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CORROSION PREVENTION/DETERIORATION CONTROL IN ELECTRONIC COMPONENTS AND ASSEMBLIES

DEPARTMENT OF THE ARMY CONTRACT DA-01-021-AMC-12641(Z)
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FINAL SUMMARY ENGINEERING REPORT
CR 6-347-958-001

PREPARED BY
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U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama

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JUN 19 1967

FOREWORD

The purpose of this document is to focus the attention of designers on corrosion and the consequent degradation of reliability of electronic items. The report points out dangerous combinations of materials and processes, emphasizes the importance of proper selection of materials, and provides the designer with modern techniques for prevention of deterioration.

The aim of this report is not to dictate design, but to help the designer meet environmental requirements.

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SECTION 1 INTRODUCTION

1.1 OBJECTIVE

1.1.1 **PURPOSE.** The purpose of this program is to improve the reliability of military electronic equipment by preventing deterioration or malfunction due to corrosion. If corrosion did not interfere with the performance of electronic equipment, it would not be a serious concern; but changes in materials, properties and components due to corrosion (or deterioration) do significantly decrease reliability. Therefore, it is essential that designers of electronic assemblies be informed of the dangers of corrosion and be guided in selecting preventive techniques and materials. Many problems are blamed on the failure of design engineers to apply existing knowledge.⁽¹⁾

1.1.2 **DETERIORATION.** Many engineers associate "corrosion" with rust on a steel bridge. In electronic equipment, it is more likely to be a film of organic contaminant on a relay contact, causing failure of an arming mechanism⁽²⁾; or moisture leading to malfunction of stripline assembly⁽³⁾; or fungal attack fogging lenses⁽⁴⁾ or "whiskers" ruining sealed capacitors⁽⁵⁾. Deterioration, as used in this report, refers to any unwanted change in properties, size or function, caused by environmental or service conditions. The problem may be as small as water absorption of 0.1%, which will cause most capacitors to fail.⁽⁶⁾ Corrosion proceeds slowly and is often invisible, but nearly always degrades performance. It cannot be avoided by "coating everything" after manufacture; it must be considered and prevented, in the design.

1.1.2.1 **Effects.** The effects of corrosion, from the electronic point of view, include such things as decreases in metal conductivity because of oxidation; short circuits caused by fungi growing across two conductors and bridging the gap, or from "whisker" growth inside sealed containers during storage; or loss of several db in stripline antenna from water absorption. These are the types of problems discussed in the following sections.

1.1.3 **REASON.** Modern electronic equipment is much more vulnerable to corrosion than that made a few years ago. Dense packaging, high impedance circuitry, and high amplification make modern devices more sensitive to surface contamination and the resultant "noise". Yet today, as never before, the success of military operations depends in large part on the accuracy and reliability of electronic equipment.

1.2 SCOPE

The Department of Defense is the largest market for electronics, buying \$7.5 billion out of a total of \$17 billion in 1965, with NASA spending an additional \$1.5 billion. It is also the most demanding user, because of the close correlation between electronic reliability and military success. The aim of this study is to improve reliability in this area, under the conditions military equipment will encounter.

1.2.1 **EARTH'S ATMOSPHERE.** Since the great majority of military electronic items are fabricated, transported, stored and used on or near the earth's surface, primary attention will be given to deterioration in the earth's atmosphere. This includes altitudes up to 100,000 feet, temperatures from -62°C to 74°C (-80 to +165°F), and relative humidity from

(1) Superscript number refers to references at end of each section.

0 to 100 percent. Even space vehicles are made and stored on earth, so in addition to provision for those environments peculiar to space satellites and moon probes, they need protection from corrosion on earth before they are launched.

1.2.2 TYPES OF DETERIORATION. This study is confined to deterioration caused by environmental and service conditions such as temperature, humidity, salt spray, fungus and the like. Mechanical damage from mishandling, vibration or shock is outside the scope of this program.

1.3 MAJOR PROBLEM AREAS

There are several problem areas in the production of environmentally rugged electronic devices. First, the anticipated environment should be defined before design is started. Second, the materials and processes used should be reviewed individually and as assemblies, since each one affects others. Third, specific protection against deterioration should be provided by coatings, fungicides, seals and desiccants, as well as by proper selection of materials. Fourth, parts should be manufactured under high standards of cleanliness and with care to prevent damage. Fifth, packing, preservation and storage should assure good condition of all parts, even after long time in adverse environment.

1.4 RESPONSIBILITY

Primary responsibility for the prevention of corrosion lies with the designer of the original equipment. The fabricator sometimes (although he should not do so) substitutes materials or changes manufacturing sequence, and produces corrosion. Sometimes the user exposes articles to more severe environments than were anticipated. But the designer cannot evade responsibility. He should be thoroughly aware of the environments under which his device must work. He should know which circuits are susceptible to noise, or malfunction from moisture. He should be cognizant of the importance of the item he is designing, and he should know whether its failure will compromise the mission. While practical notes on handling in shop and field are included herein, most of the information is for the designer.

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SECTION 2 ENVIRONMENTS

2.1 NATURAL EXTREMES

Reliability has been defined as "the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered".⁽¹⁾ Before the item is operated, it is exposed to many environments during fabrication, assembly, transportation, rework or repair. Any military electronics must be able to withstand these non-operating environments without harm to final performance. Therefore, in addition to operating field conditions, all prior environments must also be considered in design. They may be natural climates such as pressure, temperature, humidity, wind, dust; or they may be man-made conditions such as ozone from welding machines, or smog, or corrosive gases emanating from organic materials.

2.1.1 SPECIFICATION REQUIREMENTS. In Military Standard 210A "Climatic Extremes for Military Equipment"⁽²⁾ and Army Regulation 705-15 "Operation of Materiel Under Extreme Conditions of Environment"⁽³⁾ these climatic conditions are summarized. Each document has five categories for operation: MIL-STD-210A lists desert, tropics, arctic, shipboard, and world-wide; AR 705-15 has hot-dry, warm-wet, cold, extreme cold, and intermediate (corresponding to the temperature zone). Many of the values are identical, and others are very close, as seen in Table I. Temperatures from AR 705-15 are those for air 4 to 6 feet above the ground rather than ground temperature. The radiation values are the same, expressed in different units. The rise in temperature due to solar radiation depends on the material receiving radiation. The chief difference between these two documents is the statement in Section 6.b of AR 705-15 is that while all materiel must operate under intermediate conditions, modification kits may normally be used in hot-dry, warm-wet, or cold conditions. Although there are other important environments such as corrosive or salt air, dust and the like, the combinations of temperature, pressure and humidity are the governing factors. Fortunately, the worst conditions do not occur simultaneously. Usually, only one condition at a time is critical,⁽⁴⁾ although there are instances where two environments intensify each other.⁽⁵⁾ An excellent discussion of probable concurrent environments is given in the Handbook of Environmental Engineering.⁽⁶⁾

2.1.2 ELECTRONICS. Structural designers are accustomed to considering climatic extremes, but some designers of electronic equipment argue that their modules are always enclosed, or in an air conditioned van, or protected from climatic conditions. This belief is unfortunately not valid. How about antennas which must work in rain, snow and sleet? How about operations in vans when the air conditioning breaks down? Think of the high temperature in quonset huts under a blazing sun, often appreciably hotter than the unsheltered items left outside.⁽⁷⁾ Inspection, maintenance, repair and rework of military electronic items are frequently performed under extremely adverse conditions, such as a canvas shelter in a tropical rain forest. Even in air conditioned factories, the temperature is controlled but not the humidity, and condensate in the early morning is not at all unusual. For a more complete discussion of the various climatic factors affecting electrical and electronic equipment, refer to the recent book by Rychtera and Bartakova.⁽⁸⁾

Table I*
ENVIRONMENTAL EXTREMES

Atmospheric Environment	MIL-STD-210A Ch. 1, 30 Nov. 1958	AR 705-15 Ch. 1, 14 Oct. 1963
<u>Temperature:</u>		
<u>Max</u> Hot-dry or desert	51.7°C (125°F) +105 W/sq ft radiation	48.9°C (120°F) +360 BTU/sq ft/hr radiation
<u>Max</u> Warm-wet or tropics	35°C (95°F) +90 W/sq ft radiation	35°C (95°F) +310 BTU/sq ft/hr radiation
<u>Min</u> Cold or arctic	-53.9°C (-65°F)	-53.9°C (-65°F)
<u>Min-Max:</u> Intermediate	—	-31.6°C (-25°F) 40°C (105°F)
<u>Min-Max:</u> Transport and Storage	-62°C (-80°F) 71.1°C (160°F)	-62°C (-80°F) 68.3°C (155°F)
<u>Humidity, Max:</u>		
Absolute	13 grains/cu ft	13 grains/cu ft
Relative	97% at 29.4°C	100% at 29.4°C
<u>Pressure Range:</u>		
Operating	7.1 - 15.4 psi	9.04 - 15.46 psi
Transport and Storage	1.68 - 15.4	2.47 - 15.46

*Section 2.1.1

2.2 NATURAL TYPES

Insofar as military electronics are concerned, climates may be divided into five classes:

Temperate
Polar
Desert
Tropics
Space

2.2.1 TEMPERATE. European and North American areas are mostly in the "temperate" range. In different areas at various times of the year, certain points may approximate the extremes of polar, desert or tropical temperatures or humidity. In general, the temperate climate has mean temperatures between -5° and +15°C (21° - 59°F) in winter and +15° and 25°C (59° - 77°F) in summer. (8)

2.2.2 POLAR. The polar regions offer many problems to electronic designers, in spite of the fact that little corrosion of metals occurs at sub-zero temperatures. In arctic and antarctic areas, there are three special factors of concern:

1. Mechanical difficulties caused by differential thermal expansion or contraction are especially significant on electromechanical devices with moving parts.
2. Condensation occurs when cold equipment is brought into a warmer area, with resultant fogging of lenses and corrosion of leads. The breath of personnel operating the equipment may condense on the apparatus and cause trouble. Or condensate may come from the dense fogs which often cover coastal areas of the polar regions.
3. Properties change radically at sub-zero temperatures. Most materials become brittle and harder; many lubricants solidify; seals and gaskets may crack. Electrical properties (inductance, capacitance and resistance) undergo such marked changes at low temperatures that critical circuits may be completely out of tolerance.

Since most extremely cold climates are also very dry, fungal attack is not a problem. Hordes of tiny insects in summer are more of an irritation to operating personnel than a hazard to the equipment; but they may get inside assemblies and cause shorting.

2.2.3 DESERT. The hot, dry wind-swept deserts create a bad maintenance problem because the powdery dust penetrates even into supposedly sealed components. High daytime temperatures, ultraviolet radiation, and this fine dust, are the three worst factors of the desert climate. The heat produces low viscosity which may cause leakage at seals.⁽⁹⁾ It also makes waxes soften, paints crack, and plastics deteriorate. But since there is little moisture in desert areas, corrosion is held to a minimum, as evidenced by the excellent condition of the Lady-Be-Good airplane after 17 years in the North African desert.

2.2.4 TROPICAL. The greatest challenge to the electronics industry is the design and production of electronic equipment which will maintain high reliability in the hot humid conditions of the tropics. In this report, special emphasis is placed on tropic-proofing electronic equipment, for the following reasons:

1. The tropics include 26 percent of the earth's land area - (16% humid and 10% semi-humid conditions)⁽⁸⁾.
2. Tropical environments include high temperatures, high humidity, heavy plant and animal growth and hundreds of varieties of microorganisms.
3. Tropical environments, being less familiar to us than those of the temperate zones, need more conscious attention.

2.2.4.1 Cost. One Army report⁽¹⁰⁾ gives the cost of maintenance to overcome deterioration from tropical environment as 50% of the total expenditure! While this figure seems extraordinarily high, it becomes reasonable in view of the time required for inspection, the cost of tests, the records which must be kept, and the problem of spare parts to replace those found to be corroded.

2.2.4.2 Combined Effects. High tropical temperatures intensify the effects of humidity, salt spray, outgassing, and (in some temperature ranges) the growth of fungus. The combination of temperature variations and high humidity results in condensation and absorbed moisture. Engineers experienced in the tropics point out that the monthly or even the daily average temperature is not significant. It is the variation in temperature which causes condensate. In some areas of Panama, all equipment is wet from condensation at least once a day, because of the sharp drop in temperature at night.⁽¹¹⁾ Field service results show that the combination of natural environments in the tropics has markedly greater effect than would be anticipated from separate laboratory tests.

2.2.5 SPACE. During fabrication, test, storage and transportation, space vehicles are exposed to the earth's atmosphere. Therefore, they need protection against moisture and other sources of corrosion, until launch. In space, there are two additional environments which affect electronic systems: low pressure (vacuum) with consequent outgassing of organic materials, and radiation, which affects materials and semiconductors. The subject of space environments and their effects on electronic components and systems has been studied extensively and reported in numerous volumes. Only a brief resume, with a list of recent publications, will be presented in this document. (See Section 3.9.)

2.3 MAN-MADE CONDITIONS

In addition to the hazards of natural environments, electronic parts are exposed to all sorts of man-caused attack during manufacture, storage, shipment, rework or operation. Assembly in areas which are air conditioned but not humidity controlled; or near a welding machine liberating ozone; or storing without proper protection; or packing for shipment with materials which give off corrosive vapors - these are some of the man-made problems. A typical list is given in Table II. Each manufacturing facility can probably add a few more examples. The effect is the same, whether corrosion occurs naturally or as the result of someone's mistake.

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Table II*
MAN-MADE CORROSIVE CONDITIONS

Environment	Produced by	During	Attacks	Discussed in Section
Corrosive Liquids	Cleaning	Fabrication	Insulation, Components	8.4.3
High Temperature	Exotherm, Encapsulant	Fabrication	Insulation, Components	7.2.2
High Temperature	Cure Encapsulant	Fabrication	Insulation, Components	7.10.4
High Temperature	Lack of cooling or short	Test or service	Insulation, Components	7.2.2
Ozone	Welding Machines	Fabrication or Storage	Rubbers	7.6.1
Acid	Incomplete Cleaning	Fabrication	Metals	6.7.3
Air	Insufficient Packaging	Fabrication or Storage	Conductor Surfaces	6.2.1
Corrosive Gases	Sulfur in paper	Fabrication or Storage	Silver	6.7.4.9
Corrosive Gases	Undercured Organics	Storage	Metals, Plastics	3.4.4, 5.3.7
Corrosive Gases	Packing Materials	Storage	Cadmium, other metals	11.3
Corrosive Gases, Acid	Overheated Insulation	Test or Service	Metals, Conductors	7.5.6, 3.4.4
Corrosive Gases	Propellant	Test or Service	Plastics, Metals	5.3.8
Oil or Grease	Leakage	Storage or Rework	Cadmium, Paint	7.7.2
Pool of Water	Sump area (poor design)	Storage	Everything	3.1.1
Diester Oils	Lubricants	Storage	Neoprenes, Plastics	5.3.8

*Section 2.3

SECTION 3 CAUSES OF DETERIORATION

3.1 MOISTURE

Moisture, whether in the form of humidity, vapor, or liquid water, is the greatest contributor to corrosion. It attacks both metals and non-metals, and it aids the growth of microorganisms. Of the six major causes of corrosion - moisture, temperature, pressure, chemical attack, dust, and living organisms - moisture is the most destructive.

3.1.1 SOURCES. Moisture from external sources (such as rain, hail, ice, snow, sleet and fog) can be kept out of electronic assemblies. But moisture is present in air, and often it contains dissolved contaminants such as chlorides, sulphates and nitrates, which multiply its corrosive effect.⁽¹⁾ Also, moisture is formed by condensation when the temperature or pressure changes; it is pulled in at capillary joints or by hygroscopic materials; it is liberated by some materials and processes. Moisture enters compartments which are supposedly sealed.⁽²⁾

3.1.1.1 Condensate. During temperature variations, equipment which is sealed with O-rings or other gaskets will breathe, pull in cool moist air at night and expel warm (but not moist) air in the hot daytime hours. Eventually, there will be enough moisture to condense, and to collect in moisture traps such as sump areas. Similarly, electronic equipment shipped by air "breathes" because of the differential pressure between earth and flight conditions.⁽³⁾ Precipitation may occur inside compartments when cooling air is introduced. The cooling air meant to prolong the life of the equipment by removing heat, may, if unfiltered and undried, be an excellent source of moisture and contaminants. It may do much more harm than good. Moisture may condense as liquid water even when desiccants are used, either because there is not enough desiccant, or because it is not in the right location, or because a rapid change in temperature produces precipitation before the desiccant can react. This is especially liable to occur in static applications like shipping containers where there is no forced circulation of air. A pool of condensate was found in the container of one of the large missiles only a short distance away from quantities of desiccant.⁽⁴⁾

3.1.1.2 Hygroscopic Materials. Another possible source of moisture is a hygroscopic material. Some gaskets and packaging materials will absorb several times their weight of water. One memorable case of corrosion occurred when a structural part (magnesium missile fin) was surrounded by wet cushioning material.

3.1.1.3 Nonuniform Humidity. It is not necessary that all the air in a compartment be saturated with water vapor, or drop below the dew point temperature, in order to have condensation in one small area. Conditions of temperature and humidity are not necessarily identical throughout an enclosure. For instance, in some parts of missile silos, there is "standing water, running water, and dripping water"⁽⁵⁾ yet other areas are dry.

3.1.2 EFFECTS OF MOISTURE.

3.1.2.1 Properties. Water vapor has two intrinsic properties of special interest to the electronic designer:

1. Its vapor can and does absorb electromagnetic energy.
2. Water vapor in air increases flashover voltage between two electrodes.⁽⁶⁾

However, most of the effect of moisture on electronic equipment comes from its interaction with other materials, not from its own electrical properties. In a survey of field failures of electrical and electronic equipment, 35 percent were directly due to increased humidity.⁽⁶⁾ The detailed effects of moisture on various materials and components used in military electronics will be discussed later, but a brief review of the effect of moisture on common materials is given below:

3.1.2.2 Metals. Moisture is the most common corrodent. Galvanic corrosion between metals, stress corrosion, crevice corrosion, surface oxidation, electrolysis, silver migration, and whisker growth are all promoted or caused by the presence of an electrolyte, which is usually moisture. (See Section 6.)

3.1.2.3 Other Materials. Almost all materials, even glass, absorb moisture to some degree.⁽⁷⁾ Many organic materials lose mechanical strength or swell and lose dimensional stability, or like paper, completely disintegrate. Moisture lowers the dielectric strength, ignition voltage and volume insulation resistance of organic materials such as insulation and plastic laminates, while increasing the loss angle.⁽⁹⁾ In every instance, the effect of moisture is the opposite of that desired. Water vapor as it condenses and forms a thin layer on the surface of material, rapidly becomes ionized. Thus, it provides a conducting path and in addition, a capacitance effect because of its high dielectric constant. Tests have shown that most capacitors fail after the water absorption exceeds 0.1 percent. Quartz crystals fail if the amount of water vapor in the can is more than 0.004 percent of the volume.⁽⁶⁾ It is easy to see why hermetic sealing is necessary for such items. One factor seldom obvious to the electronic designer who runs short laboratory tests, is the gradual diffusion of water vapor through such seals as rubber, paint and many other materials. A molecule of water has a diameter of only 3.4 Å, so it can penetrate through a very small opening.⁽⁹⁾

3.1.2.4 Fungus Growth. The growth of microorganisms may occur anywhere in the world, but is most apt to be a severe problem under tropical conditions of high temperature and high relative humidity. Low humidity does not kill fungi but it slows down their growth so that they simply subsist and do no damage. Ideal conditions for maximum growth of most microorganisms are temperatures between 20° and 40°C (68° - 104°F) with relative humidity 85 percent to 100 percent. It was formerly thought that fungal attack could be prevented by coating nutrient material with a moisture proofing coating, or by drying the interior of the compartment with desiccants; but recent work has shown that some microorganisms remain in spore form for long periods of time, even under extremely dry conditions. They later revive to flourish again when moisture is available. Furthermore, many electrically insulating varnishes and some moisture proofing coatings are attacked by mold, bacteria, or other microbes, especially if the surface is contaminated by dust or other airborne particles.

3.1.2.5 Components. The components of interest to this study include electro-mechanical items such as switches, relays, circuit breakers, rotating devices, and indicating instruments; and electronic components such as resistors, capacitors, terminal boards, transformers, tubes, sockets, semiconductors, connectors, wire and cable. In many of these items the design is the governing factor, rather than the material of which it is made. However, in general, moisture has an adverse effect because it forms leakage paths, decreases the dielectric strength and insulation, and in some instances, causes electrolysis. It must be kept out. A survey of over 3,480 "unsatisfactory reports" on connectors at Norton Air Force Base showed 20% of the failures were due to moisture entering the plug.⁽¹⁰⁾ One must remember, in discussing the effect of moisture, that sand and dust are nearly always hygroscopic. A film of dirt or dust will maintain a higher moisture level on the surface of the part than is present on an identical part which is completely clean.

3.1.2.6 Low Humidity. Keeping the equipment dry will prevent corrosion from moisture but pose other problems. Very low humidity results in drying out rubber and other seals, shrinkage of many organic insulants and marked changes in electrical properties. While increases in insulation resistance and dielectric strength, with decreased loss angle, could be considered improvements, still any change can be detrimental to a precision electronic device.⁽¹¹⁾

3.2 TEMPERATURE

3.2.1 HIGH TEMPERATURE. High temperatures damage many electronic components and electro-mechanical devices, because they change the dimensions and properties of materials, and greatly increase chemical activity. A rule of thumb is that the rate of any chemical reaction doubles for every 10°C (18°F) increase in temperature; thus chemical attack, acid corrosion, and other harmful processes such as outgassing are stimulated and aggravated by high temperatures.⁽¹²⁾ Many organic insulating materials such as polyvinylchloride outgas at high temperatures with the two bad results of changing their own electrical characteristics, and emanating vapors which are corrosive to neighboring parts.⁽¹³⁾

3.2.1.1 Advantages. High temperatures can help electronic equipment by drying the atmosphere within the compartment. In some humid locations, operators have maintained reliability by burning a light globe all night inside the cabinet, thus keeping the temperature high enough to prevent condensation. When the equipment is started in the morning, its operating temperatures are high enough to maintain a dry condition. Another advantage of really high temperatures, (especially if accompanied by low humidity) is that they kill or discourage fungi. Molds and bacteria reach their maximum growth at temperatures between 20° and 40°C, (68° - 104°F), but temperatures much in excess of 40°C (104°F) deter them.

3.2.2 LOW TEMPERATURE. Low temperatures are not really dangerous from the point of view of corrosion. The greatest problem with extremely low temperatures, as in the polar regions, is the shrinkage of seals and gaskets with resultant leakage.

3.2.3 CYCLING. In most cases, the major corrosion problems are caused by changes or variations in temperature. The concurrent effect of temperature and humidity is the important thing. As the temperature drops and the relative humidity rises, precipitation occurs. In the tropics, for example, cool nights result in water condensate; in the northern temperate zones, cool nights may cause moisture to freeze. Figure 1 illustrates the amount of water vapor which can remain in the air at various temperatures. It is obvious that 50 percent relative humidity at 25°C (77°F) temperature becomes liquid water as the temperature drops to 10°C (50°F).

