course, be done in a ventilated booth which exhausts the overspray and solvent vapors to the outside or preferably to a fume and solvent trap system. Not only are the fumes and paint aerosol obnoxious, but also they may be a flammability hazard, or may be toxic, especially when inhaled from repeated exposures.

Vapor Spray (Pressurized Volatile Solvents). For solventless, very high viscosity coatings which are difficult or impossible to apply by the conventional techniques of spraying or dipping, the Zicon vapor carrier or spray method* may be employed. Zicon equipment is successfully being used by many companies for applying viscous coatings to circuit boards and other electronic assemblies. This technique utilizes a preheated, dry, inert vapor such as that of a hydrocarbon, in place of compressed air, to atomize and transport the coating to the part. Besides its ability to apply viscous coatings, other advantages of this method include precision control of thickness, surface uniformity, and coating integrity. The probability of pinholes and other imperfections due to moisture or contaminants is virtually eliminated because the hydrocarbon gas used is dry, inert, and of high purity, and because the console such as the series 9000 (Zicon) employs an ultraclean horizontal laminar-flow chamber.

A second advantage, deriving from the first, is that dry film coating thicknesses from 3 to 30 mils may be easily applied, simply by continuous spraying. Thus, heavy conformal coatings may be applied not only for protection, but also for vibration damping and ruggedization. Zicon sprayers are used for applying conformal coatings to printed-circuit boards, photoresists for integrated circuit and semiconductor device manufacture, magnetic oxide coatings to memory disks, and numerous types of protective coatings to metal substrates. Commonly used coating types are epoxies, polyurethanes, and fluorocarbons.

Airless Spray (High-velocity Jet Stream). One disadvantage of pressure air spraying is the tendency for the blown cloud of atomized paint to "swirl" out of recesses, holes, and corners owing to the velocity of the accompanying airstream, leaving these areas lightly coated or bare. Airless spray equipment has been developed

*Marketed and trademarked by the Zicon Corporation, Mount Vernon, N.Y.

(available from firms such as Nordson Corporation or the Gray Company) which depends, not on atomization by high-velocity air, but on producing the spray pattern by forcing the material under high pressure through tiny orifice nozzles. The coating material, which is circulated continuously in the storage system, is normally also heated to reduce its viscosity and to volatilize solvents more rapidly. This system is efficient, especially for coating parts with many recesses or for coating the inside of hollow objects.

Hot-melt Flame Spraying. According to the hot-melt flame-spray method, a cloud of powdered resin suspended in air is interjected into a special spray gun and melted on being blown through the flame-shrouded nozzle of the gun. The melted plastic solidifies immediately on impinging on the object. This technique is limited to plastics that are stable above their melting temperatures. Powders used are normally thermoplastics such as polyethylenes, polypropylenes, other polyolefins, and polytetrafluoroethylenes. Techniques have also been worked out for spraying even some unstable plastics providing they have a sufficiently long induction period before decomposition occurs.⁶⁹

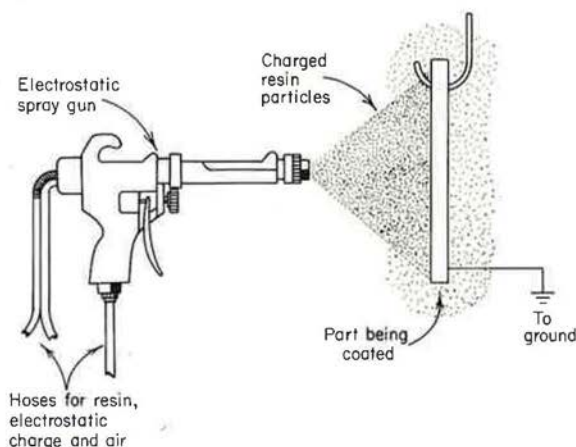


Fig. 14 Electrostatic spray-coating technique.

Other Spray Equipment. Coatings, such as epoxies or polyurethanes, provide a high degree of chemical and solvent resistance but have been difficult to apply in production because they are two-component systems and have relatively short pot lives. Equipment is now available which facilitates the application of these two-component coatings. This equipment continuously proportions and mixes the two components and feeds the mixture to the spray head or extrusion nozzle for application. After loss of solvent, if any, from the film, the coating readily polymerizes under the proper curing conditions of temperature and time.

Electrostatic spray coating Several modifications of the spray method have been developed and are in use. One of these, the electrostatic spray process, developed by the Ransburg Electro-Coating Company, is extensively used for coating objects having intricate shapes or a high proportion of open areas. The technique consists in the deposition of negatively charged spray-paint droplets or plastic powders onto a metal part. The particles are rendered electrostatic as they are propelled through a diffuser on the front of the spray gun and are then rapidly attracted to the part (Fig. 14). Subsequent drying or curing of paint is done by usual methods, whereas powdered-resin coatings are fused in as little as 20 to 60 sec at 400°F, or at lower temperatures for a longer period of time.

Rules governing other forms of liquid spraying apply to electrostatic spraying. In powdered-resin spraying, coatings may be applied in thicknesses from 2 to over

20 mils, depending on the plastic powder selected. The method is very amenable to thermoplastic coatings, but thermosetting types such as epoxies are being used extensively.

Particular advantages of the electrostatic spray process over other spray processes include the high deposition efficiency whereby very little material is lost as overspray and the uniform buildup that can be obtained in one application, saving time and cost. Paint savings of 25 to 50 percent over conventional spray coatings are not uncommon. The process is also less susceptible to human errors, lending itself very well to automated production and to the coating of a wide variety of metal articles. In the electronics industry, for example, this method is valuable for the electrical insulation and corrosion-protective coating of heat dissipators (Fig. 15), metal brackets, "black box" enclosures, circuit-board housings, and motor armatures and stators before winding.