3.3 SALT ATMOSPHERE

3.3.1 OCCURRENCE. In addition to moisture, salt dissolved in water is an important factor in deterioration of electronic equipment. The ocean contains 3.5 to 3.9% salt,⁽¹¹⁾ so it is easy to understand how areas such as Indo-China, the Malay Peninsula, Central America and islands experience so much corrosion from salt spray. Many designers believe that rain, fog, sleet and condensate do not contain salt and therefore argue that only equipment intended for on-deck service in the Navy should have to withstand the salt spray test. Unfortunately, this confidence is misplaced. Table III shows that a significant amount of salt is carried by winds, many miles from the seashore. Actually, an appreciable amount of chloride ions has been measured in rainwater as much as 500 miles inland! Salt and other contaminants in the atmosphere are factors which must be acknowledged.⁽¹⁴⁾

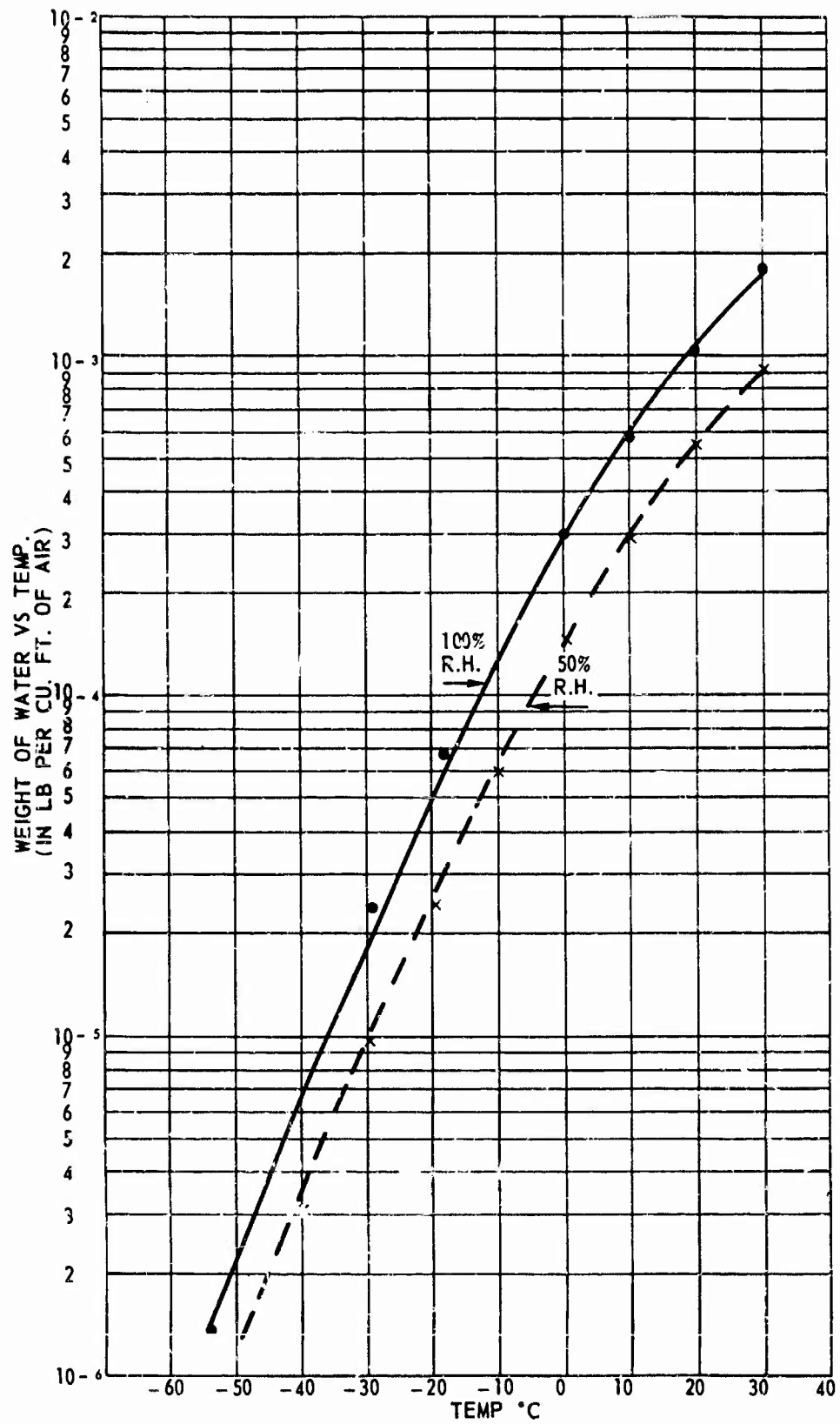


Figure 1. Water in Air Versus Temperature.

Table III
AMOUNT OF SALT IN AIR⁽¹¹⁾

Zone	Distance from seashore for salinity indicated (in mg salt/ cu. m. air)		
	Moderate (0.01 - 0.1)	Medium (0.1 - 1.0)	Intense (more than 1.0)
Polar	1.2 miles	—	—
Temperate	12.	1.2	exceptional
Tropic	124.	21.	0.6

3.3.2 EFFECTS. Salts dissolved in moisture have two separate damaging effects: (1) they are corrosive to many metals as well as to inorganic materials, and (2) they provide an active electrolyte which aids galvanic corrosion of dissimilar metals and promotes electrolysis of metals which either have different electromotive potentials, or are under different voltage in the circuit.

3.3.3 TEST. The salt fog test is resented and attacked by most design engineers, because it does not correlate with service life. But the salt test does intensify attack so that it quickly locates danger areas which could cause malfunction in operation. Repeated salt fog tests are often more severe than one continuous exposure of the same total time. Any salt test provides a rapid method (usually 50 hours) for comparing the effectiveness of coatings and protective techniques. Increasing the exposure time from 50 to 650 hours resulted in very few more corrosion spots, when testing electroless nickel deposited on magnesium alloys. Instead, the spots already visible after 50 hours exposure grew considerably in size.⁽¹⁵⁾ The salt fog test is valuable as a quick screening technique, and should continue to be used until a better method is developed.

3.4 OZONE AND CORROSIVE FUMES

3.4.1 OZONE. Ozone, one of the best known constituents of smog, is becoming a more serious problem in industrial atmosphere every year. It is formed naturally during thunderstorms and is especially prevalent in the tropics where such storms occur frequently. Ozone accelerates the oxidation of many insulating materials, being particularly harmful to natural (and some types of synthetic) rubber. Ozone is also produced by many welding machines. Instances of complete degradation of rubber seals have been traced to storage near welding equipment.

3.4.2 NITRATES. Nitrates occur naturally in rain water, with about five times as much present in the tropical zones as in temperate areas. However, most nitrate contaminants result from industrial processes, and thus reach a high level in the air of London, New York, Prague, and other manufacturing centers.

3.4.3 SULPHATES. Sulphur dioxide and other sulphates also occur in smoke and industrial gases. The combination of ozone, nitrate, sulphate and dust particles contributes to the rapid deterioration of organic insulation in urban areas.

3.4.4 OUTGAS. Plastics and other organic materials which are not completely cured often volatilize or "outgas", liberating corrosive vapors. These gasses are primarily moisture, hydrogen sulfide, hydrochloric acid, ammonia, and organic acids - all active in

attacking metals, plastics, elastomers, and insulation. The dangers of outgassing during storage have long been recognized: when items are confined in a closed package, even small amounts of vapor produce a harmful concentration. Outgassing may occur rapidly if temperatures are high, as in overheating during operation. Outgassing proceeds under normal room temperature conditions, but is accelerated by high temperature or low pressure, and is most serious in closed containers.

3.4.4.1 Sources. Most corrosive vapors come from incompletely cured organic material; examples are listed in Table IV. The extent of attack depends on the degree of cure, the plasticizer used, the temperature involved, and the assembly; whether it is closed or open to air. Paper and wood are very harmful. Paper liberates hydrogen sulfide, which tarnishes silver, copper, and brass; and acid vapors from wood (especially oak, chestnut, and cedar) attack metals. An unexpected source of trouble is adsorbed plating solution, which gives off acidic vapors. Another problem is that some volatile corrosion inhibitors actually attack cadmium. The worst offenders in regard to outgassing are polyvinylchloride insulation, polysulfide sealant, phenolic plastics, paper, and wood.

3.4.4.2 Materials Attacked. Cadmium is most susceptible to corrosive vapors, followed by silver, zinc, copper, and magnesium. Plastics and elastomers are also harmed, although not so quickly as the metals.

3.4.5 OXYGEN. The oxygen in air or water contributes to the corrosion of metals, deterioration of non-metallics, and growth of microorganisms such as bacteria, molds, and fungi.

Table IV*
ORGANICS AS SOURCE OF CORROSIVE VAPOR

Material	Severely Corrosive	Somewhat Corrosive	Not Corrosive
Adhesive	Ureaformaldehyde	Phenol-formaldehyde	Epoxy
Gasket	Neoprene/asbestos Resin/Cork	Nitrile/asbestos Glue/cellulose	—
Insulation (wire)	Vinyl Polyvinylchloride Vinylidene Fluoride	Teflon Nylon Polyimide	Polyurethane Polycarbonate
Sealer	Polysulfide	Epoxy	Silicone
Sleeving	Vinyl Polyvinylchloride	Silicone	—
Tubing	Neoprene, shrinkable		
Plastics	Melamine ABS Phenolic	Polyester Diallyl Phthalate	Silicone Epoxy Polyurethane
Varnish	Vinyl	Alkyd	—

*Section 3.4.4

3.5 SAND AND DUST

3.5.1 OCCURRENCE. Dust, as mentioned previously, is present in industrial areas where it often contains a number of tar products, ashes, and soot. Dust is also found in the desert, the dry powdery portion of sand carried by wind. In the arid regions, these small sand particles are often blown for miles by the sirocco winds.

3.5.2 EFFECTS. Sand and dust are highly hygroscopic, and when present on the surface of an electronic part, hold moisture and maintain a much higher level of humidity there than on a clean one. By their very presence, sand and dust can interfere with electrical contacts, prevent proper action of rotating and motor driven devices, and cause malfunction of indicating instruments.⁽¹⁶⁾ Moreover, dust from volcanic areas contains sulfur, which is highly corrosive to many materials.⁽¹¹⁾ ⁽¹⁷⁾

3.6 MICROBES AND ANIMALS

3.6.1 IMPORTANCE. "Microbial attack" (which as used herein, includes action of fungi, bacteria and molds) was first recognized as a significant problem in military logistics in World War II Pacific Theatre Operations. It deserves even more attention today. Modern microelectronics are more densely packaged and more susceptible to damage; today's equipment has a higher sensitivity, making it more subject to malfunction if attacked by fungi; many organics contain curing agents or plasticizers which make them funginutrient, and some molds and bacteria are developing resistance to formerly effective fungicides. The fungi commonly found, and most used in testing, are *aspergillus niger*, *aspergillus flavus*, *aspergillus versicolor*, *chaetium globosum*, and *penicillium funiculosum*.

3.6.2 NUTRIENTS. Molds, bacteria, and similar organisms are growing, living members of the plant world. They must have water and they need a supply of both hydrogen and oxygen for nourishment. Twenty years ago it was thought that only materials which had lived were fungi nutrient. Thus wool, cotton, rope, feather, and leather were known to be sustenance for molds, while metals and minerals were considered funginert. This belief is still considered valid, to a large degree. But the increasing complexity of synthetic materials makes it difficult, or impossible, for the designer to look at the name of a circuit board laminate or encapsulating resin and decide whether it will support fungus. Many otherwise resistant synthetics are rendered susceptible to microbial deterioration by the plasticizer or hardener used.⁽¹⁸⁾ Also, there are many different types of fungi and bacteria with diverse eating habits. In one area of Southeastern China, over 670 distinct kinds of molds were isolated from electrical insulating material.⁽¹¹⁾ The size, shape, surface smoothness and cleanliness; the environment; the type of microorganism; the service life - all of these affect the degree of fungal attack. There are many differences of opinion among authorities, probably due to the many factors influencing fungi, as illustrated in Table V. Instead of the definitive list of materials which do (or do not) support fungus, the trend today is that of MIL-STD-454, which lists a number of materials that may or may not be resistant, and recommends testing to establish the facts.

3.6.3 DAMAGE. The damage from microbial attack occurs in several ways:

1. Most molds are damp and after they grow across an insulating surface, can carry current and thus cause a short circuit.
2. Insulation is deteriorated and weakened.
3. Acids produced by microbial metabolic processes are corrosive to metals and glass, as well as to organic and synthetic materials.

4. Seals and gaskets of natural rubber are destroyed, permitting entrance of moisture and other corrosive agents.
 5. Microorganisms, in growing, form an expanding mass which can rupture, loosen, crack or blister any protective coating. (19)
 6. A semi-permeable capsule of microorganisms, under a blister, produces a local corrosion cell which accelerates corrosion of metals.
 7. Molds, in consuming solids or gases, can upset the electrical balance at the surface of metals and thus remove the passive film which confers resistance to corrosion. (19)
- While molds, fungi, yeasts and other such microorganisms can be destructive to electronic equipment, they do not always cause failure, (20) but they are very repulsive to operating

Table V*
FUNGUS RESISTANCE OF ELECTRONIC MATERIALS
(From Literature)

Material	Resistant	Some Types Resistant	Funginutrient
Acrylics	X		
Alkyd-Phenolic Lacquer		X	
Asbestos	X		
Cellulose			X
Cellulose Acetate	X	X	
Cellulose Nitrate		X	X
Ceramics	X		
Chlorinated Polyether	X		
Cotton			X
Diallyl Phthalate	X		
Epoxy Resin	X	X	
Glass	X		
Glyptal Varnish			X
Hair and Felt			X
Leather			X
Linen			X
Metals	X	X	
Mica	X		
Paper			X
Phenol Formaldehyde	X	X	
Phenolic		X	X
Polyacrylonitrile	X		
Polyamide	X		X
Polyester	X	X	
Polyethylene	X		
Polymethyl Methacrylate	X	X	
Rubber, Chloroprene	X	X	
Rubber, Natural		X	X
Rubber, Silicone	X		X
Silicone	X		
Silk			X
Fluorocarbon	X		
Wood			X

*Section 3.6.2

personnel. The presence of fungi and molds - damp, slimy, and bad-smelling - has a markedly demoralizing effect on people using the equipment. (21) For this reason alone, it would be important to take every precaution against microbial growth.

3.6.4 METALS. Because of the acidic nature of microorganisms and their action (see 3.6.3) even metals are sometimes subject to microbial attack. Minor surface contamination can be so aggravated by bacterial growth that it becomes a major problem - either because of local corrosion cells, or additional acid liberated. (19) Tests show that certain molds weaken or destroy metal wires. After 28 days exposure at 30°C, the results in Table VI were obtained. (22) (See 6.2.7.)

Table VI*
CORROSION OF METALS BY FUNGI (22)

Fungus	Metal (diameter in mm.)		
	Steel .415	Copper .070	Aluminum .420
Stachybotrys arta	No Effect	No Effect	No Effect
Chaetomium globosum	No Effect	No Effect	No Effect
Aspergillus niger	Formless Debris	80% Loss in strength	Some disintegration
Aspergillus amstelodami	Disintegrated	Weakened	Somewhat weakened
Penicillium cyclopium	Disintegrated	Disintegrated	Somewhat weakened
P. brevicompactum	Disintegrated	Weakened	Somewhat weakened
Paecilomyces varioti	Severe loss in strength	Weakened	Somewhat weakened

*Section 3.6.4

3.6.5 GLASS. Glass and optics are more susceptible to damage by microorganisms than are metals because of the coating used on optical parts. There are three kinds of fungus patterns: a spider-web, a flat starfish shape which leaves a milky stain, and minute circular spots which etch the glass. (23) The U.S. Army Electronics Command is quoted as saying "under proper condition of humidity, temperature and pH, fungi may grow on almost any surfaces." (24) This was borne out by tests of the Jupiter, in which many materials considered funginert were attacked. (24)

3.6.6 DUST. One of the least recognized contributors to microbial attack is the presence of dirt, dust and airborne contaminants on the surface of parts. Although unnoticed by operating personnel, these small amounts of airborne debris may be sufficient to promote fungal growth, as shown in Figure 2.

3.6.7 CONSENSUS. There is much disagreement about the habits and importance of specific molds. But there is one thing on which all using Services agree: treatment for the

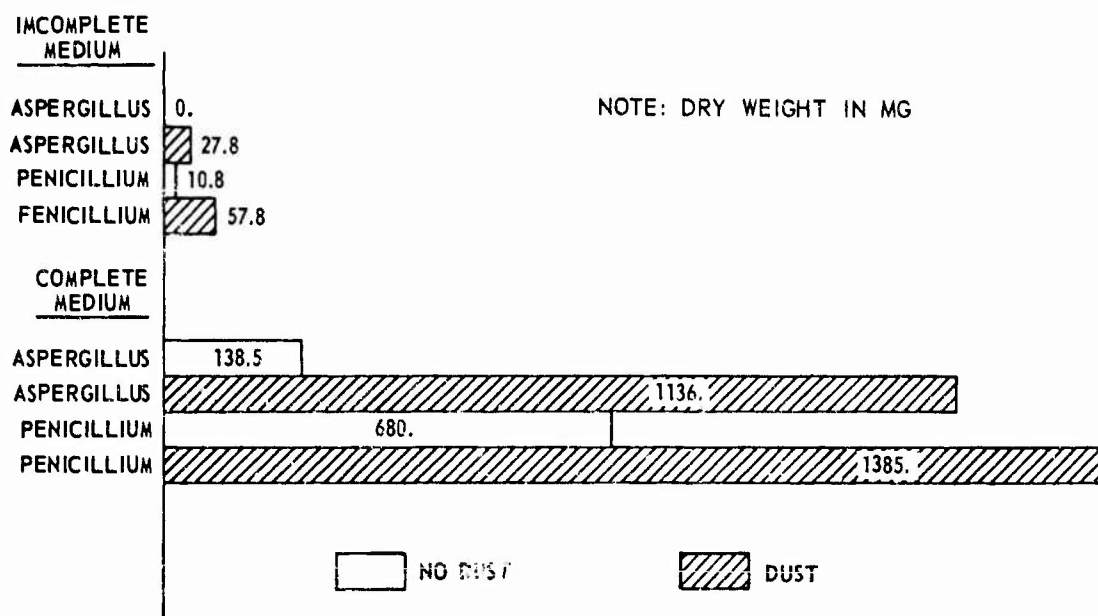


Figure 2. Effect of Dust on Fungal Growth.

prevention of moisture and fungal attack is worthwhile in protecting equipment, and should be used regardless of inconvenience. (11, 16, 21, 26)

3.6.8 INSECTS AND ANIMALS. A minor problem which should not be overemphasized but cannot be neglected, is the possibility of damage from termites, beetles, and even larger animals, in the tropical zones. These forms of animal life can harm electronic equipment

1. By devouring the structure (as termites have done, eating wooden antennae or posts)
2. By destroying insulation
3. By causing short circuits

Termites ("white ants") are the worst danger. Their ability to ruin wooden buildings is well known, but it is not so well recognized that they also eat all materials of cellulosic base, such as paper, cardboard, plywood, and the like. Studies in Australia indicate few common plastics are wholly immune to termite attack. Polyvinylchloride, polyethylene, and cellulose esters are most severely attacked. (27). Insect larvae such as clothes moth destroy rayon, PVC, polyacrylonitrile, polyester, and polyamide (in order of decreasing susceptibility). (28) Rats have done much damage by eating cable coating. Table VII, based on information from Rychtera and Bartakova, (11) illustrate the need for careful selection of materials and for use of preventive techniques.

3.7 PRESSURE (ON EARTH)

If electronic equipment is intended for service in a high-pressure environment (such as deep submergence vehicles) it must be designed to withstand the mechanical loads caused by high pressures. Ordinarily, no special corrosion problems are anticipated, except that structural parts under pressure are subject to stress corrosion. But if equipment is to operate at low pressure (high altitude) or even is to be transported by air under low pressure conditions, the designer should take special care. Low pressure presents three problems:

1. Arc-over, because the breakdown voltage is proportional to the gas-pressure times the flash-over distance.
2. Corona, at lower voltages.
3. Poor cooling, since convective heat transfer is proportional to air density.

Table VII*
TERMITE ATTACK⁽¹¹⁾

Not Attacked	Slightly Attacked	Markedly Eaten
Ceramics	Polytrifluorochloroethylene	Polyamide (Nylon)
Epoxy	Polytetrafluoroethylene (Teflon)	Polypropylene
Glass	Rubber	Polyvinylbutyral
Melamine plastic	Soft Metals	Polyvinylchloride
Phenolic plastic		(plasticized)
Polymethylmethacrylate		
Polyvinylchloride (hard)		
Synthetic wax		

*Section 3.6.3

Wave guides are very subject to damage from low pressure. Such components as terminal boards, resistors, capacitors and transformers are especially liable to damage from arc-over or corona.⁽¹⁶⁾ Moreover, if equipment is shipped by air, and thereby exposed to cycling low and high pressures, there is danger of leaky seals and "breathing", with consequent condensation. Problems of extremely low pressure in space are discussed in 3.9.1.

3.8 SOLAR RADIATION

3.8.1 OCCURRENCE. The two ranges of the solar spectrum which are most damaging to materials are the ultraviolet, about 3800 Å, and the infrared, 7800 Å. On earth (for space, see 3.9), maximum solar radiation occurs in the tropics and equatorial regions, but there is still considerable damage in the temperate zones from solar heating, photochemical effects, and combinations of these two phenomena.

3.8.2 EFFECTS. Non-metallics, especially organic and synthetic materials, are the ones most affected by sunshine. Both natural and synthetic rubber deteriorate rapidly; plastics darken; paints lose their protective characteristics; polymers undergo marked decreases in strength and toughness; colors fade, thus removing essential color coding. Fortunately, most electronic equipment is within enclosed structures, and is protected from solar radiation. When parts such as cables, harnesses and the like are mounted outdoors, extra care must be taken in the selection and surface treatment of organics thus exposed to sunshine.

3.9 SPACE ENVIRONMENTS

The two space environments of major importance in deterioration control are extremely low pressure, or vacuum, and radiation - cosmic, solar and nuclear. Electronic components are much more affected by these space environments than are structural parts, primarily because of the widespread use of non-metallic materials. So much has been published on the effect of space environments, that only brief mention will be made in this report. For details, refer to Redstone Scientific Information Center Reports 150 and 151 (references 29 - 39) on Space Environmental Effects on Materials and Components; to reports and accession lists from Radiation Effects Information Center; and to other recent publications, references 40-53.

3.9.1 VACUUM. The primary effect of the high vacuum in space is to produce outgassing, or weight loss, which usually causes a considerable change in properties. A secondary but often very important effect is the deposition of the outgassed constituents onto nearby surfaces, thus contaminating electrical contacts or optics. In addition, the problems of arc-over and corona (see 3.7) are present. Metals as well as organic materials will evaporate in vacuum. Cadmium, selenium, zinc, tellurium, magnesium, and lithium are the worst offenders in this regard. However, the major danger of deterioration arises from the outgassing of plasticizers, with resultant changes in properties of the plastic remaining; or breaking a long-chain polymer into smaller fragments, again with different properties from the original material. Most oils and greases have too high a vapor pressure to be useful in space; sometimes the various constituents evaporate at different rates, changing the lubricity. In selecting materials for use in vacuum, consideration should be given to the degree of vacuum anticipated, the time of exposure, and the detailed design.

3.9.2 RADIATION. Solar radiation has already been mentioned (3.8). Cosmic radiation, while not significant on structural materials, does affect some components such as transistors; it also produces "noise" in some circuits because of ionization effects. But the big problem in space, for electronic components and materials, is nuclear radiation. To summarize the effects:⁽²⁷⁾

Metals:	Hardness increased, ductility decreased.
Elastomers:	Strength decreased.
Fluorocarbons:	Strength and hardness degraded markedly.
Plastics:	Properties change.
Insulation:	Chemical changes, weakening.
Dielectrics:	Little effect on electrical properties.

For specific effects on various kinds of components, check references 29 - 53.

3.10 TEST METHODS

In order to establish the ability of materials, components, and equipment to withstand the environments discussed above, standard test procedures have been developed through the years. In the past, there were a number of different, often conflicting, test methods. Today, the trend is towards unification and simplification. The number of tests has been minimized, and the conditions have been made more realistic.⁽⁵⁴⁾ Components are generally tested per MIL-STD-202 and equipment per MIL-STD-810, as indicated in Table VIII.

Table VIII*
TEST METHODS

Environment and Paragraph	Component (MIL-STD-202)	Equipment (MIL-STD-810)
Moisture - 3.1		507
Humidity	103B	—
Moisture	106B	512
Immersion	104A	506
Rain	—	
Temperature - 3.2		501
High	—	502
Low	—	504
Cycling	102A	503
Thermal Shock	107B	
Salt Fog - 3.3	101B	509
Sand and Dust - 3.5	110	510
Fungus - 3.6	—	508
Pressure, Low - 3.7	105C	500
Sunshine - 3.8	—	505
Space - 3.9	—	517

*Section 3.10

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SECTION 4 DEGREE OF PROTECTION

4.1 CATEGORIZATION - SYSTEMS

There are many ways of classifying items to determine the environments anticipated and the degree of corrosion protection needed. Some of the classifications are based on the physical location of the equipment, others on the end use. MIL-STD-466 lists eight classes: equipment for ground use; for use where electric stability is of prime importance; for shipboard and ground service, for aircraft and missiles; for specialized applications in aircraft and shipboard; for nuclear-powered aircraft and ballistic missiles; for specialized applications in aircraft and missiles; and for nuclear-powered weapons. MIL-STD-810 has three groups of electronic equipment: ground equipment sheltered; ground equipment unsheltered; and aerospace equipment, electronics and communications. MIL-STD-454, Requirement 16, suggests metals be classified as to whether they will be submerged in sea water, exposed to atmospheric environment, in protected environments, or for use in unusual temperature or chemical environments. MPD 11101 has two large groups, missile and ground service. A contractor suggests classification by mission, into air-to-air missiles, ground-to-air missiles, mobile ground equipment, space vehicles, supersonic aircraft, and fixed installations.