Dip coating As the name implies, dip coating involves the immersion of a part into a liquid composition (or dry powder, in the case of fluidized-bed coating), withdrawal, and drying or curing. It is a highly desirable method from the stand-

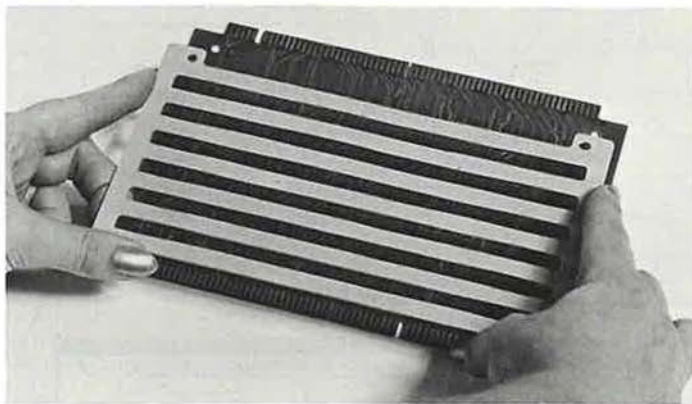


Fig. 15 Heat-sink rail electrostatically insulated with epoxy coating.

point of achieving a continuous automated manufacturing operation and has the advantage over spray coating of assuring coverage of all areas and crevices. Dip coating is most suitable for one-component plastic systems having sufficiently long pot lives. Since many of the high-reliability coatings used in electronics production are two-component systems of limited pot life, it therefore has limited usage. Techniques that have been used to maintain a stable dip bath include:

1. Replenishing solvents (lost by evaporation) to maintain constant viscosity
2. Refrigerating or maintaining the dip bath at a low temperature to extend its pot life

The final thickness of a dip-coated part (which may range from a fraction of a mil to several hundred mils) is dependent upon the viscosity of the bath, the rates of immersion and withdrawal, the temperature of the bath, and the number of dips. Adequate drainage must be provided to avoid trapping liquid coating in pockets or recesses in the part. Continued paint flow after withdrawal of the part may result in "tears" along the edge of the part, which may be removed by "touching off" or by electrostatic removal. Adequate air drying to remove solvents is recommended since entrapped volatiles may result in blistering of the coating upon subsequent oven curing. Hot-dip coating may be used to ensure greater wettability and minimize pinholes. This variation consists of preheating the part (where allowable) to an elevated temperature, followed by dipping into a bath maintained at room temperature, and results in faster drying or even fusion of the coating, as in plastisol dipping.

Here preheated parts are dipped in vinyl plastisol, which becomes gelled by the heat, leaving a solid layer on the surface. The cooler outer layer which is picked up on withdrawal remains liquid and drains off. An alternative technique involves dipping parts at ambient temperature into a molten resin such as asphalt, in which solidification of the coating occurs on removal from the bath and cooling. These coating resins will normally be of a thermoplastic type.

With high-viscosity coatings, such as the 100 percent solid types, numerous air bubbles may be entrapped after mixing of the two components. In these instances a technique commonly employed with encapsulants—vacuum degassing—may be used. Evacuation of the mixture, at 25 to 20 in. mercury (about water aspirator pressure) for several minutes, is recommended.

Fluidized bed A unique variation of dip coating and one that is finding ever-increasing uses is the fluidized-bed process, also known as the aerated-bed process. The basic process and modifications of it are the subject of numerous patents,

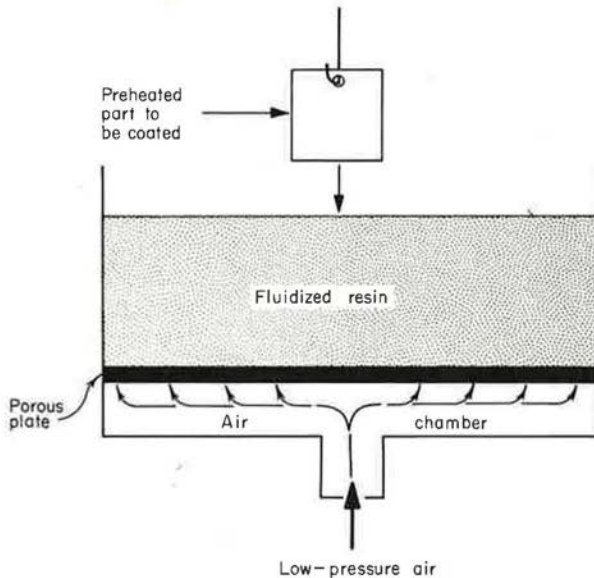


Fig. 16 Fluidized-bed-coating technique.

both in the United States and in other countries.^{20,69} According to the method, dry powdered resins or partially reacted powdered coatings are placed in a container in which they are suspended and set in motion by controlled velocity air introduced from the bottom of the container through a screen and porous membrane (see Fig. 16). The resultant low-density powder is in constant motion and behaves like a low-viscosity, low-surface-tension fluid. The part to be coated is then preconditioned by one of several methods to promote adhesion of the particles to the surface and then is dipped into the fluidized powdered resin. The principal pretreatment methods are as follows:

1. Preheating the part (usually metal) to a temperature above that required to melt and fuse the plastic powder.
2. Applying a thin adhesive primer. This patented proprietary process has an advantage over preheating in that areas of a part may be selectively coated.
3. Applying an electrostatic charge to the part, to attract oppositely charged coating particles.

In all three cases, the part is normally heated in an oven after removal from the fluidized bed. For epoxy and other thermosetting coatings, this postbaking step

results in further fusing and curing the coating, thus improving its physical and electrical properties. For thermoplastic coatings, the postbaking operating is important in smoothing out the surface and in obtaining a less porous coating.

Process Parameters. The number of process parameters for fluidized-bed coatings is very large, with a list of at least 20 being reported.⁶¹ However, once these parameters have been optimized, fixed, and controlled, the process can be automated and gives highly reproducible results.^{62,63}

The thickness of the coating deposited depends on a number of factors, including time of immersion (Fig. 17), heat retention of the part, mass of the part, and characteristics of the powder. Probably the most important parameter is the ability of the part to retain heat, which, in turn, is a function of the specific heat, thermal conductivity, thermal stability, and mass of both the part and the coating material.

Coating Materials. Both thermoplastic and thermosetting coatings can be applied by fluidized bed. Some thermoplastic materials, notably vinyls and polyethylenes, can often be completely fused by the heat retained in the preheated part; thermosetting coatings usually require postcuring after the dipping step. Epoxies, chlorinated polyethers, polyethylene, and silicones are other examples of coatings commonly applied by fluidized bed. Although TFE and FEP fluorocarbon powders may be applied by fluidized bed, very little practical use has been found here, probably because of the very high preheat temperature required and adhesion problems. Poor adhesion is a problem common to other coatings also, and in these cases primers should always be used.

Examples include cellulose acetate butyrate, nylons, and vinyls. Other coating types such as epoxies, polyethylenes, and chlorinated polyether normally do not require the use of primers. A list of some powder coating types and some important deposition parameters is given in Table 30. A list of some proprietary formulations and manufacturers is given in Table 31.

Sprayed-powder Process. The sprayed-powder process involves the spraying of powdered coatings onto preheated metal parts using flock-coating spray guns. As in the fluidized-bed process, powder particles contacting a hot surface will fuse, forming an integral coating. Flocking spray guns may be purchased from DeVilbiss (no. GB), Binks (no. 171), Paasche (FF 3/4 in.), and others. The same powders sold for fluidized-bed coating are normally used for spray-powder coating (see Table 31).