4.2 CATEGORIZATION - CIRCUITS

Probably all circuits are essential, or they would not be included. However, some circuits are critical - for instance, the launch circuitry in a missile silo - while others are useful or convenient. In deciding what degree of protection is needed, a good criterion for the designer is to assign a rating of critical, major, or minor, to each part. A fuse, or guidance for a missile, or any other item which must operate satisfactorily the first time, is a "critical" part which requires all the best techniques available.

4.3 FACTORS CONSIDERED

4.3.1 IMPORTANCE OF FUNCTION. The controlling factor in determining the degree of corrosion protection needed is the importance of the specific part or circuit. What would be the consequence of malfunction? Is there a back-up or alternate in case of system failure?

4.3.2 ENVIRONMENTS ANTICIPATED. The next step in establishing the degree of protection needed is to define the environments expected. A missile, or any military electronics, must be operative and reliable under tactical conditions of damp and dark and confusion, as well as in an air conditioned laboratory. For an all-weather world-wide missile, the extremes of MIL-STD-210A should be considered reasonable. In addition to temperature, pressure, and humidity, there is a fourth important environment - time. The period of storage or the time between inspections differs from one system to another, and has a significant influence on the amount of corrosion protection required. Ground installations with monthly maintenance need less attention to deterioration prevention than is necessary for missiles with a five-year storage life.

4.3.3 TYPE OF DESIGN. Much commercial equipment is designed to achieve reliability by allowing wide space between conductor paths, making reasonable demands on components, and in general, accepting less than maximum design efficiency. In missile electronics, designers can seldom do this. They are given a minimum space envelope, a maximum weight, and a fantastic number of functions which must be performed. Nevertheless, some circuits

are definitely more critical than others. The designer should decide which are the high impedance, high amplification, densely packaged items, and provide maximum protection for them. Among the things to be considered are:

1. Density of packaging
2. Size of components and leads
3. Amplification of circuit
4. Impedance
5. Spacing between conductor paths

4.3.4 REPAIR OR REPLACEMENT, ACCESSIBILITY. A part which is easily accessible for inspection, maintenance or replacement, may not require the extreme corrosion protection given to other components less fortunately situated, especially if regular checkouts are scheduled. In missiles, there are many areas which are physically inaccessible in the field or in forward echelon repair shops. At the time of initial design, little is known of which parts will be furnished as spares, what repair facilities will be available at what echelon, and other logistic factors. Therefore, the designer must assume the worst, to ensure reliability in all instances.

4.3.5 SPECIFIC APPLICATION. Missiles are intended for one-time use in an emergency situation, after an extended period of transportation and storage which may last for years after manufacture. To determine how much corrosion protection is needed, each designer should consider, in addition to the factors listed in Table XI, "What would be the effect of a failure of this part in service?" Corrosion and deterioration control measures should be based on realistic answers to this question.

4.4 TRADE-OFFS

When all the factors are known, the decision must be made whether optimum corrosion protection is worth the time necessary, the extra cost, and the additional weight. Often this decision is made by the procuring agency. Also, the time, money and weight needed for complete protection can be minimized if corrosion is considered at the inception of design instead of being added later, to overcome problems discovered in environmental testing. The purpose of this report is to provide data which will enable the designer to make intelligent decisions on corrosion preventive measures and to achieve maximum reliability without excessive expenditure of time, money, or weight (see Table IX).

Table IX*
FACTORS AFFECTING NEED FOR CORROSION PROTECTION

Non-Operating

Storage and Shipment

Type of Packaging
Environments
Time

Frequency of Inspection

Time Intervals
Maintenance?
Checkout?

Operating

Function

Critical - Major - Minor
Consequence of Malfunction
Back-up or alternates?

Environments

World-wide, all weather?
Time

Design - Type of Circuitry

Trade-off

Cost)

Weight) - vs. Loss in Reliability

Time Required)

*Sections 4.3.5 and 4.4

SECTION 5

TECHNIQUES FOR CORROSION PREVENTION

5.1 SCOPE

Basically, there are four ways to preclude damage from corrosion of electronic equipment:

1. Use materials and finishes which are not attacked by moisture, temperature, salt, fungi, etc.
2. Change the environment so it is not harmful, by removing moisture, cooling, killing fungi, etc.
3. Prevent the corrosive media from reaching the surface of materials, by sealing assemblies, encapsulating components, coating parts, etc.
4. Detect deterioration before it progresses, by periodic inspection and maintenance.

It is usually expensive and impractical to rely only on one of (1), (2), (3), or (4) above. Few materials are completely unaffected by all environments; few environments are completely benign; and no coating is perfect. A combination of these techniques produces the best results for the least money. The selection and treatment of metals and non-metals will be discussed in detail in Sections 6 and 7. Various ways to reduce the severity of the environment, regardless of the material involved, are discussed in the first part of this section. The second half deals with techniques for preventing the environment from contacting the parts or materials. Table X gives an overall view of the methods employed.

5.2 SELECTING RESISTANT MATERIALS

5.2.1 METALS. Select the most resistant metal practical for the purpose; or apply gold or rhodium plating to protect the surface; or passivate, forming a thin protective film on the surface. Anodize aluminum where the electrically insulating layer can be tolerated. Avoid use of dissimilar metals in contact with each other. And be careful to provide for assembly without deformation which could cause residual stress. (See Section 6.)

5.2.2 NON-METALS. Use materials which are not nutrients for fungi. Select plastics with low moisture absorption, 1 percent or less. ⁽¹⁾ Use neoprene and other ozone-resistant types of rubber. (See Section 7.)

5.3 AMELIORATING THE ENVIRONMENT

5.3.1 VACUUM. In a perfect vacuum, there is minimum corrosion because there is no oxygen, no moisture vapor, and no corrosive fumes except outgas. Small components are often preserved by evacuation and sealing. Evacuation is not much used on large assemblies because of cost, difficulty of sealing, and problems of outgassing.

5.3.2 INERT GAS. Use of nitrogen or other inert gas instead of air has been tried, especially for long-time storage to remove both moisture and oxygen. This practice involves evacuating the air, filling with dry nitrogen, and sealing. It has not proved completely satisfactory as sometimes nitric acid is formed; it offers little advantage over evacuation and sealing. Use of dry argon is preferable.

5.3.3 REMOVE MOISTURE. Moisture can be excluded or minimized in electronic equipment by good design (see 5.3.3.5); proper application of seals and gaskets, including hermetic seals (see 5.4.1, 5.4.2); avoidance of hygroscopic materials (see 5.3.3.4) and use of desiccants. Relative humidity within a package or compartment can be kept at a safe level, say below 30 percent, by desiccants, usually silica gel or alumina gel. For visual

Table X*
CORROSION PREVENTION TECHNIQUES

I USE MORE RESISTANT MATERIALS

A. Metals:

1. Use stainless steel, nickel, tin, etc.
2. Plate with a nobler metal
3. Passivate or anodize surfaces
4. Avoid dissimilar metal contact
5. Avoid residual stresses

B. Non-Metals:

1. Use funginert materials
2. Use plastics with low-moisture absorption
3. Use ozone-resistant rubber

II REDUCE SEVERITY OF ENVIRONMENT

1. Evacuate, removing air and contaminants
2. Introduce inert gas instead of air
3. Remove moisture by filters, desiccants, and design
4. Cool equipment
5. Use corrosion inhibitors
6. Use fungicides
7. Avoid sources of corrosive vapors
8. Eliminate dust and dirt

III PROTECT MATERIAL FROM ENVIRONMENT

1. Hermetically seal components
2. Seal and gasket assembly
3. Encapsulate, embed, pot
4. Coat surfaces
5. Interpose insulating barrier

IV PERIODIC INSPECTION AND MAINTENANCE

1. Locate critical parts for easy replacement
2. Locate humidity indicators for good visibility.

*Section 5.1

indication of humidity level, the silica gel is modified by cobalt chloride which changes color when wet. The indicator should be placed in the air stream, where it is visible from outside. A dark blue color shows low humidity.

5.3.3.1 Solar Breather. For ground equipment, a useful device is the Solar Breather. This is a two-chamber box filled with silica gel which is placed over the only opening from the trailer, tank, or equipment compartment. Chamber 1 is in equilibrium with the outside air,

and chamber 2 is in equilibrium with the inside air. The two chambers are separated by a baffle which does not extend quite all the way to the bottom of the box. During the night, as the temperature drops, cool damp air comes into the equipment through this silica gel chamber, where much of the moisture is removed. During the day, the heat of the sun warms the box and, to some extent, dries the silica gel. ⁽²⁾

5.3.3.2 Filters. Moisture may be removed from incoming air by forcing it through traps or filters. These filters must be replaced, cleaned and/or dried to maintain adequate operation.

5.3.3.3 Limitations of Desiccants. First, silica gel or any similar drying agent will absorb moisture from the atmosphere around it only until there is equilibrium between the amount of moisture in the air and in the desiccant. Therefore, there must be enough desiccant to secure a low level of humidity throughout the package. Second, the desiccant should be distributed well enough in various parts of the compartment to assure a uniformly low moisture level. Third, desiccants do not produce "instant dryness." It takes time for the desiccant to react with moisture in the air. Fourth, if the desiccant becomes saturated, it may hold moisture on some susceptible item and corrode it.

5.3.3.4 Hygroscopic Materials. Use non-wicking, non-hygroscopic gaskets, to prevent moisture intrusion. Do not use felt, leather, cork, asbestos, nor glycol-impregnated gaskets; do not use cotton wicking in electrical cable. ⁽²⁾ Seal the cut edge of glass-laminated circuit boards to prevent moisture intrusion. One microwave group increased the gain 2 db by keeping water out of the boards.

5.3.3.5 Good Design. Water can be kept out of equipment by good design. Avoid wrinkle finish and uneven surfaces or low spots where water can collect. If moisture cannot be excluded, provide drain holes to let it escape. Keep gasket area to a minimum, because the longer the gasket, the greater the leakage. Remember that crimped, spot welded, and threaded joints all draw in moisture through capillary action, due to alternate expansion and contraction from temperature changes, so provide for a sealant bead (see Section 5.4.2).

5.3.4 COOL. Keeping equipment from getting too hot by use of cooling air, heat sinks, fins, etc., is an important part of prevention of deterioration. However, cooling air can introduce contaminants. Sometimes the effort to provide clean dry cooling air is self-defeating. In one plane recently, the moisture filters for the cooling air became completely clogged with fine dust after brief service at a desert air base, and the electronics malfunctioned because of overheating.

5.3.5 CORROSION INHIBITORS. First introduced during World War II for rust prevention, volatile corrosion inhibitors (VCI) can be incorporated in oils or greases, or in packing material. VCI materials are particularly effective in preventing rust on ferrous metals. The original inhibitor, dicyclohexylamine nitrite, attacked bare cadmium and zinc, but did little damage to chromated surfaces. New VCI materials are made specifically for preventing sulfide tarnish on silver or oxidation of copper, or stains on aluminum. ⁽³⁾ The inhibitor can be obtained in crystals, liquid, or tablets; or in oils or greases or packing papers.

5.3.5.1 Limitations. Volatile corrosion inhibitors do not reduce the amount of moisture in the air; they simply render moisture non-corrosive to ferrous metals. Certain types are harmful to nonferrous metals. VCI is not useful for non-metallics.

5.3.6 FUNGICIDE. To protect equipment against microorganisms, a fungicide is frequently introduced into a varnish or other coating. Around 500 fungicides are now available commercially, for treating different types of material and killing various kinds of molds and

bacteria. In this country, electronic designers usually depend on MIL-V-173, a paraphenyl phenolformaldehyde varnish containing salicylanilide as the fungicide. However, the copper 8-quinolinolate which has been so successful in fungus-proofing textiles, is preferred by many instead of salicylanilide.

5.3.6.1 Requirements. A fungicide must kill microorganisms, of course, but it must accomplish this action without affecting other properties. An ideal fungicide should have six features:(4)

1. Destroy the organisms expected to attack that material or part .
2. Be compatible with the carrier, (the material in which it is incorporated), not affecting color fastness, or other properties.
3. Be harmless to parts or materials to which it is applied.
4. Be nontoxic to humans.
5. Remain stable for long periods of time under varying environmental conditions, including color stability.
6. Do the above at low cost.

Possibly the most difficult problem is getting a fungicide which can meet requirement (5), long-time stability. Many of the "best" fungicides, including salicylic acid, are so volatile that they lose their effectiveness in a short time.(5) The copper 8-oxyquinolinolate has lowest volatility, but has the disadvantages of a dark green color and relative insolubility in organic materials.(6) No fungicide meets all desires.

5.3.6.2 Types. Much work is being done, not only in this country but all over the world, on new and better fungicides. No one composition is suitable for incorporation in the many coatings, waxes, and varnishes used, and for treatment of plastics and cellulosic materials. One determined German scientist tested 41 different modifications of 8-quinolinol, 33 types of nitroso compounds, 20 oximes, and 10 phenanthrolines.(7) He concluded the 8-quinolinolates are best. But recent attempts in this country to incorporate copper-8-quinolinolate in encapsulants, while effective in killing fungi, resulted in "blooming" of the fungicide on both silicone rubber and polyurethane.(8) Sometimes the carrier destroys fungicidal properties.(9)

5.3.6.3 Application. In addition to applying a fungicide in a coating or varnish, and using funginert materials as much as possible in preference to those which are funginutrient, the designer should keep humidity as low as practical, by sealing or desiccant. The manufacturer should insist on maximum cleanliness, minimum dust in assembly areas, and wearing of gloves when handling electronic components. The number and variety of microorganisms present in the human fingerprint are amazing.

5.3.6.4 Avoiding Fungal Attack. Observe the following rules:

1. Use funginert materials
2. Use fungicidal coating
3. Use desiccant to maintain low humidity
4. Seal compartments to maintain low humidity
5. Hermetically seal, if necessary
6. Avoid dust, handling, and fingermarks

5.3.7 AVOID CORROSIVE VAPORS. Preventing corrosion by excluding air or oxygen (5.3.1) and moisture vapor (5.3.3) have already been discussed. It is equally important to prevent contact by other corrosive gases, such as those liberated by outgassing plastics (3.4.4) during manufacture, storage, and operation. In restricted spaces, such as closed packages, even small amounts of vapor can reach dangerously high concentrations.(10) Sources of corrosive vapors are listed in Table XI. To prevent deterioration from corrosive

gases, the designer should:

1. Select organic materials which do not give off corrosive vapors; epoxys, polycarbonates, polyurethanes, silicones;
2. Avoid overheating, this accelerates outgassing;(11)
3. Avoid materials which outgas badly; polyvinylchloride, polysulfide, phenolic, paper, wood;(12)
4. Cure organics completely before assembly to minimize outgassing;
5. Never use cadmium in a closed assembly with organic materials. (Even paint films can outgas enough to attack cadmium.)
6. Clean thoroughly after plating; trapped plating solution gives off acidic vapors. (13)

Table XI*
SOURCES OF VAPOR

Source	Vapor	Attacks
Welding Machine	Ozone	Rubber, Plastics
Organics (Table IV)	Sulfur, acid, (H Cl) ammonia	Metals
Propellants	Ammonia, Acid	Plastics, Metals
Lubricants	Hydrocarbon	Plastics
Adhesive	Acid	Metals
Paper	Sulfur	Silver, Copper
Plating Solutions	Acid	Cadmium, Zinc

*Section 5.3.7

5.3.8 INCOMPATIBLE MATERIALS. Some materials are harmful even though they do not give off corrosive gases. They may attack chemically (see 7.2.6) or accelerate failure (see 6.2.4) or simply be incompatible, like oil and water. Oils, greases, thread lubricants and some sealants "creep" from their original location, contaminating adjacent plastics and loosening protective paint films. Examples are given in Table XII. Propellants pose a special problem, especially to plastics and elastomers. Data on specific materials and their reaction to propellants is summarized in a recent report "Compatibility of Plastics with Liquid Propellants, Fuels, and Oxidizers" published by the Plastics Technical Evaluation Center, Picatinny Arsenal, in January 1966.

5.3.9 ELIMINATE DUST AND DIRT. The importance of dust as a contributor to corrosion and fungal attack has already been discussed. Precision instruments are usually assembled in a "clean" room to avoid contamination from dust. Another source of corrosion is the human fingerprint - always damp, often acid, and sometimes transferring harmful microorganisms to the surface of items handled. Wearing gloves when handling electronics, and using fingerprint remover to clean parts before final assembly, are good insurance against contamination.

Table XII*
INCOMPATIBLE MATERIALS

<u>DO NOT USE</u>		
Copper, Manganese	with	Rubber
Cyano-Acrylate Sealants	with	Cellulosics, Methacrylate, Polycarbonate, Styrene Vinyl
Diester Oils	with	Neoprene, Plastics
Hydrocarbons, Ketones	with	Acrylics, Cellulosics, Vinylchloride
Ketones, Esters, Alcohol	with	Vinyl Butyral
Paper	with	Copper or Silver
Silicone Oils and Greases	with	Metals to be coated

*Section 5.3.8

5.4 PROTECT EQUIPMENT FROM ENVIRONMENT

5.4.1 HERMETIC SEALS. A true hermetic seal is completely airtight, preventing the entrance (or escape) of air and, therefore, of moisture. It is usually a metal-to-metal or metal-to-glass seal, both of which are impervious to air and moisture. A hermetic seal is a permanent seal, normally used only on miniature or small parts because of cost and weight involved. For maximum reliability in adverse and extreme environments, the hermetic seal is a very effective design technique. One disadvantage is that these sealed parts do not dissipate heat, and are hard to cool. (15) Also, a hermetic seal does not always guarantee freedom from corrosion. Materials inside can outgas and deposit on contacts..

5.4.2 SEALS AND GASKETS. When parts must be accessible for repair, adjustment, or maintenance, the entire assembly cannot be sealed hermetically. Then, gaskets and sealants prove very useful in keeping out moisture, especially in conjunction with proper surface protection and added desiccants. However, gaskets and sealants do NOT produce a hermetic seal.

5.4.2.1 "Seals" and "Sealants". "Seals and gaskets" are considered to be those solid pre-shaped items used to prevent moisture and/or air from entering (or leaving) an assembly. They may be metal, rubber, leather, asbestos, tape, shrinkable tubing, etc., and are normally chosen for mechanical rather than electronic reasons. "Sealants" are bulk materials, usually liquids or paste, which solidify after application and form "seals." Either seals or sealants are needed around threaded closures, spot-welds, and mechanical joints, due to danger of capillary action pulling moisture in.

5.4.2.2 Caution. One dictionary meaning of the word "seal" is "a tight and perfect closure." This definition has led to misconceptions. Actually, only a hermetic seal affords a "perfect" closure: all other seals provide a controlled, perhaps very small and slow, rate of leakage. Many seals "breathe" and permit moisture to enter the package or compartment. Some sealants do not adhere perfectly to the mating surfaces. Others form an air-tight seal

for a short time, but lose this quality when temperature variations cause dimensional changes, or changes in pressure cause breathing. It is important to remember that within a "sealed" package moisture can condense and corrosive vapors can be very damaging. Also, a "humidity-sealed" component is not "hermetically sealed." For instance, a potentiometer using O-rings for a moisture barrier, was ruined by vacuum encapsulation at a later stage of assembly. The encapsulant was drawn into the device because the O-ring seal was not tight enough to withstand the pressure differential. The engineer who specified vacuum encapsulation did not understand the difference between "hermetic" and "humidity" seals.

5.4.2.3 Requirements. The choice of type of gasket or seal is dictated largely by mechanical design considerations. For use in electronic assemblies, there are five attributes needed. Regardless of whether a solid gasket or putty-like caulking material is used, it must be:

1. Moisture proof
2. Non-corrosive (see Table XI, 5.3.7 and 5.3.8)
3. Funginert
4. Non-hygroscopic
5. Flexible, to compensate for thermal expansion and contraction.

5.4.2.4 O-Rings. When choosing O-ring type seals for electronic equipment, specify virgin neoprene, chlorosulfonated polyethylene, Teflon, or silicone rubber, to avoid deterioration from ozone, maintain properties through a wide temperature range, and provide minimum permeability to moisture vapor. (See 7.6.1.) Avoid blended or re-used materials which have shown a markedly higher leakage rate than virgin compositions.

5.4.2.5 Sealant/Adhesives. If one of the many caulking-type sealants is to be used, check it against the five requirements in 5.4.2.3. In addition, consider the parts to be sealed. Epoxy, polyurethane, polyester and polysulfide adhere well to metal. (Polysulfide liberates sulfur - see Table IV). For sealing silicone rubber, silicone varnishes, etc., a silicone adhesive must be used. On fluorocarbons, a preparatory surface treatment is necessary to get adhesion. A recent case of failure in a "sealed" device was traced to poor adhesion between polysulfide sealant and a Teflon-jacketed cable which had not been adequately prepared. Moisture entered the device and caused a short circuit.

5.4.2.6 Tape. Adhesive-backed tapes are used in electronic equipment primarily for electrical insulation. However, they can also provide moisture-proof, conformable, flexible seals around a component or assembly. Both unsupported and supported films are used. Vinyl tape is a good insulator between dissimilar metals. The self-bonding silicone rubber tape forms a continuous mass with the moisture-proofing and insulating qualities of silicone rubber. With tape as with other parts, the designer should select materials like silicone rubber, which are non-corrosive, and do not outgas nor absorb moisture nor support fungus.

5.4.2.7 Shrinkable Tubing. A recent innovation in sealing is the use of irradiated tubing which shrinks as much as 50 percent in diameter when heated to temperatures of 100° to 150°C. As it shrinks, it conforms to the shape of the object inside, providing electrical insulation, mechanical support, and corrosion protection. Tubing is available in polyolefin, neoprene, polyvinylchloride, polyvinylidene fluoride, TFE, and silicone rubber compositions; it may be rigid or flexible, translucent or opaque. Heat shrinkable polytetrafluorethylene (TFE) must be heated to 327°C, but FEP will shrink at 150°C. Silicone rubber is preferred because it is resistant to ozone, temperature, moisture and fungus, and does not corrode metals. Combination sealing and encapsulating is possible with a two-part polyolefin tubing, also available in closed-end caps. The inner wall melts during heating and is forced to embed

whatever it surrounds by shrinkage of the outer wall, thus achieving moisture proof encapsulation. This type of seal-encapsulation is especially good on crimped joints and connectors.⁽¹⁵⁾ Polyester tape can also be obtained in heat-shrinkable compositions.

5.4.2.8 Zippered Tubing. A similar method of protecting wires, cable, and harness is to zipper them inside a tube, then apply a liquid sealer to the zipper tracks. After sealing, it becomes a water tight, permanent assembly. This tubing can be bought in polyvinylchloride, silicone rubber, heat shrinkable vinyl, polyethylene, and many special materials. From the viewpoint of corrosion prevention, silicone rubber is preferred.

5.4.3 ENCAPSULATION. A technique which approaches hermetic sealing in effectiveness is that of encapsulation (sometimes called embedment) or enclosure in an impervious coating. Encapsulation methods include impregnation, potting, casting, transfer molding, and conformal coating⁽¹⁶⁾ all of which are discussed in Section 7.10. No matter what method is used, encapsulation provides protection from corrosive attack and mechanical shock, and increases electrical insulation. If properly done with good adhesion between parts and all cavities and voids completely filled, encapsulation affords a high degree of environmental resistance,⁽⁶⁾ but it is still not hermetic sealing, even though so-called in some foreign publications.⁽¹⁷⁾ All resins do absorb moisture, but so very slowly that about 0.060 in. thickness will protect components.⁽¹⁶⁾ Because it adds weight and concentrates heat, encapsulation is mainly used on small parts.

5.4.4 COATINGS. Thin coatings are often sufficient to insulate parts from moisture or other corrodents in the environment. Such instances as paint films, and metallic plating, are common. However, many plated layers are porous or cracked, and most organic coatings have pinholes. For electronic items, where protection is so important, a multilayer coating system is required to provide an impervious barrier. Three thin layers give much more protection than one layer of the same total thickness. Metallic coatings are discussed in Section 6.7, and organic coatings in Section 7.13. Generally, the epoxy, polyurethane and silicone coatings are most widely used for moisture proofing and corrosion resistance.

5.4.5 INSULATING BARRIER. Interposition of an insulant such as vinyl tape, is a good way to prevent contact which could cause galvanic corrosion (see 6.3), but care must be taken to select non-corrosive tape. Organic insulation is also widely used to protect cables and harnesses. Basically, coatings and encapsulants are also insulating barriers.

5.5 MAINTENANCE

Deterioration is a gradual, progressive change. If designers can locate sensitive items where they can be inspected and serviced, much failure can be precluded. It is especially important to have visible indications of humidity conditions within a closed compartment.

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SECTION 6 METALS - DETERIORATION

6.1 METALS IN ELECTRONICS

A recent survey of 86 leading aerospace and electronics manufacturers brought out the facts that (1) corrosion is a frequent cause of malfunction of electronic equipment, and (2) galvanic corrosion of metals is the factor most often blamed. There are three reasons for the prevalence of metal corrosion problems in electronic equipment:

1. Almost every metal is being used in electronic equipment;
2. The resistance of a metal to attack is not a constant quality;
3. Many designers of electronic devices are not aware of corrosion dangers.

The deterioration of metals and the preventive techniques necessary are quite familiar to designers of structures for outdoor service. Designers of electronic equipment, however, remember that electronic devices are within a compartment, protected from rain and snow, and not so subject to corrosion. Unfortunately, corrosion of metals can be much more damaging in electronic parts than on structures because electronic items are usually so small that a very slight dimensional change is important; and since corrosion also changes resistance and conductivity, the result may be loss of contact, a short circuit, or other malfunction.

6.1.1 METALS USED. Modern electronics makes use of many metals never considered for structural service, as is evident in Table XIII. Some rarer metals are found in transistors, solid state devices, and integrated circuits. Furthermore, many different metals are used in any one assembly.

Table XIII*
METALS COMMONLY USED IN ELECTRONICS

Aluminum	Magnesium
Antimony	Mercury
Arsenic	** Monel
Beryllium	Mumetal
Bismuth	Netic
** Brass	** Nickel
** Bronze	** Palladium
Cadmium	** Platinum
Cobalt	** Rhodium
** Copper	Selenium
Conetic	Silver
** Dumet	Solder
Germanium	** Stainless Steel (CRES)
** Gold	Steel
Indium	** Tantalum
** Iridium	** Tin
Iron	** Tungsten
** Kovar	Zinc
Lead	

* Section 6.1.1

** Usually considered "corrosion-resistant"

6.1.2 THEORIES OF CORROSION. Various theories explaining the corrosion of metals are thoroughly discussed in the excellent books listed as references 1, 2, and 3. Some authorities state that corrosion results from the electron structure of the elements. Oxygen, sulfur, chlorine, iodine, etc., are electron-capturers; the metals are mainly electron donors. When the two come together, the metal gives up electrons and becomes corroded⁽¹⁾. Other scientists suggest that all metallic corrosion is an electrochemical phenomenon, with a cell formed by two different metals, or by different areas in the same metal⁽⁴⁾. One well-known theory is the "return-to-nature" idea, based on the fact that metals tend to revert to their original state, usually an oxide, hydrated oxide or sulfide⁽⁵⁾. Examples are rust (ferric oxide) on steel, tarnish (silver sulfide) on silver; and grayish powder (magnesium hydroxide) on magnesium.

6.1.3 FACTORS AFFECTING CORROSION. The main contributors to metallic corrosion are moisture and oxygen (see 3.1, 3.3.2). However, a metal's resistance to corrosion is not a consistent quality. Metals considered extremely corrosion resistant under ordinary conditions (such as titanium) can be attacked and embrittled by chlorinated hydrocarbon cleaners. Aluminum, steel, "stainless" or corrosion-resistant steel (CRES), and brass are subject to stress corrosion; if the stress is high enough, even slightly corrosive media can cause fracture. Stainless steel is especially subject to crevice corrosion. So designers must keep in mind not only the environment and inherent resistance of a metal, but also the specific application and design. This is especially important wherever two metals are used in contact, since galvanic corrosion may result. The rate and magnitude of corrosion of metals depends not only on the metal itself and the environment surrounding it, but also on the particular application (see table XIV).

Table XIV*
FACTORS AFFECTING METALLIC CORROSION

1. THE METAL	Section
a. Inherent Resistance	6.2.1
b. Soundness	6.2.6
c. Homogeneity	6.2.2
d. Surface Condition	6.3.1.1
e. Stress (Residual)	6.2.4
f. Processing	
2. THE ENVIRONMENT	
a. Moisture	3.1
b. Oxygen	6.2.3
c. Incompatible Materials	5.3.8
d. Corrosive Fumes	6.4.4
e. Fungi	3.6.4
f. Temperature	3.2.1
3. THE APPLICATION	
a. Type of Service (Static, Bearing, etc.)	
b. Contact with Dissimilar Metal	6.3
c. Protective Coating	6.7, 7.13
d. Design	6.5
e. Applied Stress	6.2.4
f. Applied Voltage	6.4

*Section 6.1.3

6.1.4 TYPES OF CORROSION. When corrosion affects the whole surface, it is "general"; if only on small areas, it is "localized"; or if confined to small points so that holes are made in the surface, it is "pitting"(1). There is no correlation between the different types of corrosion. On metals like semi-austenitic stainless steels, which are subject to both general tarnish and pitting, the depth or seriousness of the pits cannot be determined from the appearance of the tarnish or stain.

Of the many types of corrosion, only those liable to be encountered in electronic devices are discussed in this report. For convenience, they are classified as (1) chemical attack on any one metal, including surface contamination, intergranular corrosion, stress corrosion, crevice corrosion, hydrogen embrittlement, problems with porous castings, fungus, and whiskers; (2) galvanic corrosion of two dissimilar metals; and (3) corrosion associated with externally applied voltage such as electrolysis and silver migration.

6.2 CHEMICAL ATTACK

Some metals are inherently more noble than others; this may be associated with their electrode potential, as illustrated in table XV(4). Generally, the noble metals give little trouble from atmospheric corrosion. Other metals considered corrosion resistant are the "stainless" steels (300 series), titanium, chromium, aluminum, nickel, copper, bronze and tin. These all form adherent oxide coatings which are quite resistant to moisture(6). From the electronics point of view, this oxide coating can be very detrimental because it decreases conductivity. Also, many of these metals are subject to stress-corrosion (6.2.4) and crevice-corrosion (6.2.3); all can be involved in galvanic corrosion (6.3). Moreover, corrosive fumes attack many materials which can withstand moisture. The effect of corrosive vapors from uncured organics on cadmium plate has already been mentioned. Sulfur attacks nickel, silver and copper; oxygen and chlorine are markedly active, even when dry. Ammonia vapor dissolves cadmium or zinc(7) and causes season cracking of brass. Moisture accelerates and intensifies such attacks, but they can occur even under dry conditions.

Table XV*
ELECTRODE POTENTIAL OF METALS(4)

Potential	Corrodes	Common Metals
Less Than -0.414V	In neutral water without oxygen	<u>Base</u> : Li, Ca, Mg, Be, Al, Ti, Zr, V, Mn, Nb, Cr, Zn, Fe.
-0.414 to 0.V	In neutral media without oxygen; in acid without oxygen	<u>Non-noble</u> : Cd, In, Th, Co, Ni, Mo, Pb, Sn
0 to 0.815V	In neutral or acid media with oxygen	<u>Semi-noble</u> : Bi, Sb, As, Cu, Hg, Ag
More Than 0.815V	Only in acid with oxygen	<u>Noble</u> : Pa, Ir, Pt, Au

*Section 6.2

NOTE: The so-called "stainless" steels are neither stainless nor rustless, although they are more corrosion resistant than other steels because they contain chromium and often nickel. See 6.10.9.

6.2.1 SURFACE CONTAMINATION. Contamination of contact surfaces, especially bothersome to electronic designers, is one type of chemical attack. Noise in potentiometers due to a slight film on the resistance element, or poor solderability because of surface oxidation, are examples of this problem. The attack may be only superficial, so slight that it would not be noticed on a structural part, but it is serious on an electronic device. It occurs on bare metals due to atmospheric oxygen, corrosive fumes from organics or propellants, moisture, or fingerprints. Susceptibility to contamination by air, moisture, or vapor is an inherent property of the metal. Surface contamination is a special problem with thin films because the large surface-to-volume ratio promotes significant atmospheric corrosion. A film of electroless cobalt-phosphorus underwent a large percentage change in magnetic moment after exposure to humidity⁽⁸⁾.

6.2.1.1 Preventing Contamination. It is not always possible to prevent surface contamination completely but it can be minimized:

1. Select inherently resistant metals.
2. Avoid handling, or wear gloves.
3. Remove sources of corrosive vapors such as organics.
4. Store in sealed polyethylene bags.
5. Keep moisture to a minimum.
6. Improve resistance by passivating.
7. Use protective coatings when practical.

6.2.2 INTERGRANULAR CORROSION. Because metals are not completely homogeneous, some areas (often the grain boundaries) are more susceptible to corrosion than others. In aluminum alloys, the grain boundaries are anodic to the grain centers. In a damp corrosive environment, pitting may occur in a preferential pattern, clearly outlining the grain boundaries. Often the intergranular attack does not show on the surface, making it difficult to detect before the part is completely destroyed⁽⁹⁾. Brasses with more than 15 percent zinc are subject to a type of intergranular corrosion called "dezincification" in which the zinc is removed, leaving only a porous copper part⁽¹⁰⁾. "Stainless" steels of the 18-8 type containing more than 0.03 percent carbon and no columbium or titanium, are also susceptible to intergranular corrosion if they have been exposed to temperatures in the approximate range of 425° - 815°C (800° - 1500°F).

6.2.2.1 Preventing Intergranular Corrosion. Select the proper grade and heat-treat condition of metal, and provide protective coatings where practical. For instance, alclad aluminum has a surface of pure corrosion resistant metal which protects the stronger alloy from attack.

1. Aluminum: Use the 5000 or 6000 series alloys rather than 2000 or 7000; use rapid quench when heat treating; use alclad rather than bare; anodize where practical.
2. Brass: Use compositions with less than 15 percent zinc, or inhibited admiralty brass.
3. Corrosion-Resistant Steel: Use Type 304L (low carbon), 321 or 347 if welding or brazing is involved.

6.2.3 CREVICE CORROSION. This kind of attack occurs in crevices or at threaded fasteners or under washers where there is a lack of oxygen; it is also called "oxygen starvation," "concentration cell" corrosion, or "differential aeration". It is usually found on corrosion-resistant steel, Inconel, nickel, aluminum, and other metals which may be either "passive" (protected by a thin oxide film) or "active". The "passive" film does not persist in the presence of electrolyte and the absence of oxygen; thus, the metal in the joint where oxygen cannot penetrate will become "active," and therefore anodic to the rest of the part. When moisture is present, an electrochemical cell is formed and the metal is attacked. (Figure 3b). Crevice corrosion is particularly dangerous because it occurs on metals ordinarily considered corrosion resistant and therefore, is unexpected; and because it starts in

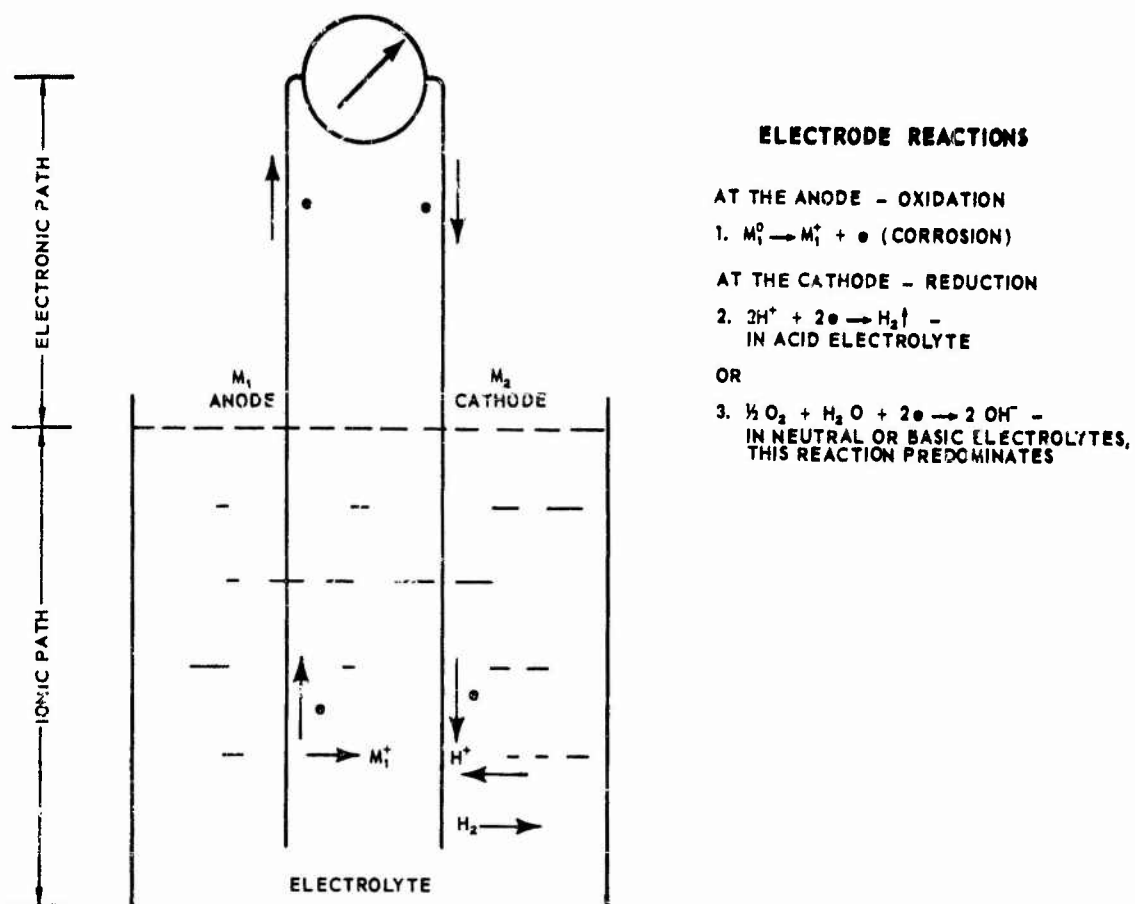


Figure 3A. Galvanic Corrosion.

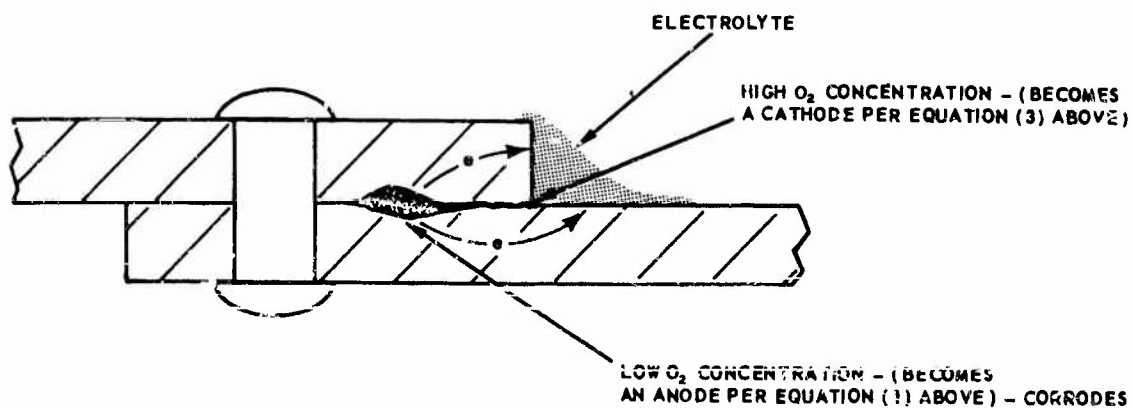


Figure 3B. Crevice Corrosion.

locations which are not easily seen, such as under a decal on "stainless" steel tubing. Residues from soldering flux can cause crevice corrosion; another common cause is partial immersion in electrolyte with condensed moisture over part of a surface. Oxygen is an important factor in most metal corrosion, but it is the governing factor in crevice corrosion⁽¹¹⁾.

6.2.3.1 Preventing Crevice Corrosion. Since moisture or other electrolyte is required to set up crevice corrosion, sealing the joint to exclude moisture will prevent this attack. Sealing is necessary even where nylon or other nonmetallic washers are used, for they keep oxygen out just as a metal would. A polysulfide (where sulfur can be tolerated) or epoxy or polyurethane or silicone rubber sealant will protect the joint. Cleaning first, then sealing, affords protection. For stainless steel joints in marine atmospheres, a seal of 50/50 lead/tin solder, or of 10 percent copper powder in petrolatum, has proved effective. (Reference 10, page 561.) Cathodic protection is also effective for the 18-8 "stainless" steels, the 300 series. Paint is not useful on corrosion-resistant steel because of the danger of pitting at pores in the paint.

6.2.4 STRESS CORROSION. When materials are under load or stress, it takes only a mild corroding agent to cause failure. There is three-way relationship between the corrodant (which may be only water), the stress level, and the time before cracking occurs. Season cracking of deep-drawn brass by ammonia is one type of stress corrosion. The phenomenon has been known for years but only recently has become a major problem in such highly-stressed parts as rocket motor cases and aerospace structures. There are two basic theories about stress corrosion: electrochemical and mechanical (references 12, 13, 14, 15, 16). Stress-corrosion differs from other types of corrosion in that tensile stress is required⁽¹²⁾; brittle cracks result, even in ductile metals; and the corrosivity of the environment is not the major factor.

6.2.4.1 Sources of Stress. The residual stress which causes stress corrosion originates in the fabrication of the part, not in service. Heat treatment, especially rapid quenching, welding, grinding, tagging, swaging, bending and other severe forming, excessive tightening of fasteners, press fits and tapered bolts, all produce high levels of stress in the parts⁽¹⁷⁾. An aluminum chassis, cabinet or housing for electronic use is just as subject to these stresses, and to stress corrosion cracking, as an airplane wing fitting.

6.2.4.2 Metals Concerned. Stress corrosion can occur in almost all metals, but the susceptible ones most used in military electronic equipment are the high-strength aluminum alloys 2014, 2219, 2024, 7075, 7079, and 7178; and the cast aluminum alloys 195, 220, 40E, and Ternalloy 7.⁽¹⁷⁾ Castings of 220-T4 broke in 12 hours under a stress which castings of A356-T61 carried for 105 days.⁽¹⁸⁾ Alloy 7079-T6 is especially subject to stress-corrosion in marine environments⁽¹⁹⁾ and even the 5000-series aluminum-magnesium alloys have been suspected of stress-corrosion⁽²⁰⁾ although their service record has been good. High-strength metals all appear susceptible to stress-corrosion, whether aluminum^(20, 21) or steel^(22, 23) or CRES, corrosion-resistant (stainless) steel⁽²⁴⁾. Environments favoring stress corrosion of various metals are listed in Table XVI. The season cracking of copper by ammonia vapor is a form of stress corrosion.⁽²⁵⁾ Magnesium alloys with more than 1 percent aluminum are subject to stress corrosion after welding⁽¹⁹⁾ unless thermally stress relieved.

6.2.4.3 Preventing Stress Corrosion. The metal, the stress level, and the environment are the three factors producing stress corrosion. Therefore, there are three main ways to prevent it: choose metals which are not susceptible; reduce the stress, both the operating stress and any residual stresses; and protect the metals from the environment or remove the corroding media. Unfortunately, measures which reduce susceptibility to stress corrosion

Table XVI*
ENVIRONMENTS FAVORABLE TO STRESS-CORROSION CRACKING⁽⁵⁾

Alloy	Environment
Steel	Alkalies, nitrates, hydrogen cyanide, hydrogen sulfide, anhydrous liquid ammonia, sodium chloride solutions, marine atmospheres.
Chromium Stainless Steels (over 12% Cr)	Halides, hydrogen sulfide, steam.
Austenitic Stainless Steel (18% Cr, 8% Ni, 300 Series)	Chlorides, caustic.
PH Stainless Steels	Chloride solutions, marine atmospheres.
Aluminum Alloys	Sodium chloride solutions, tropical environments.
Copper Alloys	Ammonia, mercurous nitrate, steam.
Gold Alloys	Iron chlorides, potassium cyanide.
Magnesium Alloys	Sodium chloride/potassium chromate, fluorides, moisture.
Nickel Alloys	Caustic, hydrofluorosilicic acid.
Monel, Inconel	Hydrogen fluoride vapors.
Titanium Alloys	Red fuming nitric acid, hydrogen chloride, dry molten chloride, salts, chlorinated hydrocarbons.

*Section 6.2.4.2

sometimes decrease resistance to atmospheric corrosion. The following rules help minimize stress corrosion:

1. Use the most resistant materials. In aluminum, these are alclad or 5000 or 6000 series for wrought alloys, or A356-T51 for castings. Select copper alloys with less than 15 percent zinc, and magnesium alloys with less than 1 percent aluminum. Use steels at the lowest strength level which is practical.
2. Reduce the stress level in parts. Do not use metals at more than 75 percent of their yield strength. Reduce residual stresses by shot peening. Do all forming in the annealed condition. Stress relieve after welding, machining, or forming. Heat treat correctly.
3. Protect from corrosive environments. Avoid moisture, oxygen, and corrodents listed in Table XVI. Keep equipment dry; clean well after salt bath, soldering or welding.
4. Use protective coatings. For aluminum, sacrificial coatings are good; use zinc plate, or zinc chromate primer followed by epoxy or polyurethane topcoats.⁽²⁰⁾ For steel, nickel-cadmium plate is effective.⁽²³⁾

6.2.5 HYDROGEN EMBRITTLEMENT. Closely associated with stress corrosion is hydrogen embrittlement,⁽²⁶⁾ primarily a problem in high strength iron-base and nickel-base alloys, and titanium.⁽²⁷⁾ When these high strength (or highly stressed) metals are acid cleaned, pickled, electroplated, welded, or otherwise exposed to nascent hydrogen, they may pick up enough hydrogen to cause them to crack spontaneously, in what is known as "delayed fracture".^(28, 29) If high strength steel is not stress relieved immediately after plating,

fracture can occur in as little as 5 minutes.⁽²⁸⁾ Titanium picks up hydrogen easily and it causes marked brittleness. Electrolytic tough-pitch copper is also subject to hydrogen embrittlement when "bright annealed" in an atmosphere containing hydrogen. The corrosion process, liberating hydrogen (see Figure 3) may itself cause hydrogen embrittlement.⁽³⁰⁾

6.2.5.1 Preventing Hydrogen Embrittlement. It is extremely difficult to remove hydrogen when it is once held in a metal. The real way to prevent embrittlement is to avoid acid cleaning, pickling, and electroplating. The designer should select materials and processes to minimize the danger of embrittlement:

1. Use organic coatings, or vacuum deposited film, or electroless coating processes, instead of electroplating.
2. If plating is necessary:
 - a. Use alkaline baths or other processes specially designed for low hydrogen pick up.
 - b. Use cadmium instead of zinc or chromium plate.
 - c. Shot peen before plating.
 - d. Stress relieve before plating and immediately afterward - a minimum of 3 hours at 180°C (375°F) but preferably 24 hours at 180°C.
3. Use materials not subject to hydrogen embrittlement:
 - a. Use 300 series 18-8 corrosion resistant steels.
 - b. Use oxygen-free or deoxidized copper.

6.2.6 POROUS CASTINGS. Any surface which is porous is of great aid to corrosion. Moisture, dust and other contaminants collect in the openings and not only attack that part but also contribute to failure of those nearby. Seal any castings used for housings, covers, and the like by impregnation prior to plating or other finishing, if porosity is present.

6.2.7 FUNGI. The attack of fungi and bacteria on metal is discussed in 3.6.4 and Table VI. Any condition which holds moisture, such as porous areas in castings or poorly applied coatings (the fungi grow between metal and coating), encourages microbial action. Fungi liberate acid, destroy protective coatings, and thus damage metals even though the metals themselves are non-nutrients. To prevent microbial attack, keep equipment dry, use funginert materials and fungicide; see Section 5.3.6.4.