Electrostatic Fluidized-bed Process. As the name implies, this process combines elements of both the fluidized-bed and the electrostatic spray processes. The normal fluidized bed is used, but, in addition, the plastic particles are given a negative charge by applying a high-voltage (~90,000-volt) direct current to the container. The part to be coated is then given the opposite electric charge and suspended in the bed, so that the charged particles can be attracted toward the part.

Advantages and Limitations. The main advantage of the fluidized-bed process is that it allows the application of coatings without use of solvents, and in rather thick films (5 to 25 mils) in only one or two dips. These thicknesses are not readily achieved by other coating methods. Rather complex parts having sharp edges and corners are easily and uniformly coated. Extra-thick coatings thus produced solve many chemical, solvent, erosion, and corrosion problems. Other advantages over the conventional methods of liquid dipping and spraying include: (1) lower cost because of the elimination of waste material; (2) greater ease of handling

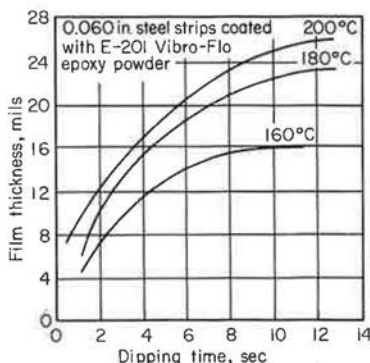


Fig. 17 Effect of preheat temperature and immersion time on coating thickness when fluidizing a steel bar with epoxy fluidizing material. (Armstrong Products Corp.)

TABLE 30 Summary of Plastics for Fluidized Bed Coating

Resin	Fluidizing conditions			Fluidized-bed powder		
	Preheat temperature, °F	Cure or fusion		Maximum operating temperature, °F	Adhesion	Weather resistance
		Temperature, °F	Time, min			
Epoxy.....	250-450	250-450	1-60	200-400	Excellent	Good
Vinyl.....	450-550	400-600	1-3	225	Poor	Good
Cellulose acetate butyrate.....	500-600	400-550	1-3	225	Poor	Good
Nylon.....	550-800	650-700	1	300	Poor	Fair
Polyethylene.....	500-600	400-600	1-5	225	Fair	Good
Polypropylene.....	500-700	400-600	1-3	260	Poor	Good
Penton.....	500-650	450-600	1-10	350	Poor	Good
Teflon.....	800-1000	800-900	1-3	500	Poor	Good

since the powder resins are one component; (3) time savings since no weighing, mixing, or deaerating are necessary, as for the two-component coatings; (4) no cost for solvents and reduction of fire hazard, because no solvents are employed. Some disadvantages should also be recognized. Among these are: (1) parts that can be coated are limited to metals or other materials having a high heat retention; (2) heat-sensitive electronic components and assemblies cannot be coated; parts must be capable of withstanding preheat temperatures of 400 to 650°F; (3) thin, pinhole-free films less than 5 mils thick are difficult to achieve; (4) some coating powders are degraded by the high processing temperatures used; and (5) the process is economical only for large production runs.

TABLE 31 Typical Examples of Fluidized Bed Coatings*

Chemical type	Proprietary designation	Manufacturer or supplier
Epoxy.....	Scotchcast 260, 265, XR-5133, and XR-5162	Minnesota Mining & Manufacturing Co.
Epoxy.....	PK Series Nos. 60 (gray) and 61 (blue)	Hysol, Division of Dexter Corp.
Epoxy.....	Dri-Kote Series: DK-1, DK-2-02, DK-4, DK-4-01	Hysol, Division of Dexter Corp.
Epoxy.....	E Series Nos. 200, 300, 600, 7000, and 8000	Armstrong Products Co.
Epoxy.....	Epocast Series: 2613, 2612, 268	Furane Plastics
Epoxy.....	Corvel Epoxies Series	The Polymer Corp.
Epoxy-silicone.....	DC-3100	Dow Corning Corp.
Silicone.....	R-5061, R-5071	Dow Corning Corp.
Vinyl.....	Micron 400 Series	Michigan Chrome and Chem.
Vinyl.....	Corvel 1289 and 1325	The Polymer Corp.
Nylon.....	Corvel Nylons Series	The Polymer Corp.
Cellulosic.....	Corvel Cellulosics Series	The Polymer Corp.
Penton chlorinated polyether.....	Corvel Penton Series	The Polymer Corp.
Polyolefin.....	Corvel Polyethylene	The Polymer Corp.
Phenolformaldehyde	Durez 175	Hook Chemical Co.

* Most of these are also suitable for powder spray and electrostatic spray coating.

Because of the high speed and automation possible with the fluidized-bed process, it is being used for many diverse electronic and electrical applications. Among these uses are the coating of electronic enclosures, housings, covers, brackets, wire harness guides, heat sinks and dissipators; and the insulation of transformers, motor rotors, and stators. Fluidized-bed coatings are also being used for the moisture sealing and packaging of resistors and capacitors.

Vacuum impregnation Still another variation of dip coating, known as vacuum impregnation, employs vacuum or vacuum-pressure cycling during the dipping operation. This technique is particularly useful for the thorough coating (impregnation) of intricate parts or assemblies containing numerous small cavities, such as coils, windings, porous metal, and ceramic surfaces. Associated hardware such as porous metal castings may be sealed to maintain vacuum or hold pressures or to contain certain gaseous environments. Thorough impregnation is important, especially for high voltage, because any small void may act as a moisture trap or a corona region, resulting in insulation breakdown.

Many porous specimens may be impregnated by simply soaking in the resin or coating; however, vacuum evacuation techniques are helpful in reducing the amount of entrapped air and moisture. Air is first removed, and then replaced with impregnation material. In order to do this more effectively, it is desirable to evacuate the specimen before immersion in the resin. After immersion, vacuum is again applied, and then interrupted periodically to force the liquid into the evacuated pores. A combination of vacuum followed by pressure is even more effective for impregnation of very closely wound coils or porous substances. The amount of vacuum and time of immersion will be determined by the temperature, viscosity, volatility, and pot life of the resin.