6.2.8 METAL WHISKERS. Some metals grow "whiskers" during storage, even in hermetically sealed units⁽³¹⁾. These filamentary growths on cadmium plated condensers caused trouble in World War II⁽³²⁾ and spurred an investigation of the phenomenon, which occurs with tin, zinc, cadmium, copper or iron.⁽³³⁾

6.2.8.1 Preventing Whisker Growth. Although humidity does not cause whisker growth, there is a definite relationship between moisture and whiskers. Low humidity does not prevent the growth, but it does retard it markedly. There is a closer correlation between stress and the rate of whisker growth; low stress retards growth. When using tin, apply the coating by hot dip instead of electroplating, because the hot dipped coating is thicker and less highly stressed; or fuse the tin after plating, to relieve plating stresses; and use as heavy a coating as practical⁽³¹⁾. Rate of growth can be held to a minimum by keeping equipment dry, cool, and free from organic contaminants.⁽³²⁾

6.3 GALVANIC CORROSION

The problem most frequently blamed for malfunction of electronic equipment is that of galvanic corrosion resulting from dissimilar metal contact. It occurs when two metals of different electromotive potential are in close contact, exposed to an electrolyte. This causes a flow of current from the anode to the cathode with liberation of hydrogen and formation of alkali at the cathode (Figure 3a). Four things are necessary for galvanic corrosion: (1) and (2) dissimilar metals, (3) such close contact that an electron path is possible; and (4) an electrolyte (perhaps only water) in contact with both metals. One example of galvanic corrosion is "red plague," the corrosion of copper under silver plating on Teflon-jacketed wire. Silver plate is always somewhat porous and at any small pore, all the corrosion is concentrated on the copper below. To prevent this, use nickel instead of copper. Another example is the corrosion of crimped connections such as aluminum/copper, tin-plated aluminum/gold-plated copper, etc.

6.3.1 DISSIMILAR METALS. One method of classifying metals is to divide them into four groups based on their compatibility with each other. All metals in one group are considered "similar" and unlikely to corrode from galvanic action, but are "dissimilar" to metals in any other group. Table XVII is taken from Requirement 16, Dissimilar Metals, of MIL-STD-454, and is much like the list in MIL-E-5400. By careful insulation whenever metals from different groups are in contact, most galvanic corrosion can be prevented.

Table XVII*
GROUPS OF COMPATIBLE METALS IN MIL-STD-454

Group I	Group II	Group III	Group IV
Magnesium and Alloys	Aluminum and Alloys	Zinc	Copper and Alloys
Aluminum 5052, 5056, 5356, 6061, 6063	Zinc	Cadmium	Nickel and Alloys
Tin	Cadmium	Steel	Chromium
	Tin	Lead	
	Stainless Steel	Tin	Stainless Steel
	Tin-lead Solder	Stainless Steel	Gold
		Nickel and Alloys	Silver
		Tin-lead Solder	

*Section 6.3.1

6.3.1.1 Electromotive Potential. There are some instances where two metals in the same group form a galvanic cell, corroding the anodic metal. Designers need more specific data on the differences between metals, in order to select those which are compatible. The Electromotive Series gives this information. It is a list of the metals arranged according to their standard electrode potentials, measured in an 0.1N calomel scale. The precious metals,, with positive potentials, are most cathodic and least attacked; magnesium, with the lowest negative potential, is most anodic and most attacked. To aid in estimating the likelihood of galvanic attack, Army Missile Command has listed the electromotive potential of various metals, and has indicated which can be used together without danger. This list of permissible galvanic couples, taken from MIL-STD-186, is shown in Table XVIII.

Table XVIII*
GALVANIC COUPLES(34)

Group	Metallurgical Category	EMF (Volt)	Permissible Couples
1	Gold, gold-platinum, platinum	0.15	o
2	Rhodium, graphite	0.05	o
3	Silver	0	o
4	Nickel, monel, high nickel-copper alloys, titanium	-0.15	o
5	Copper, low brass or bronze, silver solder, German silver, high copper-nickel alloys, nickel-chromium, austenitic (type 300) stainless steels	-0.20	o
6	Commercial yellow brass and bronze	-0.25	o
7	High brass and bronze; naval brass, muntz metal	-0.30	o
8	18 percent chromium type steels	-0.35	o
9	Chromium, tin, 12 percent chromium steels	-0.45	o
10	Tin-plate; tin-lead solders; terneplate	-0.50	o
11	Lead; high lead alloys	-0.55	o
12	Aluminum, wrought, 2000 series	-0.60	o
13	Iron, low alloy steels, armco iron	-0.70	o
14	Aluminum, 3000, 6000 and 7000 series; aluminum-silicon castings	-0.75	o
15	Aluminum castings (other than silicon); cadmium	-0.80	o
16	Hot dip zinc, galvanized steel	-1.05	o
17	Zinc	-1.10	o
18	Magnesium	-1.60	o

*Section 6.3.1 o = cathodic • = anodic

With few exceptions, MIL-STD-186 limits permissible couples to those with a maximum of 0.10V potential difference – for instance, commercial yellow brasses (-0.25) and 18 percent chromium type corrosion resistant steels (-0.35). To use the table, note the permissible couples indicated by the dots and arrows. Note that a metal may be anodic (yellow brass against copper) or cathodic (yellow brass against 18 percent chromium type steels) depending on the other member of the galvanic cell. Any combination of metals not shown as "permissible" can, if in intimate contact in an electrolyte, result in harmful corrosion. The greater the difference between the EMF's of the metals listed, the worse will be the attack on the anodic metal.

6.3.1.2 Galvanic Series. When metals are arranged in the order of anodic to cathodic (or vice versa) in some specific electrolyte, this is the Galvanic Series or Table. It may not be exactly the same as the Electromotive Series, because the relative position of metals is affected by the electrolyte used, its concentration aeration, circulation, etc. Galvanic

Tables seldom list values for electromotive force. They are not "standard", but vary slightly with the electrolyte. But they are very helpful to designers because they give information on specific conditions, such as dilute sea water.

6.3.1.3 Using Tables. When consulting Tables XVII or XVIII or a different Galvanic Table, keep in mind:

1. The surface metal is the one involved, whether it be solid, plated, dipped, sprayed, or laminated.
2. Graphite acts like a metal, and forms galvanic cells.
3. Different alloys of the same metal (especially aluminum and copper) can form a galvanic cell.
4. Tin or nickel plate on hardware is considered compatible with aluminum, regardless of potential difference, except for exterior service.

6.3.1.4 Passivity. Many galvanic series show two values for corrosion-resistant steel, nickel, and other metals which are capable of forming a tight adherent protective oxide film; one for the "active" surface condition, and one for the "passive". The passive condition is more resistant to corrosion⁽³⁵⁾ but does not always last, depending on availability of oxygen and freedom from shock. Therefore, the design engineer need not pay attention to the active or passive state so far as galvanic attack is concerned.

6.3.2 AREA. In galvanic corrosion, the relative area of the anodic (attacked) and the cathodic (more noble) metal is of great importance. When the anodic area is larger, the rate of corrosion is reduced: the potential voltage differential is not changed, but since the current is spread over a larger area, the current density is lower. The areas considered are only those wetted by the electrolyte. If an assembly is totally immersed, then all the metal is part of the galvanic cell. But if moisture is only present in local pockets, as from condensation around a joint, then only those surfaces which are wet enter into the cell. The influence of area explains why steel nuts and bolts are sometimes satisfactory in a large aluminum structure, while aluminum hardware on a steel sheet would be quickly corroded away.

6.3.3 EXFOLIATION CORROSION. Some people consider exfoliation corrosion of aluminum (a type of attack occurring under, but parallel to, the plane of the surface) a form of stress corrosion⁽⁷⁾ but others think it is intergranular, and some say it is a type of galvanic corrosion. It has been found primarily in aluminum sheet around steel fasteners, and prevention involves insulation (zinc chromate primer, etc.) at the interface.

6.3.4 PREVENTING GALVANIC CORROSION. Anything which reduces the potential difference between the metals involved, or insulates so there is no contact between them, or removes the electrolyte, prevents galvanic corrosion. Proper control of relative area minimizes attack. As pointed out in Table XIX, there are ways to preclude corrosion even when dissimilar metals must be used. Remember, it is not the inherent corrosion resistance of a metal which matters, but the potential difference between it and those it contacts. The values in Table XVIII are a good guide to selection. The greater the potential difference between two metals, the more care must be taken in drying, insulating and sealing the joint.

6.3.4.1 Polarity Paper. In galvanic corrosion, alkali is always liberated at the cathode, so a quick test with polarity paper will show whether the combination is subject to this problem. "Polarity paper" is coated with potassium chloride (which when wet becomes the electrolyte) and also has phenolphthalein which turns red in alkali. Wet the paper, place between the two metals, press together and observe whether a red color appears on the more noble side; this indicates galvanic corrosion⁽⁷⁾.

Table XIX*
PREVENTING GALVANIC CORROSION

Problem	Solution	Example
Dissimilar Metals	1. Select metals in "Permissible Couples" in Table XVIII	Use nickel, not naval brass, next to silver
Dissimilar Metals	2. Plate with compatible metal to reduce potential difference	Tin coat steel and bronze used together
Dissimilar Metals	3. Keep affected area of less noble metal (anode) as large as possible	Stainless steel hardware in aluminum may be satisfactory because of large area of aluminum
Dissimilar Metals	4. Apply corrosion inhibitors such as zinc chromate paste	Assemble dissimilar metal hardware with zinc chromate
Contact	5. Interpose inert barrier or gaskets to prevent contact (be sure to extend 1/4 in. beyond joint)	Vinyl tape, cadmium plated washer, rubber gasket
Contact	6. Paint cathode, or both metals, with alkali resistant organic coating	MIL-P-52192 or MIL-P-15930
Electrolyte	7. Avoid designs where moisture can be trapped	See Section 5.3.3.5
Electrolyte	8. Use desiccant	See Section 5.3.3
Electrolyte	9. Seal joint with organic insulator, alkali resistant	MIL-S-7124
Electrolyte	10. Seal faces of metal against contact with electrolyte	Primer, paint or sealant
General	11. Use cadmium in preference to zinc plating	
	12. Use tin or nickel plated hardware	MIL-E-5400
	13. Avoid use of magnesium	See Section 6.3.4.2

*Section 6.3.4

6.3.4.2 Magnesium. Magnesium is so dissimilar to all other metals that it deserves special attention. It is extremely hard to protect from galvanic corrosion. Do not use it in conjunction with another metal unless absolutely necessary; then take extra precautions: finish in accordance with MIL-M-3171, then use at least two coats of zinc chromate primer on both the magnesium and the other metal, and also interpose an insulating gasket or tape between them, followed by sealing the joint area. A coating of electroless nickel followed by reflowed tin, is good in contact with aluminum or steel.⁽⁷⁾ Or use organic coatings such as epoxy (four layers are usually required for protection).

6.3.4.3 Aluminum. Different alloys of aluminum have markedly different potentials and can form a galvanic cell. Equipment using both cast aluminum and 2024 can get badly corroded just during cleaning. Anodized aluminum is insulating and is considered as a nonmetal, but this assumes a continuous anodic coat after all drilling, reaming, machining, etc., have been completed.

6.3.4.4 Dry Film Lubricant. Galvanic corrosion has occurred from the use of dry film lubricants containing graphite, which acts as a metal. In conditions where galvanic corrosion can result, use only lubricants certified to be graphite-free.

6.3.4.5 Useful Galvanic Corrosion. The anodic metal, in being attacked and destroyed, protects the nobler or cathodic metal. This is the principle of cathodic protection. The anode may be naturally the baser metal, like magnesium sacrificial anodes in steel hot water heaters, or the metal may be made anodic by external current, like lead anodes to protect steel ship hulls. Although extremely useful in retarding marine and underground corrosion, cathodic protection has little application in electronic items. The most familiar type of useful galvanic corrosion is the storage battery.

6.4 EXTERNALLY APPLIED VOLTAGE

Electronic applications differ from structural usage in that voltage differentials are often present, perhaps between a ground and an adjacent working circuit. Such differentials can accelerate corrosion, especially by electrolysis and silver migration.

6.4.1 ELECTROLYSIS. In some ways, electrolysis is similar to galvanic corrosion. There must be two metallic parts with different voltage potential, and an electrolyte. But the two parts may be the same metal, and they do not have to touch each other or provide an electron path. Instead, because of the voltage differential, one will migrate toward the other. Electrolysis caused a short circuit on a terminal board near a propellant discharge area. The vapors, which contained moisture and acid, condensed on the board; then copper grew from one conductor to the other, finally causing a short. Electrolysis is usually gradual, but this failure occurred in a matter of minutes.

6.4.2 SILVER MIGRATION. Under certain conditions of voltage differential plus high humidity, silver migrates across ceramic or plastic, causing short circuits. (36) It has been known to cross a gap of 0.060 in. with voltage differential as low as 1 to 2V, in 15 seconds. Silver migration has been observed on ceramic, mica, glass and Fotoceram, but only occasionally on glass-plastic laminate. (37) Silver also diffuses easily through copper and gold (38). The silver may be plated, foil, fired-on, air dry or contained in an epoxy. Capacitors have been especially subject to failure from silver migration. (39)

6.4.3 PREVENTING ELECTROLYSIS AND SILVER MIGRATION. The voltage differential is usually necessary to the design, but other steps can be taken to minimize problems associated with it:

1. Clean carefully with deionized water to remove soluble salts, and dry;
2. Coat with organic moisture barrier such as epoxy or polyurethane to retard action;
3. Use wider spacing between conductor paths where voltage differential exists;
4. Keep equipment as dry as possible.
5. Use platinum or gold in place of silver.

6.5 PREVENTING CORROSION BY DESIGN

As has already been discussed, much or most of corrosion difficulties can be avoided by proper design. A cross reference to various forms of metallic deterioration and the suggested preventive measure is shown in Table XX. These recommendations can be summarized as follows:

1. Use the most resistant metal practical.
2. Use it at the lowest stress level practical.
3. Consider the special problems of surface, intergranular, crevice, stress, and exfoliation corrosion.
4. Avoid dissimilar metal contacts.

5. Avoid sources of corrosive fumes.
6. Keep moisture out.
7. Use funginert materials.
8. Provide maximum space between conductors
9. Protect by metallic or organic coatings as required.

Table XX*
PROTECTION OF METALS BY DESIGN

Type of Attack	Problem Section No.	Solution Section No.
Crevice Corrosion	6.2.3	6.2.3.1
Electrolysis	6.4.1	6.4.3
Exfoliation	6.3.3	6.3.3
Fungal Attack	6.2.7	6.2.7, 5.3.6
Galvanic Corrosion	6.3	6.3.4
Table XIX		
Hydrogen Embrittlement	6.2.5	6.2.5.1
Intergranular Corrosion	6.2.2	6.2.2.1
Joints	6.3	8., 5.4.2
Moisture	3.1	5.3.3.5
Oxygen	6.2.3	6.2.3.1
Porous Castings	6.2.6	6.2.6
Red Plague	6.3	6.3
Silver Migration	6.4.2	6.4.3
Stress Corrosion	6.2.4	6.2.4.3
Surface Contamination	6.2.1	6.2.1.1
Summary	—	6.5
Whiskers	6.2.8	6.2.8.1

*Section 6.5

6.5.1 IMPROVING ENVIRONMENT. So far as dehumidifying, sealing, and use of corrosion inhibitors is concerned, the original designer has control. Review Table X, Sections 5.3 and 5.4, to select the atmosphere and seals best suited to the design.

6.6 COATINGS

Protective coatings for metals may be divided into three groups:

1. Anodic or conversion coatings;
2. Metallic, whether electroplated, sprayed, vacuum deposited, clad, or applied chemically;
3. Organic, including resins, lacquers, paints, oils and greases.

The properties, advantages and limitations of the various coatings are thoroughly discussed in the following documents:

MIL-HDBK-132	Protective Finishing ⁽⁶⁾
MIL-STD-171	Finishing of Metal and Wood Surfaces ⁽⁴⁰⁾
AMCP-706-311	Corrosion and Corrosion Protection of Metals ⁽⁴¹⁾
ORDP-608-OW-RIA3	Protective Coating and Plating ⁽⁴²⁾

Additional requirements for Army missiles are given in MIL-STD-186, Protective Finishing Systems for Rockets, Guided Missiles, Support Equipment and Related Materials. (34)

6.6.1 IMPORTANCE OF CLEANING. Regardless of which type of protective coating is selected, its usefulness depends on the surface preparation before coating. Cleaning may be mechanical, chemical, solvent, electrical, or ultrasonic; but it must be thorough. Surface cleaning is especially important before vapor deposition, since that is an extremely thin coating. Dust, fingerprints, surface oxides, contaminants, or other foreign material on the surface can undo all the good expected from protective coatings.

6.6.1.1 Hazards of Cleaning. Designers seldom specify cleaning methods, but perhaps they should, because of the corrosion problems involved. Acid cleaning can cause hydrogen embrittlement of steels and titanium (see Section 6.2.5); either acid or alkaline cleaning will cause galvanic corrosion if dissimilar metals are assembled, cleaner can be trapped in crevices or seams, interfering with later coating as well as causing corrosion; vapor degreasing with chlorinated hydrocarbon can attack titanium, or if left in crevices, may later form hydrochloric acid in the presence of moisture. (42) Parts with crevices where cleaning solvent could be trapped, should be dried for 30 minutes at 93°C (200°F) after vapor degreasing and should NEVER be put in water. (43) Ultrasonic cleaning can harm diodes. If scrubbing of printed circuits is too vigorous or too prolonged, the board can be damaged. Proper cleaning, keeping these problems in mind, spells the difference between success and failure in protective coating of metals.

6.6.2 ANODIC COATINGS. Anodic coatings are a special type of conversion coating formed by electrolytic action, producing an electrically insulating oxide layer on the surface of the aluminum, magnesium, or beryllium. For maximum resistance, this surface layer should be sealed at once, because it is porous and unless sealed, holds dirt, dust, and moisture. Anodized aluminum has excellent resistance to corrosion and is a good base for paint, although organic coatings are not really needed. There are three types of anodize for aluminum: chromic acid, sulfuric acid, and hard anodize. (44) The anodic treatments for magnesium (HAE and Dow #17) also produce hard electrically insulating oxide layers, but are not so protective as the aluminum anodize. Magnesium still needs further coating.

WARNING: Be especially careful to avoid copper, brass, nickel, and stainless steel in anodic baths for magnesium.

6.6.3 CHEMICAL CONVERSION COATINGS. Chemical film treatments can produce an oxide, chromate, or phosphate, or complex layer on metals. These surfaces are thinner, softer and more easily damaged than the anodized layers, but offer some protection and are an excellent paint base. Commonly used coatings are listed in Table XXI. Chromate coatings are in general use on aluminum and magnesium as prepaint treatment and on cadmium and zinc plate as a supplementary protection. The color varies from iridescent yellow to a deep bronze or olive drab. Leaching to produce a clear bright finish removes chromium and reduces the effectiveness of chromate finishes. A thorough discussion of these treatments is given in Military Handbook 132, Section 4. (6)

6.6.3.1 Aluminum. The chromate chemical film produced on aluminum is so soft and thin that it is easily pierced by any electrical contact. The electrical resistance of a "typical" chromate film is low enough to classify it as a conductor. (45) There are many variations of chemical film treatment all meeting MIL-C-5541, but the alloy being coated, the bath, the length of treatment, clear or colored, etc., all affect the conductivity of the coating. Figure 4 shows the resistance measured on films produced by four different processes, on three aluminum surfaces, both before and after exposure to 1000 hours humidity. (46) Either clad 2024 or 6061 is preferable to bare 2024, if low resistance in humid environment is required.

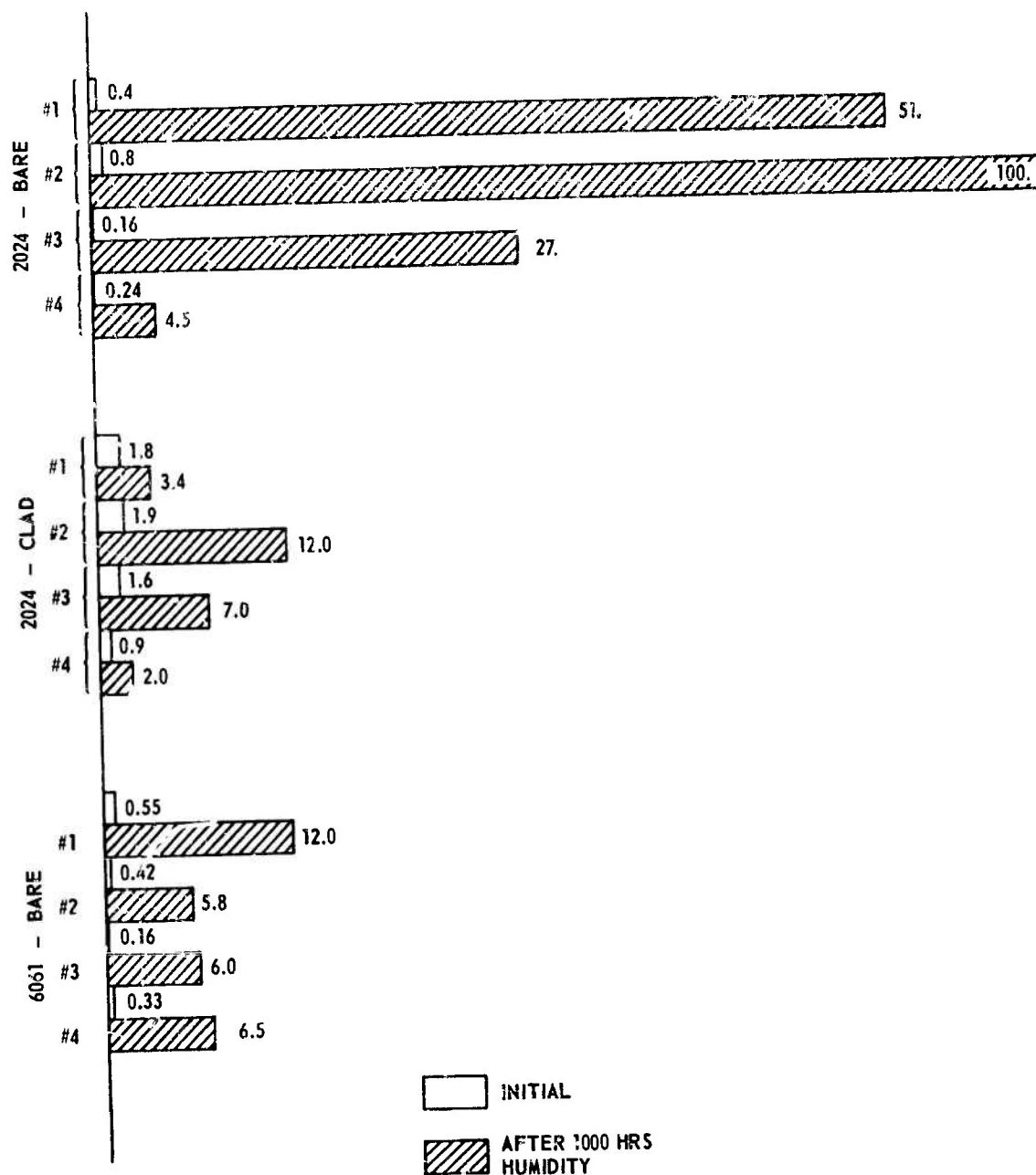


Figure 4. Electrical Resistance, in Milliohms, of Four Chemical Film Treatments.

Table XXI*
INORGANIC (CONVERSION) COATING SPECIFICATIONS

Process	Metal	Salt Spray Resistance (hrs)	Specification
Anodize, Chromic Acid	Aluminum, less than 5% copper	240	MIL-A-8625, Type I
Anodize, Sulfuric Acid	Aluminum, except castings	240	MIL-A-8625, Type II
Hard Anodize	Aluminum	240	AMS 2468 (AMS 2469)
Dow #17	Magnesium	NR	MIL-M-45202
HAE	Magnesium	NR	MIL-M-45202
Chemical Film	Aluminum	168	MIL-C-5541
Dichromate	Magnesium	NR	MIL-M-3171, Type III
Black Oxide	Steel	1/2	MIL-HDBK-205
Black Oxide	Copper	NR	MIL-F-495
Passivate	Stainless Steel	NR**	QQ-P-35
Chromate	Cadmium	192	MIL-T-12879
Phosphate	Iron	Prepaint	MIL-C-490

*Section 6.6.3

**Must stand 4 to 5 hours at 100% RH, 100°F

NR - Not Required

The chemical film protects aluminum from salt spray attack, too; although bare metal has lower resistance before salt spray, the chromated surface is much lower afterward. While the corrosion resistance of chemical film treated aluminum is adequate for interior applications which do not involve wear or abrasion, it is not good enough for exterior service without paint. In addition to the common chromate films, aluminum can be given an oxide film. "Boehmite" is a hydrated crystalline oxide formed in boiling distilled water; it is extremely thin and fragile, adequate only for mild environments. (47)

NOTE: Although chemical film treatment is widely used under paints and enamels, it is not recommended under epoxy adhesives or wash primers. The bond between the film and the epoxy is stronger than the bond between aluminum and film, and the chromate film may lift off the metal. (48)

6.6.3.2 Magnesium. The various chemical films produced by Types I, II or III of MIL-M-3171 are all temporary protection or prepaint coatings. None, by itself, provides sufficient protection for magnesium.

6.6.3.3 Cadmium and Zinc. Chromate treatment of plated cadmium or zinc retards the formation of "white rust" but removes a little of the electroplate. Leaching the chromate impairs corrosion resistance (6.6.3). Phosphate coatings are frequently used to improve adherence of paint films. Molybdate treatment produces a black color but no protection.

6.6.3.4 Copper and Copper Alloys. The black oxide formed by MIL-F-495 is primarily decorative; also, it affords a better base for adhesive bonding or organic coatings than the bare copper. Much work has been done abroad on passivation of copper to prevent corrosion of waveguides; one method is to oxidize the surface, then passivate in acid. (49)

6.6.3.5 Iron and Steel. Black oxide films are decorative, not protective. Phosphate coatings may be prepaint (MIL-C-490) or may be heavy enough to hold oil or wax. A phosphate treatment useful in electronic applications is the zinc phosphate coating sealed with tin hydroxide (MIL-C-16232) which produces a tight adherent corrosion resistant coating, usually olive drab in color.

6.6.3.6 Stainless Steel. An oxide or passive film improves the corrosion resistance of stainless steels, mostly because it involves thorough cleaning and removes all traces of other metals and contaminants. Passivation should be the last operation performed after forming, machining, or welding.

6.6.3.7 Silver. There are several patented processes for passivating silver, both chemically and electrolytically. Electrolytic passivation produces a citron-colored coating with good resistance to sulfur and all corrosive media except acid fumes. The passivated surface is said to be solderable and to have negligible effect on conductivity. (50)

6.7 METALLIC COATINGS

6.7.1 USAGE IN ELECTRONICS. Metallic coatings are selected for their inherent properties of conductivity, plus solderability (on printed circuits); or wear (on contacts); or weldability (in leads for welded modules). Deterioration of these coatings adversely affects contacts, solderability and other desired characteristics. There is no one perfect metallic coating and no one technique best for every application. The following sections review the status of the coating industry today, with emphasis on the problems which can arise and suggested solutions.

6.7.2 TYPES OF METALLIC COATINGS. Metallic layers are applied to metal by one of the techniques listed in Table XXII. When it is necessary to put a metal coating on a non-conductor such as plastic or ceramic, other methods may be used - fired-on coatings, or metal-filled resins, are common. (See Section 6.7.6.) Detailed information on the various metallic coatings is available in MIL-Handbook 132, or Quality Assurance Pamphlet ORDP-608-OW-RIA3, or "Plating", the Journal of American Electroplaters Society. The most generally used coating technique is electroplating. Brush plating is a portable type of electroplating, especially good for small areas or for field application. Vacuum deposition is widely used in semiconductor and integrated circuit manufacture. Electroless deposits are advantageous for uniform thin coatings on irregularly shaped parts. Hot dipping is preferred for many applications of tin or solder. The main application of metal spraying in electronic devices is for electromagnetic shielding. Soft metals may be applied mechanically. (51) Specifications for metallic coatings are listed in Table XXIII.

6.7.3 ELECTROPLATING. The large number of metals which can be applied economically by electroplating, and the wide range of thicknesses available, make plating the usual way of getting desired metal coatings. There are, however, several items which should be kept in mind:

1. Plating other metals on aluminum or magnesium requires a zincate and a copper strike, or stannate or electroless nickel, before the desired electroplated deposit.
2. Plating high strength steels or titanium, or coating from acid baths even without electrical current, may cause hydrogen embrittlement. (See Section 6.2.5.)

Table XXII*
WAYS OF APPLYING METALLIC COATINGS

Method	Typical Metals	Notes
Vacuum Deposition	Gold	Thinnest Coatings
Immersion Plating	Tin, Gold, Platinum	Thin coating. Minimum porosity.
Electroless Plating	Nickel	Good for irregularly shaped parts.
Electroplating	Cadmium, Chromium, Copper, Gold, Indium, Lead, Nickel, Palladium, Platinum, Rhodium, Silver, Solder, Tin, Zinc	Most common technique. Porous. Builds up on edges.
"Brush" Plating	Cadmium, Chromium, Copper, Gold, Indium, Lead, Nickel, Palladium, Platinum, Rhodium, Silver, Solder, Tin, Zinc	Use on small or restricted areas.
Hot Dip	Solder, Tin	Fairly heavy coating; stress-free.
Spray	Aluminum, Cadmium, Copper, Nickel, Tin	Most porous coating; thickest.

*Section 6.7.2

Table XXIII*
SPECIFICATIONS FOR METALLIC COATINGS
(Electroplated unless noted)

Metal	Specification
Aluminum, vacuum deposited	MIL-C-23217
Cadmium	QQ-P-416
Cadmium, vacuum deposited	MIL-C-8837
Chromium	QQ-C-320
Copper	MIL-C-14550
Gold	MIL-G-45204
Lead	MIL-L-13808
Lead, Hot dip	MIL-L-13762
Nickel	QQ-N-290
Nickel-phosphorus, electroless	MIL-C-26074
Palladium	MIL-P-45209
Rhodium	MIL-R-46085
Silver	QQ-S-365
Tin	MIL-T-10727
Tin-Cadmium	MIL-P-23408
Zinc	QQ-Z-325

*Section 6.7.2

3. Plating any surface with crevices, such as a porous casting or an assembly, can trap plating solution in the cavities, causing subsequent corrosion.
4. Contamination by plating solutions is a constant danger. Good cleaning after as well as before plating is essential.
5. Some plated coatings are brittle and crack when deformed. All forming should be done before plating.
6. Electroplated coatings build up at corners and edges but do not deposit well on threads, and interior of holes.
7. Plated coatings are porous. Electroplated tin may be fused after application to remove porosity, but this procedure does not work for the other metals.
8. Each specific metal has its own advantages and problems, which should be considered.

6.7.4 SPECIFIC METALLIC COATINGS

6.7.4.1 Copper. Use as a base coat for other metals, to promote adhesion and smoothness, not as a topcoat because of tarnish. (38)

6.7.4.2 Cadmium. Use on hardware, and to prevent galvanic corrosion between steel or copper, and aluminum. Cadmium needs a chromate coating to retard corrosion; is extremely subject to attack from organic vapors; is soft, not for wearing surfaces, not for use about 230°C (450°F); and can grow whiskers. (52)

6.7.4.3 Chromium. Use for wear resistance. It is not good for corrosion protection, unless applied over nickel; is porous, with a tendency to crack.

6.7.4.4 Gold. Traditionally considered the best coating for corrosion resistance and solderability, gold is widely used on printed circuits, semiconductors, leads, contacts; it is usually applied in a thin layer over silver or copper. However, at least 0.0001 in. thickness is required for satisfactory contact after 6 months outdoor exposure; thinner coatings are not adequate. (53) Moreover, solderability decreases with time (7); gold combines with solder to form a brittle tin-gold compound (54); when gold is plated over copper, the latter diffuses into the gold (55); and gold over either silver or copper, accelerates corrosion of the less noble metal at the pores or pinholes in the gold. (7) Tests at tropical sites in Panama show that gold plate is not permanently corrosion resistant. (56) Gold will alloy with aluminum causing "purple plague", a brittle intermetallic compound which cracks and causes open circuits (57) if silicon is present, for example, when bonding aluminum to gold plated Kovar post. (58) When using gold over chromium in integrated circuit production, the gold deposit must be fairly heavy to prevent diffusion between the chromium and the gold. (59) Problems have been reported when cyanide gold plating reduced the peel strength of conductors on phenolic, epoxy or melamine circuit boards. (60)

6.7.4.4.1 Nickel Under Gold. To avoid diffusion and corrosion, yet combine a mechanically strong base with corrosion resistance, use nickel instead of silver under gold. (38) On printed circuits, the system is copper plate, nickel plate, then gold flash 0.000050 in. Contacts, pins, and sockets with 0.000100 in. of nickel and 0.000050 in. of gold, stand salt spray and humidity tests without trouble. (61) Even in sulfurous atmosphere, where contacts with 0.000100 in. gold over silver began to degrade immediately, those with as little as 0.000050 in. gold over nickel were unaffected. (62)

6.7.4.5 Lead. It is not used much in electronics except as tin-lead solder, but is very good in protecting steel structures in hot humid climates.

6.7.4.6 Nickel. Apply nickel by either electroplating or electroless deposition. Nickel plated hardware is compatible with both aluminum and steel. Nickel under silver (instead of copper) prevents "red plague"⁽⁶³⁾; its use under gold was discussed in Section 6.7.4.4.1; it is finding increased usage under rhodium.⁽³⁹⁾ Electroless nickel may be applied directly to aluminum or magnesium without the zincate treatment. When followed by reflowed (fused) tin, electroless nickel provides an excellent system for galvanic protection of magnesium.⁽⁷⁾ One disadvantage of nickel is its poor solderability.

6.7.4.7 Platinum and Palladium. Platinum, like rhodium, has extremely high stresses as deposited, and is little used. Palladium is said to polymerize organic vapors.

6.7.4.8 Rhodium. Rhodium has excellent wear resistance, reasonable conductivity and very good corrosion resistance⁽³⁸⁾ but also has extremely high tensile stresses as deposited; the high stress level causes cracking. It is not wet by solder.

6.7.4.9 Silver. Because of its tendency to oxidize or form sulfides, silver is not left bare. Overcoat silver immediately, or passivate to prevent tarnish⁽⁶⁴⁾; the silver sulfide is not detrimental electrically, but it looks bad and interferes with soldering.⁽⁶⁵⁾ The ARP-18 protective coating is preferred.⁽⁶⁶⁾ Silver plated parts must be stored in polyethylene bags, avoiding any contact with paper.

6.7.4.9.1 Red Plague. When silver is plated over copper, there is accelerated corrosion of the copper at pinholes or breaks in the silver.⁽⁶³⁾ (See 6.7.4.6.) This problem is solved by using nickel plate over, or instead of, the copper.

6.7.4.10 Tin. Tin, either hot dipped or electroplated and reflowed, has the best combination of solderability and corrosion resistance of any metallic coating. Furthermore, it is compatible with aluminum and magnesium, even though not close in the Galvanic Series. Tin, over electroless nickel or copper⁽⁷⁾, is recommended as the best metallic coating for magnesium. Sprayed tin is more compatible with magnesium than 5056 aluminum; tin is also good with aluminum, steel, stainless steel, and copper.⁽⁶⁷⁾ Like electroless nickel, tin may be used as the base coat for plating aluminum alloys. After the stannate bath and a bronze strike, any other metal can be deposited on the surface. Tinned surfaces can be soldered.⁽⁶⁸⁾ Furthermore, tin plate is an effective RF shield.

A problem with tin is its tendency to grow whiskers, or filiform corrosion, under conditions of long storage⁽⁶⁹⁾ but this growth can be prevented or minimized by correct application and low humidity (see Section 6.2.8.1). By using tin with at least 0.5 percent impurities, good storage life can be achieved.⁽⁷⁾ The protective action of tin is promoted by a surface layer of colorless oxide, which should not be removed by overzealous cleaning.⁽⁶⁷⁾

6.7.4.10.1 Tin Alloys. Alloys of tin with lead, zinc, cadmium, copper, etc., can be applied by hot dip or electroplating. The best known is tin-lead solder, treated in more detail in Section 8.3.

6.7.4.11 Zinc. For many years, zinc was an accepted alternate to cadmium for plating steel hardware, but poor experience has led some Services to ban the use of zinc plate. Zinc embrittles steel at temperatures above 300°F⁽⁴¹⁾; it forms white salts (white rust) in moist conditions; like cadmium, it is subject to attack by ammonia, acids, and vapors. Zinc causes the breakdown of polyvinylchloride producing a highly acidic and harmful salt, zinc chloride.⁽⁷⁰⁾ Zinc is not recommended as a metallic coating for electronic devices, housings, hardware, or cabinets, or for service in tropical climates.

6.7.5 SELECTION OF METALLIC COATINGS. In addition to the immediate requirement of conductivity, the designer should consider future conditions when he selects metallic coatings. Will the part be stored with organic materials? Will it be soldered? Will it be painted? Suggestions are listed in Table XXIV.

Table XXIV*
SELECTING METALLIC COATINGS

For	Use	Do Not Use
Contact with aluminum or magnesium	Cadmium or Tin	Chromium, Copper, Gold, Silver
Prepaint coating	Cadmium or Tin	Chromium, Nickel, Gold, Silver
Under other metals	Nickel under Silver Nickel between Copper and Silver Nickel under Gold	Copper under Silver Copper under Gold Silver under Gold
Solderability	Tin or Gold	Nickel, Chromium, Rhodium
Storage	Reflowed Heavy Tin, Gold, Rhodium	Cadmium, Zinc, Silver, Copper
Wear	Chromium, Nickel, Rhodium, Hard Gold	Cadmium, Tin
Easy etching	Cadmium, Nickel, or Indium	Rhodium, Nickel, Tin, Lead

*Section 6.7.5

6.7.6 METALLIC COATINGS ON NON-METALS. There are many applications in electronic equipment which require a conducting metallic surface on a plastic or ceramic substrate — for instance, copper-clad laminates for printed circuits. The metal may be a foil which is bonded to a plastic film or laminate. Or metal may be applied to non-metallics by one of the following methods:

1. Metal-loaded resin coatings
2. Electrodeposition
3. Vacuum deposition

The metal-loaded resins may be air-dry lacquers, resins which cure by air-dry or baking, or fired-on ceramics (see Section 9.6.4). Many of these organic coatings can be electroplated or soldered; all are electrically conductive. The corrosion problems of any metallic surface are the same, whether over a metal or plastic or ceramic substrate, with one exception: thin metallic films are more susceptible to oxidation because of their high surface-to-volume ratio.

6.8 ORGANIC COATINGS FOR METALS

Since most organic coatings may be used on either metals or non-metallic materials, they are all discussed in Section 7. Paint coatings for housings and structures are not considered a part of the electronic device.

6.9 SURFACE CONDITION

Resistance to corrosion is very much influenced by surface condition, especially smoothness, freedom from cracks and grooves, and cleanliness. These factors are intimately connected since dust and dirt lodge in any surface roughness and cause corrosion.⁽⁷¹⁾ Surface finish can be improved by mechanical means or by electropolishing (especially good for stainless steels and copper alloys).

6.10 SUMMARY -- METALS

The metals commonly used for coatings (copper, cadmium, chromium, gold, lead, nickel, platinum, rhodium, silver, solder, tin, and zinc) have already been discussed. General corrosion is discussed in a recent book edited by F.L. LaQue.⁽⁷²⁾ To complete the section, a brief resume of the treatment of metals used for parts, whether electrical or structural, is given below. The degree of protection listed herein may be greater than that required in some specifications, because the latter are mainly concerned with structural damage such as loss of strength, embrittlement, and cracking. For electronic devices, the problems of loss of conductivity, decreased solderability and possible harmful corrosion products must also be considered.

6.10.1 ALUMINUM. Used for housings, cabinets, chassis, structure. Subject to intergranular, stress, crevice and galvanic corrosion. Anodize unless conductivity is required, in which case use chemical film treatment, cadmium, tin or nickel plate. Apply paint coatings over the chemical film for exterior use; paint over anodize if desired, but the anodize gives adequate corrosion resistance without it. Be alert for "purple plague" when welding aluminum and gold (see 8.6).

6.10.2 BERYLLIUM. Used for gyros, instruments. Subject to pitting and to galvanic corrosion; very similar to magnesium. Difficult to anodize. Clean carefully, coat with electroless nickel⁽⁷³⁾, paint.

6.10.3 COPPER. Various alloys used for contacts, springs and leads. Corrosion resistance depends on the alloy but all require surface protection to prevent tarnish, usually a black coating MIL-F-495.

6.10.4 INDIUM. Sometimes used in bearings, or as heat transfer medium. While resistant to the atmosphere, it is attacked by salt and acids, and should be protected by oil.

6.10.5 IRON. Subject to corrosion regardless of its use (shielding, a core, transformer, hardware) and must be plated, oiled, or painted to prevent rust. Bolts, screws, nuts and hardware are plated with nickel, tin or cadmium.

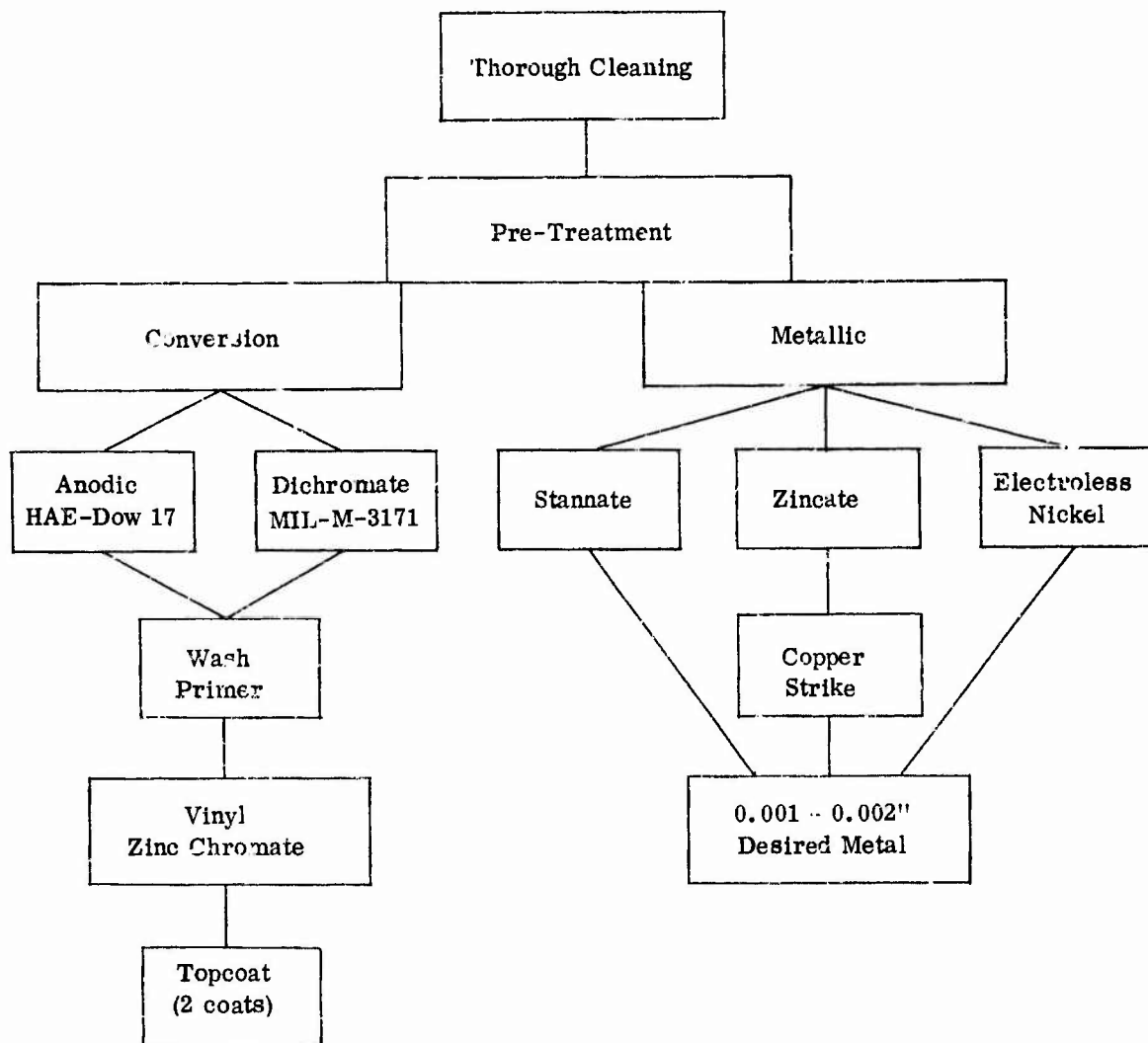
6.10.6 MAGNESIUM. Because it corrodes so easily, many agencies forbid the use of magnesium. It is subject to chemical attack, pitting, intergranular corrosion, and stress corrosion. Magnesium forms a strong galvanic cell with every other metal, and is always the one attacked. However, it can be protected adequately if care is used in the design and if every precaution is taken to avoid water traps, provide complete coverage of the magnesium surface, use multilayer protective systems, and insulate dissimilar metal contacts. To ensure freedom from galvanic corrosion when using magnesium, it is often necessary to coat with a more compatible material, remove moisture, use organic coatings, and seal the joint with tape or sealing compound. (See 6.3.4.2.)

6.10.6.1 Metallic Coating Magnesium. A new improved surface treatment for magnesium is the stannate (tin) treatment, a chemical immersion coating with four advantages:

1. Corrosion resistance equal to, or better than, anodic treatment DOW-17. (1)
2. Can be used on magnesium-steel assemblies such as steel inserts: will tin coat the steel.
3. Good paint base.
4. Good undercoat for other metals.

Table XXV indicates some of the metal treatments for magnesium such as stannate, immersion zinc, and electroless nickel. At least 0.001 to 0.002 in. thick plating of good quality is needed to withstand 50 hours salt spray. (74) However, because of its position in the Galvanic Series, magnesium is not easy to plate.

Table XXV*
FINISHES FOR MAGNESIUM



*Sections 6.10.6.1 and 6.10.6.2

6.10.6.2 Organic Systems. Although the topcoat is often specified by the procuring agency, the choice of pretreatment of magnesium for paint is frequently left to the contractor. Remember:

1. Heavy anodic coatings are best.
2. Where parts must flex, the anodic coatings (being ceramic) cannot be used. Select the chemical treatments in MIL-M-3171 best suited to the alloy.
3. Chemical treatment is a paint base, not a corrosion preventative. Overcoat IMMEDIATELY.
4. Heavy anodic coatings, sealed with wax, provide some protection from galvanic corrosion. Chemical treatment does not.
5. The usual wash primer (MIL-C-15328) is too acid for magnesium. Use 25 percent of the specified phosphoric acid.
6. Use topcoats which are alkali resistant.

The magnesium-lithium alloy LA 14A-T7 can withstand 14 days of 95 $\pm$ 5 percent relative humidity at 35°C (95°F) and 50 hours salt spray, after being treated with fluoride anodize and two coats of polyurethane sealant. (75)

6.10.7 NICKEL. Much used as leads for welded modules, and for special purpose parts such as springs. Attacked by sulfur, but is freer from atmospheric tarnish than silver, copper or brass (reference 72, page 493).

6.10.8 STEEL. Like iron, steel must be protected from rust. Special care must be taken to prevent embrittlement from plating strong steels. Thorough cleaning is essential before any coating.

6.10.9 STAINLESS STEEL. There are many varieties of "stainless" steel, but only a few are free from rust. The four main grades are:

1. Martensitic: heat treatable chromium steels, types 403, 410, 416, 420, 431, 440, 501, 502.
2. Ferritic: chromium steels, not capable of strengthening (types 430, 446).
3. Austenitic: nickel-chromium steels of familiar 18-8 type (300 series) 301, 302, 303, 321, 347, etc.
4. Precipitation Hardening: nickel-chromium steels which can be heat treated to high strength, 17-7PH, 17-4PH, AM 350, AM355, 15-7Mo, etc.

All of the "stainless" steels contain enough chromium to retard corrosion, but are rust resistant, not truly stainless. They should be passivated to clean the surface, remove any contaminants, and promote resistance to corrosion. The properties of various kinds of stainless steels are listed in Table XXVI.

6.10.9.1 Special Notes. Susceptibility of stainless steels to attack is markedly affected by composition, heat treatment, and surface condition as well as the corrodent. Consult the Metals Handbook(9) or a competent metallurgist before selecting a specific type for corrosive service. Suggestions:

1. Do not temper martensitic stainless steels in the range of 370° - 950°C (700° - 1200°F) as they will be very subject to stress corrosion.
2. Double-temper martensitic stainless (cool to room temperature then repeat the tempering operation) to increase resistance to stress corrosion.
3. Remove heat tint from PH steels by mechanical means or electropolishing rather than acid, to prevent intergranular attack.
4. The smoother the surface, the better the corrosion resistance.
5. Electropolishing produces a passive surface which does not require further passivation treatment.