Screening Coating formulated with suitable thixotropic and wetting agents may be applied by squeegee through a silk, nylon, or stainless steel screen. To apply coatings by the screening process, surfaces must be fairly flat. The thickness of the applied coating may be varied from a fraction of a mil to above 6 mils, depending on the screen-mesh size and on the number of coats applied. Once all parameters have been established, very reproducible thicknesses are obtained. In order to minimize pinholes or other imperfections, it is advisable, as with other coating methods, to apply and superimpose two or three layers of coating, each layer being partially or fully cured before application of the next one. By using screens with a photoresist pattern, insulation coatings may be applied to substrates, such as ceramics or epoxy laminates, in selected areas only. This is often necessary in isolating a thin- or thick-film conductor or resistor from an active device which is to be placed above it. A number of screenable epoxies, polyurethanes, and other coating types are available. The screening process for applying conductor, resistor, and capacitor units in selected areas for fabricating thick-film circuits is a highly developed art. Automated equipment for high-production schedules is available. Photoemulsion compositions such as the gelatin-chromate or photoresist types are formed into masks to yield the desired pattern of open screen. Line thickness of 10 mils with 10-mil spacings are easily attainable, but advances are being made in improving definition to 2-mil lines and 2-mil spacings.⁶⁴

Rollercoating Rollercoating is a highly mechanized and closely controlled method for coating flat stock. It provides a means for applying a fixed amount of liquid coating to one or both surfaces of any sheet or strip requiring an even coating. Thus, it is finding use for the application of photoresist coating to copper laminate stock, upon which etched circuitry is to be developed, and for applying thin films on metal foil for use in capacitors, as well as for coating sheet metal for fabrication into cans, boxes, or covers for housing or shielding electronics. In this process, the liquid coating material is transferred by means of a series of metering and transfer rolls from a reservoir pan to the flat surface. The printing roll may be cut out to lay down a pattern, or the metering roll may be lithographed to print a functional or decorative design. After the coating operation, the material passes through a zoned drying and curing oven, and the sheets are stacked or the strip is rerolled. Besides its usage for applying photoresist, this is the method

universally employed for metal decorating, the process whereby stock for such end products as cans, bottle caps, toys, TV trays, wastebaskets, automobile instrument panels, and lighting fixtures is coated.

Brush Brushing is not usually a primary method of applying electronic coatings. However, when small areas on a part are to be coated, or when rather inaccessible areas require coating, a skillfully handled brush is often the answer. Thickness will not be carefully controlled, and outlines will not be strictly observed (unless masking is used), but the job is quickly done with a minimum of investment but a high labor cost.

Brushing is extensively used for touch-up and repair work. Examples would be to repair skips or damaged areas of the coating, to cover spots where components have been removed and replaced or pinholes left from electrical test probes.

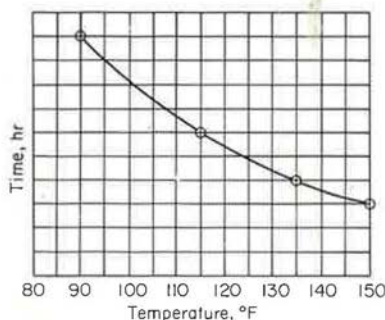


Fig. 18 Time-temperature cure schedule for a polyurethane con-formal coating.

organic materials are developed and as techniques are refined for the deposition of thin films, more uses will be made of organic thin films. Among the advantages of ultrathin organic coatings are their high dielectric breakdown strengths, ability to form pinhole-free layers, and in some cases, high purity of the coating, thus avoiding tunneling effects and leakage currents. Among their disadvantages are thermal and oxidative instability inherent in so many of the presently available polymers.

Thin polymer films normally cannot be formed by the usual methods of deposition such as spraying and dipping, or by the use of two-component systems such as epoxies. Thus only a limited number of coating types and specific deposition techniques lend themselves to thin-film formation. The five most important techniques are:

1. Vacuum or vapor deposition
2. Ultraviolet-light polymerization
3. Electron-beam polymerization
4. Glow-discharge polymerization
5. Gamma irradiation

Thermoplastic linear polymers are most amenable to thin-film deposition, especially those polymerizing by a free-radical or addition mechanism. Hence, monomers such as styrene, divinylbenzene, and other vinyl and acrylic compounds are very suitable and are widely used.

Vapor Deposition. The vapor or vacuum deposition of coatings, although a highly desirable method, can be employed for only a few polymer types. Unlike metals, most plastics cannot be heated to vaporization without gross decomposition or changes in physical and electrical properties. The evaporation method is most successful with the low-molecular-weight polymers, such as polyethylene which recombines with little or no interaction and hence gives rather soft films.⁶⁵ There have been some reports of Teflon vapor deposition. Teflon was depolymerized at 1000°F in a vacuum of 10^{-5} to 10^{-6} torr and reported to repolymerize as

Thin-film deposition methods Thin polymeric films will be defined for purposes of this discussion as solid organic polymer coatings which are less than 3 microns thick (30,000 Å or about $\frac{1}{8}$ mil). The practical applications of such films have been confined largely to capacitor dielectrics; however, they are recently being used as microcircuit insulation, corrosion-protective coatings, and as barrier coatings and passivation layers for semiconductor devices. One of the main problems in the fabrication of microelectronic circuits is the difficulty in obtaining continuous ultrathin, pinhole-free dielectric coatings deposited in layers or in specific geometric patterns. To date, the inorganic materials have dominated the semiconductor device and microcircuits industry; but as new high-temperature-stable

an adherent film on a cold substrate.⁶⁶ However, by far the greatest success in vapor deposition has been achieved with the polyxylylenes. Solid dimers of *p*-xylene are pyrolyzed under moderate vacuum, forming gaseous diradicals which in turn combine on a substrate into long-chain linear polymers.* The equipment for deposition consists essentially of a pyrolysis tube and a vacuum chamber.

Ultraviolet-light Polymerization. Gaseous monomers adsorbed on a surface may be polymerized on exposure to ultraviolet light in either the presence or absence of air. Monomers most suitable for this type of polymerization are those containing double bonds (unsaturation). Styrene, butadiene, methyl methacrylate, acrolein, and divinylbenzene are a few examples of monomers that have been successfully polymerized.

TABLE 32 Source of Specifications

Abbreviation	Full name	Source of document
AMS	Aerospace Material Specifications	Society of Automotive Engineers 485 Lexington Ave., New York, N.Y.
ASTM	American Society for Testing and Materials	American Society for Testing and Materials 1916 Race St., Philadelphia, Pa.
ERF	Epoxy Resin Formulators	Society of Plastics Industry 250 Park Ave., New York, N.Y.
Fed. Std.	Federal Standard	General Services Administration 30 Church St., New York, N.Y. 300 N. Los Angeles St., Los Angeles, Calif. or 7th and D Sts., S.W., Washington, D.C., and Naval Supply Depot, 5801 Tabor Ave., Philadelphia, Pa.
MIL or MIL-STD	Military or Military Standard	Naval Supply Depot, 5801 Tabor Ave., Philadelphia, Pa.
CS	Commercial Standard	Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.
AS	American Standard	American National Standards Institute 10 East 40th St., New York, N.Y.
AATCC	American Association of Textile Chemists and Colorists	American Association of Textile Chemists and Colorists, Lowell Technical Institute, Box 28, Lowell, Mass.
(Letter)-(Letter)-(No.)	.....	Same as for Fed. Std.
IEC	International Electrotechnical Commission	American National Standards Institute 10 East 40th St., New York, N.Y.

Films, a few millionths of an inch thick, which are pinhole-free and highly adherent, have been prepared by A. N. Wright of General Electric.⁶⁷ By employing a mask in front of the substrate during the ultraviolet irradiation, very fine, well-defined insulation layers useful in microcircuits may be deposited.

Ultraviolet light has a distinct advantage over both electron-beam and glow-discharge methods in that the equipment necessary is fairly simple and inexpensive, requiring a mercury arc or some other ultraviolet source, a chamber consisting of a quartz tube or a bell jar with a quartz window to allow entrance of the ultraviolet light, and a means for evacuating, purging, and introducing the gaseous monomer into the chamber. The high-vacuum systems necessary for electron and glow-discharge bombardment are therefore not required. Besides the polymerization of gaseous monomers just described, ultraviolet polymerization may occur in the solid and semisolid state. A good example of this is the curing of photoresists as in the fabrication of printed-circuit boards or microelectronic circuits.

* Parylenes, a trademark of Union Carbide Corporation, New York, N.Y.

TABLE 33 Electrical and Electronic Requirements

Document	Title	Description
ANA Bulletin 400	Electronic Equipment: Aircraft and Guided Missiles, Applicable Documents	A comprehensive listing of specifications and other documents pertinent to aircraft and aerospace electronic systems.
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts	Establishes standard uniform methods for testing electronic and electrical component parts including environmental, physical, and electrical tests.
MIL-STD-275B	Printed Wiring for Electronic Equipment	Establishes design principles governing the fabrication of printed wiring and the mounting of parts and assemblies.
MIL-STD-446A	Environment Requirements for Electronic Parts, Tubes, and Solid State Devices	Establishes the research and development objectives, environmental design requirements for use in current and future electronic planning.
MIL-STD-454	Standard General Requirements for Electronic Equipment	The basic Department of Defense document standardizing the more common requirements for electronic equipment.
MIL-STD-750	Test Methods for Semiconductor Devices	Specification describing tests and environmental conditions for semiconductor devices.
MIL-STD-883	Test Methods and Procedures for Microelectronics	Establishes uniform methods and procedures for testing microelectronic devices, including monolithic, multichip, film, hybrid microcircuits, and microcircuit arrays for Military-NASA uses.
MIL-W-583C	Wire, Magnet, Electrical	Covers electric magnet wire of various classes and types used for fabricating coils and transformer coils.
MIL-T-945	Test Equipment, for Use with Electronic Equipment, General Specification	General requirements for design and manufacture of test equipment used in testing of electronic parts.
MIL-I-983	Interior Communication Equipment, Naval Shipboard, Basic Design Requirements for	Covers the basic design requirements, test, and operating conditions for interior communication equipment used on Naval ships.
MIL-E-4158	Electronic Equipment, Ground, General Requirements for	Requirements for design and fabrication of electronic ground equipment.
MIL-E-5400	Electronic Equipment, Aircraft, General Specification for	Gives general requirements for electronic gear, primarily in piloted aircraft by classes defined as altitude and temperature range.
MIL-E-8189	Electronic Equipment, Guided Missiles, General Specification for	Covers the philosophy of design and general requirements for the design and manufacture of electronic systems for guided missiles.
MIL-P-11268	Parts, Materials, and Processes Used in Communication Equipment	Covers the selection, application, and use of materials and processes in the construction of electronic communication equipment.
MIL-E-11991	Electrical-Electronic Equipment, Surface Guided, Missile Weapon Systems, General Specification for	Covers requirements which are common to guided-missile-systems electronic, electrical, and electromechanical equipment.
MIL-E-16400	Electronic Equipment, Naval Ship and Shore: General Specification	

TABLE 33 Electrical and Electronic Requirements (Continued)

Document	Title	Description
MIL-T-17296	Test, Checkout and Evaluation Equipment Guided Missiles (Fixed Installations) General Specification	Covers general requirements for guided-missile test, checkout for fixed installations on board ship or missile depots and schools.
MIL-F-18870	Fire Control Equipment, Naval Ship and Shore: General Specification	Covers general requirements for design and manufacture of surface, shore, anti-aircraft and underwater fire control equipment.
MIL-S-19500	Semiconductor Devices, General Specification for	
MIL-T-21200	Test Equipment for Use with Electronic and Fire Control Systems, General Specification for	Covers general requirements for design and construction of equipment used in testing electronic and fire control equipment.
NEMA, MW-1000	Magnet Wire	Gives standards for magnet wire and wire coatings and acceptance tests.
NEMA	Temperature Classifications for Electrical Insulation	

Electron-bombardment Polymerization. In 1954 it was suggested that electron-beam polymerization could be useful as a new way of depositing ultrathin films;⁸⁸ and later, in 1958, the significance of this technique in fabricating microelectronic circuits and devices was reported.⁶⁹

Gases or liquids that have been polymerized on electronic devices by electronic bombardment are normally those containing double bonds (ethylenic groups), such as monomeric tetrafluoroethylene, vinylidene fluoride, acrylic, methacrylic, acrylonitrile, styrene, and organopolysiloxanes.

The deposition of thin films may be selective by exposing only certain areas of a substrate. Hence, by employing a mask or by programming and directing the beam, very fine lines and areas may be defined.¹⁰

Germanium diodes coated with the liquid monomers, cured with high-energy electrons for periods up to 3 min at a total dose of 10^6 , showed little effect on their reverse-current characteristics. The advantages of applying coatings in this manner is the rapidity with which they can be cured and the fact that heat is not required, thus obviating the possible deterioration of heat-sensitive devices.¹¹

Glow-discharge Polymerization. The glow-discharge method for depositing and polymerizing thin films (also known as the electric or silent discharge method) involves striking an electrical discharge of several hundred to several thousand volts between two electrodes in the presence of a monomer gas.

Under direct-current conditions, the substrate to be coated is either made the anode or attached to the anode in some way. In ac discharge, the substrate is placed between the anode and the cathode. Still a third variation of glow discharge makes use of radio-frequency (Rf) excited molecules and does not require the use of electrodes at all.