Table XXVI*
STAINLESS STEELS

Property	Type of Stainless Steel			PH
	Martensitic	Ferritic	Austenitic	
Magnetic	Yes	Yes	No**	Yes
Heat Treatable	Yes	No	No	Yes
Rust	Yes	Some	No**	Yes
Susceptible to:				
Stress Corrosion	Yes	No	Yes	Yes
Intergranular	No	Yes	Yes	No
Crevice Corrosion	No	No	Yes	No
Hydrogen Embrittlement	Yes	No	No	Yes

*Section 6.9.7

**Unless highly cold - worked to extremely hard state

6.10.10 TITANIUM. Titanium has excellent corrosion resistance in most environments, although sometimes subject to stress corrosion. It quickly forms a tenacious oxide film which changes it from the "active" state to "passive", close to stainless steel in the Galvanic Series.

6.10.11 SINTERED METALS. Parts made of powdered and sintered iron, stainless steel, brass, bronze, and nickel silver are more subject to corrosion than the solid metals because of the surface area exposed and the pores permitting corrodent to enter. As would be expected, wax impregnation improves resistance a great deal. However, sintered iron must also be cadmium, chromium, or tin-zinc plated to give satisfactory protection.⁽⁷⁶⁾

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SECTION 7 NON-METALLICS

7.1 USAGE IN ELECTRONICS

In most electronic assemblies, only the conductors are metallic. The other parts may be, and usually are, non-metals. They may be dielectrics; insulants; structural parts such as knobs, boards, or spacers; or coatings to protect or isolate. Regardless of their function, they affect and react to the environment. The degradation caused by non-metallics used in electronic devices, as well as their deterioration due to the environment, is discussed in this section.

7.1.1 MATERIALS INVOLVED. Non-metallics include everything from oils and moisture-proofing liquids to organic coatings, flexible films, soft thermoplastics, molded thermosets, elastomers, reinforced laminates, paper, wood, glass and ceramic. Typical non-metallics used in electronics are listed in Table XXVII. Many of these non-metallics are impervious to degradation from moisture, fungi, or changes in temperature. Therefore, Government specifications on finishes (such as MIL-STD-171 or MIL-STD-186) put most of the emphasis on metals. However, certain non-metallics do deteriorate, and must be protected.

7.1.2 CLASSIFICATION. This report is concerned only with the deterioration of electronic assemblies, as the result of environments and corrosion. Therefore, attention is centered on materials, regardless of the purpose for which they are used. The same thermosetting plastic may be used by different designers as insulation, adhesive, seal, spacer, encapsulant, or coating. Where the form or the method of fabrication affects resistance to corrosion (as in reinforced laminates or molded parts) this is mentioned. Special attention is given to encapsulants, coatings, and tape. Except for these, non-metallics are classified as thermosetting or thermoplastics; rubbers and elastomers (7.6); oils, greases and lubricants; ceramics, glass, and optics; wood, cotton and paper.

7.1.3 CHOICE. The essential properties are surface resistivity, dielectric constant, loss factor, and availability in the desired form. Additional characteristics should be considered:

1. Compatibility with adhesive, varnish or coating used, and with other materials nearby - it should neither destroy others nor be damaged itself.
2. Low moisture absorption.
2. Stability of desired properties throughout the frequency range.
4. Stability of desired properties throughout the temperature range, including accidental overheat from soldering.
5. Resistance to fungi, molds and bacteria.

7.1.4 DATA ON NON-METALLICS. Two recent publications of special interest to the designer of electronic items are the MIL-HDBK-700 (MR), "Plastics," dated November 1965, and the Directory/Encyclopedia issue of "Insulation" (Libertyville) for May/June 1966. In addition, a comparison of the properties of common plastics is given in references 1 and 2; some of the new plastics especially useful in corrosion prevention are described in reference 3. Data sheets on many specific materials are available from the Electronic Properties Information Center at Hughes Aircraft. The designer must take into account the many variations of

Table XXVII*
NON-METALLICS USED IN ELECTRONICS

Material	Type	Purpose
Oils	Hydrocarbon	Lubrication
Compounds	Moisture displacing	Corrosion prevention
	Silicone	Heat Transfer
Dry Film Lubricant	MoS ₂ , Teflon	Lubrication
Varnishes and coatings	Alkyd, epoxy, silicone, polyurethane, etc.	Insulation, moisture proofing
Coatings	Phenol-formaldehyde containing salicylic acid	Fungicide
Laminates	Thermosetting plastics, plus cotton, linen, glass, paper	Terminal boards, structural parts
Films	Elastomer, thermoplastics, mineral	Insulation, protection
Molded parts	Plain or reinforced thermosets, thermoplastics	Varied
Seals	Elastomers, plastics, leather, fabrics	Barrier to moisture and gas
Potting and Encapsulants	Plastic, elastomers	Insulation, mechanical support
Glass	Borosilicate, etc.	Insulation
Ceramics	Mica, asbestos	Insulation, fillers

*Section 7.1.1

plastic compositions, the large effect of small differences, and the fact that non-metallics often do not have uniform properties everywhere. Long experience with metals has led to blind reliance on published figures. The manufacturers of plastics, fibers, and ceramics are no less reliable than the metal producers, but they do not have the advantage of working the material over and over to achieve uniformity throughout. Nor can plastics manufacturers limit their output to a few standard compositions, like metals. Finally, the plastic part used in electronics is often made not by the manufacturer of the material, but by a fabricator who controls the end properties, both physical and electrical. Forming a part from copper does not change its density or conductivity. But the technique of mixing, molding and curing a

molded part or an encapsulant, does determine the final characteristics of the part. Advising the fabricator or supplier of the qualities essential for performance, then working closely with him, is the best guarantee of success.

7.2 CAUSES OF DETERIORATION IN NON-METALLICS

The causes of deterioration or change have already been discussed in Section 3. Those most affecting non-metallics are weathering (sunlight, ultraviolet radiation, ozone and oxygen); moisture; temperature; microbial attack; animals and insects; and incompatible materials. It is impossible to generalize about the effect of environments on non-metallics because of the great differences in materials. Each specific material should be scrutinized for its suitability for the function involved, in that particular part and assembly, and under all environmental conditions anticipated.

7.2.1 WEATHERING. Weathering includes exposure to sunlight, ultraviolet, ozone, and oxygen, accompanied by some amount of temperature cycling and moisture. Sunlight, ultraviolet and ozone are most harmful to thermoplastic and elastomeric materials, in such applications as antennae, and insulation on cabling.

7.2.2 TEMPERATURE. Organic materials are liable to break down or start outgassing at such temperatures as 175°C, which is quite low for metals. See Section 3.4.4. Polyvinylchloride compounds are especially subject to decomposition at high temperatures, aggravated by contact with zinc, or ultraviolet radiation. Oils and greases undergo marked changes in properties when either hot or cold; many plastics and elastomers are embrittled at low temperatures. The materials developed for, and used in, electronic devices will usually withstand the military requirements of -55° to +75°C (-65° to 165°F) but the effect of temperature should always be investigated.

7.2.3 MOISTURE. The effect of moisture on the properties of non-metallics is only one of the factors to be considered. Since non-metallic coatings, films and encapsulants are often used to moisture-proof other parts, both the absorption of moisture and the rate of transmission of water vapor, are of prime importance. Moisture absorption is an inherent quality of the material: i. e., polyamide absorbs moisture, fluorocarbons do not. But the degree of absorption is greatly affected by form and condition, especially the degree of cure and the presence of fillers. For example, the water absorption of molded epoxies runs from 0.05 percent to 0.15 percent, but for flexible cast epoxies, cured at room temperature, it is 0.5 percent to 1.5 percent. The glass fabric in laminates, or fibrous fillers in cast or molded products, may let moisture enter along the filler-resin interface. (See Section 7.3.) Or surface damage - abrasion or cracks - can let water into a part. It is important to select a material with less than 1.0 percent moisture absorption; use a form which does not promote water intrusion; and have a sound solid surface. Table XXVIII lists typical water absorption values for plastics.

7.2.3.1 Moisture Vapor Permeability. Moisture transmission is of paramount importance when plastics and coatings are used to protect other parts. Elastomers, oils, seals, encapsulants, and coatings offer a high degree of protection when thick enough, thoroughly cured, properly applied, and continuous. Materials which have outstanding low rates of moisture vapor transmission are CFTE fluorocarbon, polypropylene, and polyethylene. There is little correlation between moisture absorption and moisture transmission, and some films which keep moisture out, let oxygen and other gases through. Check with the supplier for detailed information.

Table XXVIII*
MOISTURE ABSORPTION OF PLASTICS

Water Absorption Percent increase in weight, 24 hrs at 23°C, 1/8 inch thickness	Material
0 to less than 0.01	Polychlorotrifluoroethylene Chlorinated polyether Polytetrafluoroethylene Polyfluoroethylenepropene
0.01 to 0.10	Polypropylene Polyethylene Vinylidene fluoride Polystyrene Vinyl, rigid Acrylic
0.10 to 0.50	Diallyl phthalate Phenoxy Epoxy, molded Silicone Alkyd ABS Acetal Polycarbonate Epoxy, rigid, cast Filled melamine
0.50 to 1.00	Amino urea Urethane elastomer Phenolic Polyester Epoxy, flexible, cast
Over 1.00	Ethyl cellulose Cellulose butyrate Cellulose proprionate Polyamide Cellulose acetate Vinyl, flexible

*Section 7.2.3

7.2.3.2 Effect of Moisture. Moisture degrades in non-metallics three ways: physically, (swelling, distortion, and finally disintegration); mechanically, (cracking, or changing the properties); and electrically (altering essential characteristics). Moisture increases surface conductivity, decreases volume resistivity, increases the loss angle, gradually reduces dielectric strength and provides optimum conditions for microbial growth. These changes in properties can destroy the part's usefulness, and are not always reversed by drying. For example, after polymers had been exposed to 90 percent RH, the resistivity measured later at 50 percent RH increased 250 times, along with increased capacitance and dissipation factor.

7.2.4 MICROBIAL ATTACK. Glass, ceramics, and many plastics are free from microbial attack. The organic materials such as silk, paper, wood, leather, cotton, linen, natural rubber, and some plastics are fungitoxic. Coatings for optics are attacked, as are some varnishes and encapsulants. Solving the moisture problem generally takes care of the fungal problem as well, because fungi must have moisture to grow. See Section 3.6.2.

7.2.5 INSECTS AND ANIMALS. Many non-metallic materials are very attractive to insects, ants, beetles, birds, termites, and even to rats. This is a physical attack, different from the chemical effects of heat, moisture, ozone, cleaners, and microbes. Table VII in Section 3.6.8 lists results of investigations into termite damage. They seem to prefer tender, chewable materials

7.2.6 INCOMPATIBLE MATERIALS. The compatibility of plastics with other materials is a highly individual quality, depending on the exact composition and cure of the plastic, the chemical analysis and concentration of the other material, the temperature, and the time of exposure. Many plastics have excellent resistance to acids, alkalis, and commercial solvents, as indicated in Table XXIX. But others are attacked, and some decompose. Methylmethacrylates and polycarbonates, vinyls, cellulose, and ABS are crazed and cracked by common sealants and by many cleaners. Most elastomers have very poor resistance to chlorinated hydrocarbons (fluorosilicone is an exception). Some plastics break down with temperature, liberating gases which are corrosive to nearby parts: polyvinylchloride does this, unless specially stabilized with additives. For more data on the outgassing of organic materials, and incompatibility, see Sections 3.4.4, 5.3.7 and 5.3.8. One specific problem is lack of adhesion between circuit board and conformal coating, or between the coating originally used and that used for repair. The various plastic materials used in electronics are a team, either working together or damaging each other. They must be selected with care, with attention to the exact application and environment.

7.2.6.1 Cleaners and Strippers. As mentioned above, the chlorinated hydrocarbons and other common cleaners damage most elastomers and many plastics. The strippers recommended for removing epoxy coatings or encapsulants often also take off the marking and varnish from components. Chloroethene softens plastic resistor cases, and both ketones and esters attack vinyl. The choice of cleaning method and material may be somewhat outside the province of the designer, but he should be aware of the dangers.

7.3 EFFECT OF FORM

Non-metallics such as plastic resins may be used in castings, filled or unfilled molded parts, laminates, film and many other forms. However the part is made, it is essential for maximum resistance to environments that the surface be unbroken and solid. When fibrous fillers are used, water can enter parts along particles, reaching the surface, especially if the filler is paper, fabric, linen, woodflour or any other material with high moisture pickup. The filler particle, the bond between resin and filler, and the shape of any voids - whether they are channels, fissures, capillaries, or rounded cavities - are important factors in moisture absorption of plastics. The bad effect of "wicking" is especially marked in cotton-reinforced cable insulation. The smoother the surface and the more solid the part, the less tendency there is to hold condensate or dust or contaminants. Another important item is the thickness of resin over the reinforcements, especially in laminates. One danger sometimes overlooked is that cut edges of laminates may permit moisture to enter, unless sealed.

7.4 THERMOSETS

The thermosetting plastics commonly used include alkyds, phenolics, ureas, melamines, epoxies, polyesters, silicones, and polyurethanes. As indicated in Table XXX, these resins

Table XXIX*
RESISTANCE OF PLASTICS TO CHEMICAL ATTACK

Plastic	Resistance to		Solvents
	Acids	Alkalis	
ABS	E	E	Varies
Acetal	P - G	P - G	G - E
Acrylic	D	P	D
Cellulosic	D	D	D
Chlorinated Polyether	E	E	E
Fluorocarbon	E	E	E
Polyamide	P	G - E	E
Polycarbonate	F	Varies	D
Polyethylene	P	G - E	G
Polypropylene	G - E	E	Varies
Polystyrene	G - E	E	P
Vinyl Chloride	G - E	G - E	Varies
Alkyd	P	P	G
Epoxy	G - E	G - E	E
Melamine	F - E	F - E	E
Phenolic	Varies	Varies	Varies
Polyester	P - F	P - F	Varies
Silicone	Varies	Varies	Varies
Urethane	P - F	P - G	F - E

Key: E = Excellent

G = Good

F = Fair

P = Poor

D = Decomposes

Varies: with the specific composition, corrodent, concentration, temperature, and time.

*Sections 7.2.6, 7.5.6

may be used alone, or modified, or filled; they may be in any form from low viscosity liquid to hard, strong laminates. The thermosets have one thing in common: they do not melt under heat. A comparison of various types is given in reference 4.

7.4.1 CAST AND MOLDED THERMOSETS. Castings or molded parts may be either plain or filled, flexible or rigid, cured at room temperature or by baking. They are used for all sorts of electrical and electronic parts, and very seldom give any problems with corrosion. Like other organic materials, they should be completely cured; this is especially important when using an acid-activated system which might release acidic fumes. Furthermore, an additional post-cure treatment increases resistance to moisture, improves electrical properties, and lowers the probability of outgassing. Formaldehydes should be used with caution, as phenol-aniline-formaldehyde is fungus-nutrient⁽⁵⁾ and urea-formaldehyde cracks under humid conditions. If severely overheated, almost any plastic (even diallyl phthalate, epoxy, polyurethane or silicone) will outgas enough to tarnish silver and attack cadmium and zinc.⁽⁶⁾

7.4.2 LAMINATES. Much work has been done on the effect of weathering on thermosetting laminates, but primarily on the mechanical properties. The thermosets weather well⁽⁷⁾ although there is some plant growth on the surface; the loss of strength due to weathering is not severe. A major use of laminates in electronic items is for circuit boards. Do not over-clean (see 8.4.3.1) as abrasion of the resin surface damages the moisture resistance; and seal cut edges of the laminate to prevent moisture intrusion.

Table XXX*
THERMOSETS

Resins:

Alkyds	Melamine	Polyurethane
Diallyl Phthalate	Phenolic	Silicone
Epoxy	Polyester	Urea

Forms:

Adhesives	Encapsulants	Potted
Cast	Laminates	Tape
Coatings	Molded	Varnishes

Fillers:

Asbestos	Chopped Glass	Orlon
Beryllia	Flock	Paper
Cellulose	Glass	Polyamide
Cotton	Linen	Silica

*Section 7.4

7.4.3 EFFECT OF FUNGI. Most thermosets are not attacked by fungi unless they are modified by additives or plasticizers. However, phenol-aniline-formaldehyde, casein formaldehyde, melamine formaldehyde and glyptal varnishes are rated "poor" in resistance to microbial attack.⁽⁵⁾ Others such as polyurethane are in themselves resistant but may be attacked if in foam or other form which collects moisture and contaminants on the surface.

7.4.4 MODIFICATIONS. It is important to remember that all properties of plastics can be changed by modifying the composition. Epoxies, for instance, may be altered, to get higher thermal conductivity, or higher resistivity, or different mechanical properties; the types of epoxies are discussed in reference 8, which also lists applicable specifications. The word "silicone" may be used, correctly, for fluids, grease-compounds, encapsulants, elastomers, resins, coatings and varnishes, etc. In selecting non-metallics, the designer should inform himself about the specific properties of the exact item involved.

7.5 THERMOPLASTICS

Thermoplastics include a wide range of materials grouped together because of one property in common: they all soften under heat. The common thermoplastics are listed in Table XXXI. Heat distortion temperature varies with the load but few thermoplastics can carry loads at temperatures above 100°C, and many "cold flow" just above normal room temperatures. Polyimide is an exception, recommended for use to 260°C (500°F).⁽⁹⁾ Reference 10, 11, 12 and 13 list mechanical, electrical and thermal properties of thermoplastics.

7.5.1 WEATHERING. Thermoplastics are more subject to deterioration from weathering, moisture, temperature, and insects than are thermosetting materials⁽⁷⁾ especially under tropical conditions^(14, 15, 16) embrittling and losing strength. Since adding carbon black to polyethylene reduces the embrittlement, deterioration is attributed to solar radiation.⁽¹⁷⁾ Ultraviolet also increases the loss tangent, thus raising the temperature and contributing to further degradation, as explained in a study of failure of a cross-linked polystyrene feed horn window in a radar antenna.⁽¹⁸⁾

7.5.2 TEMPERATURE. All thermoplastics soften when hot, but many can be used throughout the usual range from -55° to +75°C without damage; for example, fluorocarbon, polyimide, polycarbonate, polypropylene, polyethylene, acetal. Polyvinylchloride, however, decomposes gradually at temperatures as low as 50°C. The breakdown increases with time and temperature⁽¹⁹⁾ and is accelerated by ultraviolet radiation or the presence of heavy metals.

7.5.3 MOISTURE. Polyamide (nylon), the cellulose (cellulose acetate, nitrate, propionate, and acetate butyrate) and the flexible vinyls (vinyl acetate, butyral and formal) all have more than 1 percent absorption of moisture through 0.125 in. thickness in 24 hours. Compare this with 0.01 percent or less for the fluorocarbons or chlorinated polyether. (See Table XXVIII.)

7.5.4 MICROBIAL ATTACK. Of the thermoplastic resins, only cellulose nitrate, cellulose acetate and polyvinyl acetate are rated "poor" in fungus resistance.⁽⁵⁾ See Section 3.6.2 and Table V. However, some experts believe that almost any plasticizer is subject to attack by some organism, if the temperature and humidity are right. The geometry of the part, cleanliness, and thickness of resin layer over any filler, are also important.

7.5.5 INSECTS AND ANIMALS. Plasticizers have a marked effect on a plastic's ability to withstand termite attack as indicated in Table VII, Section 3.6.8. The best way to prevent destruction by animals is through mechanical means, such as wrapping steel mesh around cables.

Table XXXI*
THERMOPLASTICS

Resins:

ABS	Polyimide
Acrylic	Polypropylene
Acetals	Polystyrene
Cellulosics	Polysulfone
Chlorosulfonated Polyether	Polyvinylacetate
Fluorocarbons	Polyvinylchloride
Phenoxy	Polyvinylidene Fluoride
Polyamide	Polyvinylidene Chloride
Polycarbonate	Urethane
Polyethylene	Vinyls

Forms:

Cable Covering	Laminates
Coatings	Molded
Extruded	Shrinkable (irradiated)
Films	

Fillers:

Asbestos	Graphite
Disulfide	Molybdenum
Glass	

*Section 7.5

7.5.6 INCOMPATIBLE MATERIALS. Polyvinylchloride, because of the acid fumes it emits, is incompatible with almost everything. Cellulose nitrate plastics decompose when exposed to ultraviolet radiation, liberating corrosive fumes, and the breakdown continues even when removed from sunlight. (20) Other non-metallics which emit corrosive fumes are listed in Table IV, Section 3.4.4. The effect of acids, alkalies and common organic solvents on plastics is shown in Table XXIX. Note especially that many common thermoplastics are soluble in alcohols or ketones, so the use of MEK as a cleaner is unwise. When cleaning an assembly, it is important to use neutral materials which will not attack any plastic present.

7.5.7 FLUOROCARBONS. Because of their good dielectric properties, zero moisture absorption, and resistance to environments, fluorocarbons find many uses in electronic devices. (22) There are four commonly used types:

Polytetrafluoroethylene (Teflon)	TFE
Polyfluoroethylenepropene	FEP
Polychlorotrifluoroethylene	CTFE
Polyvinylidene fluoride	VF ₂

(Technically, CTFE and VF₂ are halocarbons rather than fluorocarbons, but are classed with TFE and FEP because of the similarity of properties.) The fluorocarbons are available as pressure-sensitive tape with silicone adhesive, as glass-supported tape or fabric, as film, sheet, coatings, and in aerosol form for lubricant. Fluorocarbons can be used as relatively high temperatures (200° to 300°C). While they do liverste chlorine and fluorine under excessive heat, the breakdown temperature is so high that other components would fail from the heat, rather than from any gases given off by the fluorocarbon.

7.6 RUBBERS AND ELASTOMERS

In addition to the natural and synthetic rubbers, there are elastomers of chlorosulfonated polyether, acrylic, fluorocarbon, polysulfide, polyurethane, fluorosilicone, crosslinked polyethylene, ethylene-propylene, and many more. In fact, it is difficult to draw a sharp line between plastics and elastomers, especially if the latter term is used to include all materials exhibiting marked resilience and elasticity. A new word, "elastoplastics" is probably more descriptive than either "plastic" or "elastomer." Typical elastomeric materials are listed in Table XXXII. Characteristics depend on the compound and process used; by varying the ingredients, almost any desired property can be produced. For example, rubbers are normally considered electrically insulating. Yet both Buna N and Neoprene can be made conductive (with resistance around 100 ohm/cm) by loading with carbon black. Antiozants, fungicides, and fillers can be added to change the basic properties at will. Elastomers are used in electronics for insulation, seals, gaskets, caps, tubing, films, tape, molded and extruded parts, coatings, and encapsulants.

7.6.1 EFFECT OF ENVIRONMENTS. Natural rubber and the early synthetics, Buna N and Buna S, were very much affected by climatic environments. They failed by cracking when exposed to weather⁽²³⁾ especially if in contact with the "rubber poison" metals, copper, iron or manganese. They embrittled at low temperatures, and lost strength when hot. Fungi and microbes thrived on them. Today's specially developed elastomers are designed to meet severe requirements, and offer the designer of electronic equipment a wide choice of properties. However, no one compound combines the necessary electrical and mechanical properties with resistance to all common environments. Silicone rubber, although excellent for many applications, lacks the resilience and mechanical strength of natural rubber or neoprene, and is attacked by chlorinated hydrocarbons. Polysulfide has an objectionable odor and a tendency to outgas, liberating sulphur fumes. Although polyether urethanes can stand the hot humid weather of the tropics, the polyester urethanes break down severely after a year or two in Panama.⁽²⁴⁾ Films of polyurethane and silicone rubber are relatively permeable to water; the rate of transmission through these materials is five times that through a similar film of fluorocarbon.⁽²⁵⁾ Natural rubber, Buna N, Buna S and Butyl are attacked by fungi and microbes. Even silicone rubber and polyurethane, both considered funginert, have been found to support fungal growth in some laboratory tests.⁽²⁶⁾ Fluoroelastomers may corrode metal, when in contact with petroleum-base or phosphate-ester type fluids.⁽²⁷⁾ There are so many modifications of the basic elastomers that it is difficult to summarize the reaction to environments, but some specific notes are given in Table XXXIII.

7.6.2 SHRINKABLE ELASTOMERS. As discussed in Section 5.4.2.7, a number of elastomers and plastics, when irradiated, become "heat-shrinkable." They contract so much

that they provide a tight environmental seal, electrical insulation, and mechanical support.
See 5.4.2.7 for detailed comments.