The physical characteristics of these films depend on the conditions of glow discharge (voltage, amperage, time) and also on the nature of the surface on which the coating is deposited. Some surfaces lend themselves to the formation of strong chemical bonds, whereas others are rather passive and only weak adhesion results.

The key advantage of the glow-discharge method is the complete coating coverage which is provided to the part, since the polymers form within and behind all crevices and cover all surface imperfections resulting in an integral coating.¹² Other advan-

tages include: (1) the temperature of the substrate may be kept low, even at room temperature; (2) the process is fairly simple and rapid—a very high vacuum system is not necessary as in other methods since vacuum of 10^{-3} and 10^{-4} torr only is required; and (3) the choice of the monomer starting material is wide and not limited to the conventional monomer types.

A large number of monomers have been polymerized by glow discharge, yielding

TABLE 34 Finishing Systems

Document	Title	Description
MIL-HDBK-132	Military Handbook: Protective Finishes	Details inorganic and organic protective finish systems which have proved satisfactory at various ordnance corps installations.
MIL-STD-171	Systems for Preparation, Painting, and Finishing Metal and Wood Surfaces	A comprehensive index of specifications and guide to the preparation and finishing of many types of surfaces.
MIL-STD-186	Painting and Finishing Systems for Rocket and Guided Missile Material	Establishes minimum requirements for procedures, materials, and systems for cleaning, plating, and painting of electronic components for rockets and guided missiles.
MIL-STD-194	Painting and Finishing Systems for Fire Control Instruments	Establishes minimum requirements for surface preparation, surface treatment, painting, and finishing of fire control instruments.
MIL-T-704	Treatment and Painting of Material	Covers materials to be used and procedures to be followed in cleaning, treating, and painting surfaces and equipment to provide protection from environment and corrosion (including sources for color call-out).
MIL-F-7179	Finishes and Coatings; General Specification for Protection of Aerospace Weapons Systems, Structures, and Parts	Specifies coating systems, mainly for the protection on nonelectronic surfaces.
MIL-F-14072	Finishes for Ground Signal Equipment	Design guide for selection of compatible materials and specifications for individual finishing system by substrate and severity of exposure to prevent deterioration in the anticipated environments.
MIL-F-18264	Finishes: Organic, Weapons System, Application and Control of	Gives recommended materials, their characteristics, application equipment and procedures, and troubleshooting painting problems.
MIL-C-22751	Coating System, Epoxy-Polyamide, Chemical and Solvent Resistant, Process for Application of	Complete coating system for protection of aluminum and magnesium. Consists of MIL-C-8514 pretreatment etch primer, MIL-P-23377 primer, and MIL-P-22750 enamel.

films from several hundred to 10,000 Å thick.^{73,74} Of these, the best films in terms of electrical and physical properties were those derived from dimethylpolysiloxane, triethylsilane, diethylvinylsilane, vinyltrimethylsilane, heptene-2, cyclohexene, styrene, valeronitrile, and 2,5-dimethyl-2,4-hexadiene.

The glow-discharge technique has also been used to produce thin polymeric films from halogenated olefins including fluorinated derivatives.⁷⁵ These films, found suitable as dielectric and electronic device coatings, were formed by the application of several hundred volts potential difference between electrodes.⁷³

TABLE 35 Coatings, Paints, and Primers

Document	Title	Description
TT-L-20	Lacquer, Camouflage	Camouflage colors for metal; 18 colors.
TT-L-32	Lacquer, Cellulose Nitrate, Gloss, for Aircraft Use	Durable cellulose nitrate gloss lacquer. Clear and 16 colors.
TT-V-119	Varnish, Spar, Phenolic Resin	Clear, air-drying spar varnish of the phenolic resin type.
TT-E-485	Enamel, Semi-gloss, Rust-inhibiting	One grade of a semigloss rust-inhibiting enamel for use on metal; four colors.
TT-E-489	Enamel, Alkyd, Gloss (for Exterior and Interior Surfaces)	Alkyd gloss enamel for use on primed exterior and interior wood and metal surfaces; 43 colors.
TT-E-527	Lustreless Enamel	Alkyd-type air-drying or baking lustreless enamel finish; 25 colors.
TT-E-529	Semigloss Enamel	Alkyd semigloss enamel for exterior and interior wood and metal surfaces for military and special equipment; 47 colors.
MIL-V-173	Varnish, Moisture- and Fungus-resistant (for Treatment of Communications, Electronic and Associated Electrical Equipment)	Describes a commonly used moisture- and fungus-resistant varnish consisting of <i>p</i> -phenyl phenol formaldehyde resin combined with tung oil and solvents.
MIL-V-1137	Varnish, Electrical-insulating (for Electromotive Equipment)	An impregnation varnish used for wire insulation. Also used to impregnate glass fiber.
MIL-I-2707	Insulating Varnish, Electrical, Impregnating, High Temperature	Used for wire insulation and coil impregnation.
MIL-E-5557	Enamel, Heat Resisting Glyceryl Phthalate Black	Air-drying and baking type, black heat-resistant enamel.
MIL-C-7439	Rain Erosion Coating	Thermally reflective rain-erosion-resistant and antistatic coating for glass-fabric-reinforced plastic laminates.
MIL-E-7729	Enamel, Gloss	Air-dry and baking types; 16 colors.
MIL-P-7962	Primer Coating, Cellulose-nitrate Modified Alkyd Type, Corrosion-inhibiting, Fast-drying (for Spray Application over Pretreatment Coating)	Lacquer primer for use only over MIL C-8514 and under nitrocellulose or acrylic-nitrocellulose lacquer.
MIL-C-8514	Coating Compound, Metal Pretreatment, Resin-Acid	Pretreatment wash primer coating for metals to be applied before complete coating system. Has adhesion-promoting and anticorrosive properties. Air Force and Navy-Weps version.
MIL-S-8516	Coating, Sealing, and Reinforcing of Electrical Connectors	Covers accelerated organic polysulfide liquid polymer for sealing and reinforcing electrical apparatus.
MIL-P-8585	Primer Coating, Zinc Chromate Low Moisture Sensitivity	Anticorrosive primer for aircraft aluminum (alkyd). (Replaced MIL-P-6889.) (Not for use on magnesium.)
MIL-E-14002	Enamel, Corrosion Inhibiting	Quick-drying lustreless synthetic enamel for steel, magnesium, and aluminum.
MIL-L-14486	Lusterless Lacquer, Vinyl	For use as finish coat.
MIL-E-15090	Alkyd Light Gray Equipment Enamel	Air-drying and baking enamel suitable for use on equipment, furniture, and switchboard installation; one color.
MIL-C-15328	Primer, Pretreatment (Formula No. 117 for Metals)	Wash primer similar to MIL-C-8514. Navy-Ships and DOD version.

TABLE 35 Coatings, Paints, and Primers (Continued)

Document	Title	Description
MIL-P-15929	Primer, Vinyl, Red Lead	Used for ferrous alloys, only over MIL-C-8514, MIL-C-15328.
MIL-P-15930A	Primer, Vinyl, Zinc Chromate	Used only over acid-etch primers MIL-C-8514, etc.
MIL-P-15932-6	Enamel, Exterior (Vinyl Alkyd)	A vinyl-alkyd enamel for use on pretreated coating, black, white, grays.
MIL-I-16923D	Insulating Compound, Electrical, Embedding	Requirements for several types of compounds for embedding or encasing electrical components.
MIL-I-17384	Insulating Compound, Electrical, Quick-drying	Covers lacquer of several types for use on electrical panels or cases and for sealing the edges of phenolic laminates.
MIL-L-19537	Lacquer, Acrylic-nitrocellulose Gloss (for Aircraft use)	General-purpose exterior coating for metals, resistant to diester lubricating oils. Clear and 13 colors.
MIL-L-19538	Lacquer, Acrylic-nitrocellulose, Camouflage (for Aircraft use)	Same as MIL-L-19537 except in lusterless camouflage colors. White, black, and nine colors.
MIL-P-22750	Coating, Epoxy-Polyamide, Chemical- and Solvent-resistant, for Weapons Systems	Protective coating for magnesium and aluminum, over MIL-C-8514, MIL-C-8514 plus MIL-P-23377, or direct on metal. Clear, black, white, red, and four grays.
MIL-P-22808	Paint, Epoxy, Hydraulic, Fluid Resistant	An epoxy-polyamide enamel for protection of metals at temperatures up to 500°F. White and four colors.
MIL-P-23377	Primer Coating, Epoxy-Polyamide, Chem. & Solv. Resist.	Useful over Mg and Al alloys and for separation of dissimilar metals.
MIL-I-24092	Insulating Varnish, Electrical, Impregnating	Characterizes insulating varnishes, baking type for electric coils and structures.
MIL-C-27227	Coating, Polyurethane, Thermal Resistant for Aircraft Application	Gloss finish coat. May be used for magnesium.
MIL-I-46058	Insulation Compound, Electrical (for Coating Printed Circuit Assemblies)	Covers various types (epoxy, polyurethane, silicones, polystyrene low-dielectric) conformal coatings for printed-circuit assemblies.
MIL-L-52043	Semigloss Lacquer	May be used for magnesium.
MIL-P-52192	Primer Coating, Epoxy	Used for magnesium.
MIL-C-52210	Coating, Epoxy, Spray Type, for Printed Circuitry	Epoxy-polysulfide-type coating having fair flexibility for use over epoxy laminate printed-circuit boards.

General properties of thin-film polymer coatings Many of the properties of polymer thin films are independent of their chemical structure or composition. The most important of these is the very high dielectric breakdown strengths which all thin films possess. The increase of dielectric strength with decrease in film thickness is a well-known phenomenon previously described.²⁹

Many of the processes for depositing thin films result in films that are pinhole-free and continuous. The lack of pinholes and integrity of the film are largely dependent on the method of deposition, surface treatment, and cleanliness of the surface and ambient in which the coating is applied.

Still another property common to most thin films is their high degree of purity. With adequate control, the polymerization reaction may be directed so that no side reactions or by-products are formed.

TABLE 36 Solvents, Resins, and Other Coating Ingredients

Document	Title	Description
TT-R-271	Resin, Phenol-Formaldehyde, Para-phenyl	Solvent for use in organic coatings. Used as a varnish ingredient. Solvent for use in organic coatings. For use in organic coatings.
TT-T-548	Toluol (Toluene)	
TT-T-775	Tung Oil, Raw (China Wood)	
TT-X-916	Xylene	
MIL-M-261	Methyl Ethyl Ketone	
TT-E-463	Ethyl Alcohol	
MIL-A-6091	Alcohol, Ethyl, Specially Denatured	
MIL-I-10428	Isopropyl Alcohol, Technical	
MIL-T-27602	Trichloroethylene (commercial)	Used as a cleaning solvent.

TABLE 37 Cleaning and Surface Treatments

Document	Title	Description
TT-C-490	Cleaning Methods and Pretreatment of Ferrous Surfaces for Organic Coatings	Cleaning and pretreatment of ferrous metals, and ferrous metals having zinc or aluminum surfaces.
MIL-M-3171	Magnesium Alloy, Processes for Pretreatment and Protection of Corrosion	Covers Dow 1, 7, 9, and 19 treatments.
MIL-S-5002	Surface Treatments and Metallic Coatings for Metal Surfaces of Weapons Systems	Preparation, surface treatments, and metallic coatings for metal surfaces of weapons systems prior to application of organic finishes.
MIL-C-5541	Chemical Films and Chemical Film Materials for Aluminum and Aluminum Alloys	A chromate conversion coating for aluminum, covers Alodine,* Iridite,† and other proprietary treatments.
MIL-A-8625	Anodic Coatings, for Aluminum and Aluminum Alloys	Covers chromic and sulfuric acid anodization processes.
MIL-T-12879	Treatments, Chemicals, Prepaint and Corrosion Inhibitive, for Zinc Surfaces	Prepaint and corrosion-inhibitive chemical treatments for plated, hot-dipped, and solid zinc surfaces.
MIL-C-13335	Coating for Magnesium and Magnesium Alloys	Covers HAE anodize treatment.
MIL-C-38334	Corrosion Removing Compound, Prepaint, for Aircraft Aluminum Surfaces	Covers use of nonflammable phosphoric acid base liquid.
MIL-M-45202	Magnesium Alloys, Anodic Treatment of	Covers Dow 17, HAE, and CR-22 anodic treatments.
MIL-M-46080	Magnesium Castings; Process for Anodic Cleaning and Surface Sealing of	Covers fluoride-anodize treatment plus Dow 7, plus MIL-C-46070, epoxy baking coating.
AMS-2476	Electrolytic Treatment for Magnesium Base Alloys	Covers HAE anodize treatment.
AMS-2478	Anodic Treatment of Magnesium Base Alloys	Covers Dow 17 anodize treatment.

* Trademark of Amchem Products, Inc.

† Trademark, of Allied Research Products, Inc.

SPECIFICATIONS

Material Specifications

A coating material specification is written to control the engineering requirements, to establish receiving tests on batches, or even to establish explicit formulas for materials to be furnished. When written around engineering requirements, there may be many or perhaps no qualified materials on the market; whereas when written as a formulation or narrow performance specification, it may be presumed that at least one already tested and qualified material exists.

TABLE 38 Test Procedures—General Specifications

Document	Title	Description
Fed. Std. 141 (TT-P-141)	Paint, Varnish, Lacquer, and Related Materials; Methods of Inspection, Sampling and Testing	Describes methods to determine physical and chemical properties of paint, varnish, and lacquer for conformance to Federal and Military Specifications. Covers 278 methods.
Fed. Std. 406	Plastics: Methods of Testing	A compilation of 76 methods for testing plastics.
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts	Establishes uniform methods for testing electronic and electrical component parts such as capacitors, resistors, switches, relays, transformers, and jacks. Applies only to small parts such as transformers and inductors weighing up to 300 lb.
MIL-STD-810A	Military Standard Environmental Test Methods for Aerospace and Ground Equipment	A compilation of methods previously described in a variety of other specifications, as, for example, MIL-E-5272, MIL-T-5422, and MIL-E-4970.
MIL-E-4970 (USAF)	Environmental Testing, Ground Support Equipment (inactive for new design)	Procedures for testing ground-support equipment under simulated and accelerated conditions.
MIL-E-5272 (ASG)	Environmental Testing, Aeronautical and Associated Equipment	Procedure for subjecting equipment to simulated and accelerated environmental conditions to ensure satisfactory operation and freedom from deterioration in use.
MIL-T-5422 (ASG)	Environmental Testing for Aircraft Electronic Equipment	Testing procedures under simulated and accelerated environmental conditions to meet requirements of MIL-E-5400.
MIL-I-16923	Insulating Compound, Electrical Embedding	Describes or references many electrical and other tests applicable to plastics and coatings.
ASTM D 115-55	Methods of Testing Varnishes Used for Electrical Insulation	Covers tests for electrical properties, solids percent, viscosity, dry time, flexibility.

Acceptance Specifications

For electronic parts or assemblies that are coated by vendors, an acceptance specification detailing requirements and quality control tests to be performed on the coated parts may be useful. Destructive or nondestructive tests may be called out to assure that the part is adequately coated to perform the required function. Examples of tests that are commonly specified are adhesion, dielectric strength, insulation resistance, humidity, and salt-spray exposures. The fact that a material meets a military, federal, or trade association specification does not necessarily assure its suitability for a given application. Additional or tighter requirements

TABLE 39 Specific Test Methods for Coatings

Test	ASTM	Fed. STD. 141a, method	MIL-STD-202, method	Fed. STD. 406, method	Others
Abrasion	D 968	6191 (Falling Sand) 6192 (Taber)	....	1091	Fed. Std. 601, 14111
Adhesion	D 2197	6301.1 (Tape Test, Wet) 6302.1 (Microknife) 6303.1 (Scratch Adhesion) 6304.1 (Knife Test)	....	1111	Fed. Std. 601, 8031
Arc resistance	D 495	....	303	4011	....
Dielectric constant	D 150	....	301	4021	Fed. Std. 101, 303
Dielectric strength (breakdown voltage)	D 149 D 115	....	....	4031	Fed. Std. 601, 13311
Dissipation factor	D 150	....	....	4021	....
Drying time	D 1640 D 115	4061.1	....	....	....
Electrical insulation resistance	D 229 D 257	....	302	4041	MIL-W-81044, 4.7.5.2
Exposure (exterior)	D 1014	6160 (On Metals) 6161.1 (Outdoor Rack)	....	....	....
Flash point	D 56, D 92 D 1310 (Tag Open Cup)	4291 (Tag Closed Cup) 4294 (Cleveland Open Cup)	....	....	Fed. Std. 810, 509
Flexibility	....	6221 (Mandrel) 6222 (Conical Mandrel)	....	1031	Fed. Std. 601, 11041
Fungus resistance	D 1924	....	....	....	MIL-E-5272, 4.8 MIL-STD-810, 508.1 MIL-T-5422, 4.8
Hardness	D 1474	6211 (Print Hardness) 6212 (Indentation)	....	....	....
Heat resistance	D 115 D 1932	6051	....	....	....
Humidity	D 2247	6071 (100% RH) 6201 (Continuous Condensation)	103 106A	....	MIL-E-5272, Proc. 1 Fed. Std. 810, 507
Impact resistance	....	6226 (G.E. Impact)	1074	....	....
Moisture-vapor permeability	E 96 D 1653	6171	7032	....	....
Nonvolatile content	....	4044	....	....	....
Salt spray (fog)	B 117	6061	101C	6071	MIL-STD-810, 509.1 MIL-E-5272, 4.6 Fed. Std. 151, 811.1 Fed. Std. 810, 509
Temperature-altitude	....	....	....	....	MIL-E-5272, 4.14 MIL-T-5422, 4.1 MIL-STD-810, 504.1
Thermal conductivity	D 1674 (Cenco Fitch) C 177 (Guarded Hot Plate)	....	....	....	MIL-I-16923, 4.6.9
Thermal shock	....	....	107	....	MIL-E-5272, 4.3 MIL-STD-810, 503.1
Thickness (dry film)	D 1005 D 1186	6181 (Magnetic Gage) 6183 (Mechanical Gage)	....	2111, 2121, 2131, 2141, 2151	Fed. Std. 151, 520, 521.1
Viscosity	D 1545 D 562 D 1200 D 88	4271 (Gardner Tubes) 4281 (Krebs-Stormer) 4282 (Ford Cup) 4285 (Saybolt) 4287 (Brookfield)	....	....	....
Weathering (accelerated)	D 822	6151 (Open Arc) 6152 (Enclosed Arc)	....	6024	....

A more complete compilation of test methods is found in J. J. Licari, "Plastic Coatings for Electronics," McGraw-Hill Book Company, New York, 1970.

The major collection of complete test methods for coatings is "Physical and Chemical Examination of Paints, Varnishes, Lacquers, and Colors," by Gardner and Sward, Gardner Laboratory, Bethesda, Md. This has gone through many editions.

may be needed and can be incorporated as extra provisions of a company internal specification.

Process Specifications

Process specifications are detailed procedures to be used for a manufacturing operation, but should allow manufacturing as much freedom as possible and still meet the engineering requirements. As an example, if there are a number of different cure schedules which have been proved equivalent, the choice of any one of them should ordinarily be allowed, provided none of the temperatures is so high as to damage the assembly. An example of such a time-temperature cure schedule is plotted in Fig. 18. Sources of specifications are listed in Table 32. Tables 33 to 37 provide lists of many specifications with brief descriptions. Test specifications and specific test procedures are listed in Tables 38 and 39.

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