Table XXXII*
COMPARISON OF PROPERTIES OF RUBBERS AND ELASTOMERS**

Material	Dielectric Constant	Dissipation Factor	Resistivity ohm/cm	Resistance to	
				Ozone	Water
Acrylic	—	—	—	E	P
Chlorosulfonated Polyethylene	7. - 10.	.03 - .07	10^{14}	E	G
Buna N	13.	.055	10^{10}	E	E
Buna S	2.9	.0032	10^{15}	P	E
Butyl	2.1 - 2.4	.003	10^{17}	E	E
Fluorocarbon***	—	.03 - .04	10^{13}	E	VG
Fluorosilicone	6.9 - 7.4	.03 - .07	$10^{13} - 10^{14}$	E	G
Ethylene Propylene	3.17 - 3.34	.0066 - .0079	$10^{15} - 10^{17}$	E	E
Natural Rubber	2.3 - 3.0	.0023 - .003	$10^{15} - 10^{17}$	P-F	E
Neoprene	9.0	.03	10^{11}	E	G
Polysulfide	7.0 - 9.5	.001 - .005	10^{12}	E	E
Polyurethane	5. - 8.	.016 - .09	$10^{11} - 10^{14}$	E	G
Silicone Rubber	3.0 - 3.5	.001 - .010	$10^{11} - 10^{17}$	E	E

*Section 7.6

**Abstracted from Insulation (Libertyville) Directory/Encyclopedia
Issue, May/June 1966, p. 208-209

***Vinylidene fluoride perfluoropropylene

Table XXXIII*
ENVIRONMENTS - EFFECTS ON ELASTOMERS

Environment	Attacked	Resistant
Weathering (ozone, sunlight)	Natural rubber, Buna N, Buna S	Acrylic, neoprene, polysulfide, silicone, chlorosulfonated polyethylene
Moisture (absorption)	Acrylic	Natural rubber, Buna N, Buna S, Butyl, polysulfide, silicone
Moisture (transmission)	Silicone, polyurethane	Fluorocarbon, Buna N
High temperature (above 100°C)	Buna N, Buna S, neoprene, polysulfide, polyurethane	Acrylic, fluorocarbon, silicone, fluorosilicone
Low temperature (below -40°C)	Acrylic, Buna N, chlorosulfonated polyethylene, neoprene, polysulfide	Silicone, fluorosilicone
Fungi, microbes	Natural rubber, Buna N, Buna S, butyl	Other elastomers
Chlorinated hydrocarbons	Acrylic, Buna N, Buna S, natural rubber, neoprene, silicone	Fluorosilicone
Oil and gasoline	Buna S, butyl, natural rubber, silicone	Fluorocarbons, fluorosilicone, polysulfide, polyurethane

*Section 7.6.1

7.7 OILS, GREASES AND LUBRICANTS

These materials are more liable to be employed in electromechanical devices than in electronic items. However, there are a number of applications where lubricity is essential, and where an oil or grease is needed. Lubricants are non-insulating electrically, but may be somewhat insulating chemically, since they prevent moisture from reaching the surface.

7.7.1 EFFECT OF ENVIRONMENTS. Greases and oils break down at high temperatures or low pressure, losing the more volatile components and changing their properties. For severe service, either a silicone oil or grease, a fluorocarbon, or a solid film lubricant is preferred. Transformer and condenser oils lose dielectric strength if they absorb moisture; the effect is aggravated by contaminants. (23)

7.7.2 EFFECT ON NEARBY PARTS. As the temperature rises, the viscosity of oil or grease decreases and it "creeps." Some "creep" at room temperatures. All volatilize at low pressure, contaminating adjacent surfaces, lifting paint or other organic coatings, and attracting dust. To retard oil spreading, there are several commercial "migration control agents" consisting of fluorochemical dissolved in a special volatile solvent. Oil or grease on a part may induce electrical leakage: even fingerprint grease produces an electrical leakage film on ceramic surfaces. (28) Another problem is that of incompatible materials. Diester oils

attack neoprene and many plastics. Silicone oils or grease may make it impossible to get adhesion of future coatings. See Section 5.3.8.

7.7.3 DRY FILM LUBRICANTS. There are many combinations of lubricants and resins in the "dry film" category, usually containing molybdenum disulfide and graphite in phenolic, epoxy, or silicone resin. Although excellent lubricants for extremely high pressures, these materials do not protect against corrosion. Molybdenum disulfide in grease increases the corrosive tendency.⁽²⁹⁾ When used in a resin carrier, it may increase corrosion resistance or have no effect, but seldom contributes to protection.⁽³⁰⁾ Processing for maximum corrosion resistance does not produce maximum wear.⁽³¹⁾ Three facts about dry film lubricants should be kept in mind: graphite acts like a metal in promoting galvanic corrosion; the resin is intended as a carrier for lubricant and not as a corrosion protective coating; and proper preparation of the surface before applying the dry film lubricant is essential.

7.7.4 FLUOROCARBONS AS LUBRICANTS. Although they are not oils or greases, the lubricity of the fluorocarbons entitles them to mention here. As coatings, powders, films or solid parts, the fluorocarbons are noted for their low friction and lubricating qualities.

7.7.5 MOISTURE DISPLACING COMPOUNDS. Some materials can be classed as either penetrating oils or protective compounds. They have low surface tension and high capillarity, which enables them to displace water from a metal surface and seal against future moisture intrusion. Applied by spray, brush, or dip, such compounds form a film only a few microns thick, so adherent and continuous that it removes fingerprint corrosion. These moisture displacers are not temporary in-process protection, nor are they an undercoat - they are sufficient as the only protective coating for extended periods of time. Such compounds protect metal but do not harm rubber, plastics or paint as they are not actually oils; some contain only a small percentage of hydrocarbons and no silicones, no acrylics. If necessary, they can be removed by vapor degreasing.

7.7.6 HEAT SINK COMPOUNDS. While not always greases, the various heat sink or thermal compounds are frequently of a grease-like consistency. They may be silicones heavily loaded with thermally conductive metal oxides, such as beryllia. These compounds are electrically insulating, chemically inert, thermally conductive materials used between semiconductors and heat sinks, thermistors and mountings, diodes and studs.

7.8 CERAMICS, GLASS AND OPTICS

These materials might seem immune to environments. Actually, the electrical properties of both glass and ceramics change with temperature; the surface of glass and ceramics is so hygroscopic that some claim a relative humidity of 60 percent to 70 percent at room temperature is enough to deposit a thin water film. Then alkali migrates to the surface of the glass and reacts with condensate.⁽³²⁾ And the coatings used on optics are frequently attacked by microbes. See Section 3.6.5.

7.8.1 OPTIMUM CONDITIONS. Glass, ceramics, and optics should be solid, glazed, coated, and clean. Seal optics with silicone rubber or fluorocarbon to prevent moisture or dust intrusion. In the humid tropics, the coating on optics is very susceptible to fungal growth, and keeping equipment clean and dry is one of the best preventive measures. Fungicides should be incorporated in coatings.

7.9 WOOD, COTTON, PAPER

These materials are well known for their moisture absorption and susceptibility to microbial attack. If it is absolutely necessary to use such materials, they should be treated before use with a preservative and a fungicide. Poison incorporated in the glue makes plywood termite-proof.⁽³³⁾ Pentachlorophenol is the accepted standard fungicidal treatment for wood.⁽³⁴⁾ Do not use cotton, linen, duck, leather, wood, paper or other similar material without fungicidal treatment, unless completely enveloped in an inert material.

7.9.1 DAMAGE BY WOOD. Metals are especially subject to attack by vapors from wood and should not be exposed to them. Oak, chestnut, and cedar emit the most harmful gases. The most susceptible metals are magnesium, steel, zinc, copper, cadmium and nickel, at relative humidities above 75 percent.⁽³⁵⁾

7.10 ENCAPSULANTS

7.10.1 PURPOSE. Encapsulation, as the word implies, means complete envelopment of a component or assembly, usually in a continuous organic resin. It is primarily for electrical insulation, but also provides resistance to corrosion, moisture, and fungus, and supports the items mechanically.⁽³⁶⁾ Encapsulation is the most widely used method of insulation and protection for electronic modules; 97 percent of the companies contacted for this study reported that they use encapsulation. Whether the part in question is a diode, coil, transformer, welded module, printed circuit, or other type of assembly, it can be encapsulated by one of the processes and materials mentioned below.

7.10.2 PROCESSES USED. There are four common processes for surrounding electronic parts or components with protective resins:

1. Impregnation, where the compound is applied under vacuum or pressure, forcing its way into every interstice;
2. Potting or casting, where the part is placed in a container which is then filled with resin. In "potting" the container becomes part of the final assembly; in "casting" the container or mold is removed.⁽³⁷⁾
3. Transfer molding, where the compound is forced into the mold under pressure and high temperature;
4. Conformal coating, where the resin is applied by brushing, dipping, or spraying. It envelops the components and takes on their shape.

The same basic resinous materials are used for all these processes. Low-viscosity silicone or epoxy resins are popular for impregnation, but silicones and epoxies are also used for the other methods. The techniques of application, and the requirements for performance, vary somewhat with the specific material used. However, in general, the corrosion problems involved in the use of impregnation, potting, casting, and transfer molding are similar: these three processes are discussed in this section. Techniques and requirements for coatings are taken up separately, in Section 7.11.

7.10.3 MATERIALS. Encapsulants may be solid or foam, rigid or flexible, transparent or opaque, heavy or light, filled or plain, plastic, ceramic, or elastomer, and may cure at room temperature or require baking. They may be epoxy, polyurethane, silicone, polyester, polysulfide, silicone rubber, phenolic, polyamide, diallyl phthalate, acrylic, etc. Tabular comparison of encapsulants, with trade names, is given in reference 38. A recent survey of manufacturers of military electronic equipment showed that epoxy encapsulants rank first, then polyurethane, silicone, and silicone rubbers. Properties desired in an encapsulant are listed in Table XXXIV. Obviously, no one material combines all these characteristics, nor are all the properties equally important to the designer. Therefore, several different materials may be selected for the same assembly, used for different applications in different

locations, or at different stages of manufacture. Any encapsulant used must be adherent, continuous, and compatible with components and other materials in the assembly. All materials meeting the same specification are not identical, so it is important to check fabrication properties with the supplier before use.

Table XXXIV *
DESIRABLE PROPERTIES OF ENCAPSULANTS

Low	High
Viscosity	Pot life
Exotherm temperature	Ease of application
Shrinkage	Adhesion
Cure temperature	Thermal conductivity
Cure time	Surface resistivity
Moisture absorption	Fungus resistance
Dielectric constant	Mechanical strength
Dissipation Factor	Insulation resistance
Density	Thermal shock resistance
Change in properties with temperature	Repairability
Change in properties when wet	Moisture resistance

*Section 7.10.3

7.10.4 EFFECT OF TEMPERATURE. Since encapsulants are organics, they are affected by temperature, moisture and fungus. The encapsulation process often adds heat and thus creates its own problems. Table XXXV lists both difficulties and suggested solutions. For instance, alumina or beryllia filler will markedly raise the thermal conductivity of epoxy, thus avoiding heat concentration or hot spots. (39, 40) Heat decreases insulation resistance, decreases strength, changes dimensions, degrades performance of components, and, in some instances, volatilizes corrosive materials. Urethane foams are bad for outgassing and corrosion. (41) Moisture and high temperatures are the most common causes of degradation. (42) Although heat increases the rate of chemical reactions such as corrosion, it also tends to drive off moisture, so these two effects may counteract each other.

7.10.5 EFFECT OF MOISTURE. Absorption of water by the encapsulant lowers its insulation resistance, causes dimensional changes, and alters mechanical properties. A thin film of moisture on the surface provides a conducting path, causing surface leakage, lowering arc resistance, and increasing capacitance because of the high dielectric constant of water. Moisture also corrodes metal leads and conductor paths. Finally, moisture promotes fungus growth. Therefore, anything which encourages moisture (such as permeability to moisture vapor, absorption of moisture, cracks which provide entrance paths, "wicking," shrinking away from container or components, lack of adhesion to leads or container), can lead to deterioration, corrosion or failure of the equipment. Surface damage such as breakage of

the little glass spheres in syntactic foam, when transfer molding at high pressure, results in a hygroscopic condition.

Table XXXV*
POSSIBLE HIGH TEMPERATURE PROBLEMS
(ENCAPSULANTS)

Property	Problem	Suggestions**
High exotherm	Harm components; in extreme cases, harm encapsulant too. Possible bubbles, cracks, voids.	(a) Increase amount of filler (b) Redesign to use less resin and provide more surface for heat transfer (c) Change to resin with lower exotherm
Low thermal conductivity	"Hot spots" which harm components	(a) Increase amount of filler*** (b) Add metal heat sinks (c) Use high-conductivity filler (d) Change to resin with higher thermal conductivity (e) Cool equipment
Outgassing under high temperature conditions	Corrode metal leads; clog close tolerance openings with corrosion products	(a) Check reaction of encapsulant (see Table IV) (b) Change to different encapsulant

*Section 7.10.4

**In every case, review electrical requirements in selecting resins.

***Check effect on resistance.

7.10.5.1 Limitations. Encapsulation is commonly considered to be "moisture-proofing." It ranks next to hermetic sealing in protecting electronic components from moisture, but encapsulation is not perfect. Embedment in a suitable epoxy, polyurethane or silicone resin will usually provide adequate moisture proofing; but all encapsulants absorb some moisture. The rate of moisture pickup may be so low that it is not significant in ordinary designs, but when space permits only a thin layer of resin, or the geometry causes condensate to be trapped on the surface, the water absorption may become critical. For such applications, select a material with minimum water absorption. Table XXXVI summarizes effects of moisture.

7.10.6 EFFECTS OF MICROBES. "Fungal attack" includes attack by bacteria and other microorganisms as herein discussed. (Refer to Fungus, Section 3.) Table XXXVII shows fungus resistance of common encapsulants. The designer must remember: (1) the plasticizer can change the fungus resistance of encapsulant, or (2) dust and contaminants may promote fungus growth over normally fungicidal material.

7.10.7 EFFECT OF AGING. Time in storage affects some encapsulants; the degree depends on temperature, humidity, temperature changes, still or circulating air, etc. Some encapsulants develop high enough stresses to crush fragile components.⁽⁴³⁾ One way to avoid that is by using a flexible resilient conformal coating, then embedding in a rigid encapsulant.⁽⁴⁴⁾ (This system also protects against breakage of components during shrinkage.) Encapsulants may change in the container after opening and before use. Check both shelf life and date opened.

Table XXXVI*
POSSIBLE MOISTURE PROBLEMS (ENCAPSULANTS)

Property	Problem	Solutions**
High moisture absorption of resin	Loss of insulation resistance after exposure to moisture; promote fungus growth.	(a) Use encapsulant with lower moisture absorption. (b) If resin is thin, redesign to add thickness. (c) Coat with more moisture-resistant material.
Gathering moisture (condensate) on surface	Short circuit between leads or conductor paths.	(a) Change module design to permit condensate to drain. (b) Reduce moisture by desiccant. (c) Coat leads and conductors to prevent contact with moisture.
High shrinkage	Cracks in encapsulant permit moisture to enter; cracks also degrade strength of module.	(a) Change to resin with lower coefficient of thermal expansion. (b) Increase amount of filler in resin. (c) Check mold design and tooling. (d) Change to different resin. (e) Precoat with flexible resin.
"Wicking" in foamed or filled resins	Moisture enters, with consequent change in resistance and other electrical properties	(a) Seal with conformal or circuit board coating.

*Section 7.10.5

**In every case, review electrical requirements in selecting resin.

Table XXXVII*
INHERENT FUNGUS RESISTANCE OF ENCAPSULANTS AND POTTING COMPOUNDS

Resistant	Test to Determine	Nutrient
Diallyl phthalate	Epoxy	Epoxy-phenolic
Polyamide	Polymethylmethacrylate	Natural rubber
Polymonochlorotrifluoroethylene	Polyurethane	Phenolic
Polystyrene	Polyvinylchloride	
Polytetrafluoroethylene	Silicone rubber	
Silicone	Synthetic rubber	

*Section 7.10.6

7.10.8 EFFECT OF SURFACE PREPARATION. For good adhesion, adequate surface preparation of such materials as nylon, mylar and teflon is essential. Unless these are etched, adhesion will be minimal.⁽⁴⁵⁾ On any material, surface clearing is most important.

7.10.9 EFFECT OF DESIGN. The design of module or integrated circuit is often more important than the selection of encapsulant. Table XXXVIII lists some items to be considered. Design affects the exotherm, thermal conductivity, density and flow of encapsulant.

Table XXXVIII*
DESIGN NOTES FOR ENCAPSULATION

1. Consider encapsulation technique in the original design, especially the entrance and flow of resin, and how the air will escape.
2. Do not build in "moisture traps" where condensate can collect.
3. Provide adequate space between components and the side of the mold to permit free flow of encapsulant, to ensure complete coverage.
4. Design modules or components with specific encapsulant in mind, considering shrinkage, exotherm, rigidity, viscosity, etc.
5. Consider self-healing encapsulants where repair is likely.

*Section 7.10.9

7.11 CONFORMAL COATINGS

Encapsulating resins can be applied as liquids, then cured to form a tough impervious coating usually thick enough to give mechanical support to fragile components.

7.11.1 PURPOSE. Like encapsulants, conformal coatings provide a dielectric, form a barrier to humidity and surface soil, reinforce parts mechanically, and dampen vibrations. Like encapsulants, they are widely used. The advantages of conformal coatings are (1) lighter weight, (2) better heat transmission, and (3) more easily repairable.⁽⁴⁶⁾ They have the disadvantage of adding capacitance, which can be disastrous with high impedance circuitry.⁽⁴⁷⁾

7.11.2 PROCESSES. Coatings may be thinned and sprayed; dipped; brushed on; applied by fluidized bed method; or by skin packaging.⁽³⁶⁾ Fluidized bed coating involves heating the part to about 150°C (300°F) before insertion into a fluidized bed of resin powder, so cannot be used on any electronic items which would be damaged by that temperature. Skin packaging means pulling a thermoplastic resin sheet tight against an assembly, and heating the resin to seal the edges and thus encapsulate the part. However, most conformal coatings are applied as liquids by brush or dip methods. They may cure at room or moderately elevated temperatures such as 85°C.

7.11.3 MATERIALS. There are almost as many conformal coatings as there are encapsulants. In one recent study, 30 different formulations were tested, of which 28 were applied by dipping and 2 by spraying.⁽⁴⁶⁾ Among the 30 types were epoxies, silicones, polyurethanes, varnishes, lacquers, and proprietary items. Industry survey indicates a strong preference for the epoxy and polyurethane compositions, although no one particular material or type

stood out. Of the 41.5 percent of those commenting who prefer epoxy, 26 percent like the elevated temperature cure and 15.5 percent use room temperature cure. Polyurethanes are the choice of 37.7 percent; of these, 13 percent want two-part solvent-modified, 13 percent like two-part 100 percent solids, and 11.7 percent prefer one-part coating. While over three-fourths of the industry spokesmen selected epoxy or polyurethane (a total of 79.2 percent of those replying) others find silicone, silicone rubber, polyester, or other resins most suitable for their purpose. Requirements for coatings are listed in Table XXXIX. To meet the need for compatibility with other parts, special coatings are recommended for certain printed circuit laminates. Use care in selecting a coating for repair, after a portion has been removed for a rework of the item. It is best to replace with the same coating as the original one, especially if it was a silicone. There is no one coating material superior to all others, nor is any one suitable for all applications. The polyurethanes^(48, 49) and epoxies^(50, 51) have many champions, but for continuous service above 125°C, silicones are generally chosen.⁽⁵²⁾

7.11.4 THICKNESS. While the coating thickness is extremely important, the soundness, freedom from pinholes, and complete cure are equally essential to good performance. Several thin coats are much more effective than one heavy coat of the same total thickness. (If the resin does have a tendency to pinhole porosity, it is unlikely that pores will lie in exactly the same place on the different coats. And by oven-curing each coat after application, with a longer cure for the whole system after the final coat, the completion of cure is assured.) There is much argument over the exact thickness needed, but for most applications, it should be 0.005 in. to 0.025 in. It is easier to make repairs on thin coatings, around 0.005 in. thick; if very thin coats are used, say 0.0005 in. to 0.005 in., parts can be soldered right through the coating without chemical removal.

7.11.5 EFFECT OF ENVIRONMENTS. Conformal coatings are made from basically the same resins as encapsulants, and therefore, react to moisture, fungus, temperature, and other conditions in the same way that encapsulants do. See Sections 7.10.4, 7.10.5, and 7.10.6.

Table XXXIX*
REQUIREMENTS FOR CONFORMAL COATINGS

Essential	Desirable
Moisture Resistance	Ease of application
Resistance to Thermal Cycling	Low cure temperature
High Insulation Resistance	Repairability
Fungus Resistance	Short cure time
Adhesion	Transparency
Permanence	Low exotherm
Toughness	Long pot life
Compatibility with other parts	

*Section 7.11.3

7.12 STRIPPERS FOR ENCAPSULANTS AND CONFORMAL COATINGS

There are a number of commercially available coating strippers, often a combination of wetting agent, emulsifier, and dispersing solvent. Remembering the good chemical resistance of encapsulants and coating, one can understand why such "depotting agents" often soften plastic cases and remove identification marks from components. Tests on 28 strippers showed that some had no effect on the epoxy or polyurethane coating, but did attack the printed circuit board laminate. Six of the 28 discolored or corroded copper.⁽⁵²⁾ Great care must be taken in selecting and using chemical strippers. See Section 7.2.6.1.

7.12.1 "HOT" REMOVAL. To avoid the problems listed above, the coating may be softened and removed by heat from a soldering iron. However, temperatures of 150°-165°C must be reached before removal is easy.⁽⁵²⁾

7.13 ORGANIC COATINGS FOR METALS.

The usual paint systems for protecting exterior metal parts are so well known that they need no more discussion here. There are, however, some recent advances in coatings for specific purposes. Fluidized-bed coatings are used for electrical insulation as well as for corrosion protection.⁽⁵³⁾ Fluorocarbon films are applied for lubrication.⁽⁵⁴⁾ Combinations of polyamide and epoxy are recommended for tropical outdoor service.⁽⁵⁵⁾ For metals in tropic service, only baked coatings such as alkyds and epoxy had proved satisfactory in the past⁽⁵⁶⁾ but new resins are extending the life of air-dry organic coatings. Where there is a possibility of moisture entrapment, or of dissimilar metal contact, use an alkali-resistant paint such as epoxy, acrylic, and some of the vinyls. An epoxy-polyamide primer (MIL-P-52192) is recommended as an excellent alkali resistant primer for aluminum, steel and magnesium.

7.13.1 TARNISH PREVENTION. For permanent (several years) protection against tarnish indoors, silver, brass and pewter can be protected by a silicone coating only 0.1 mil thick.⁽⁵⁷⁾ Such coatings are so thin they do not significantly affect solderability or electrical resistivity.⁽⁵⁸⁾ They have proved effective against exterior exposure for 6 months to a year in microwave service.

7.13.2 RUST PREVENTION. Oils, greases or moisture-displacing compounds (see Section 7.7.5) keep iron and steel alloys from rusting, even in outdoor exposure. Some of the rust-preventive coatings do not interfere with welding; others provide lubrication as well as corrosion protection. They are easily removed by vapor degreasing or chlorinated hydrocarbon solvents.

7.14 OTHER ORGANIC COATINGS

There are many coatings used in electronic equipment for electrical insulation, sealing the surface, impregnating fibers and parts, lubrication, or decorative purposes, in addition to those discussed in this report. Varnishes, lacquers and enamels are usually of great help in combating corrosion, especially when based on inert resins such as epoxy, silicone, and polyurethane. However, before depending on any coatings for corrosion resistance, test it under conditions of humidity, fungus, and salt spray.

7.15 PRESSURE SENSITIVE TAPES

Tapes were mentioned under Seals, in Section 5.4.2.6, because they can be effective moisture barriers, as well as being electrical insulators and mechanical spacers. However, tape can support fungus, if made from cloth or paper; or absorb moisture by wicking action of mat or cloth; or be corrosive to metals, if an acidic adhesive is used.

7.15.1 MATERIALS. Of all the many materials used for tapes (plastic, paper, cotton, asbestos, glass, rubber) most are non-corrosive and help prevent deterioration of nearby parts. Fluorocarbon, polyester, polyimide, polyethylene, silicone, and silicone rubber films give no trouble. When pressed into a mat or woven into fabric, they may act as wicks, pulling in moisture. Paper and cotton, unless properly impregnated and processed, deteriorate in moisture, support fungus, and corrode metals. Check the material used for backing, the form, the adhesive, and the recommended cure before introducing a new tape into an assembly.

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SECTION 8 JOINING TECHNIQUES VS CORROSION

8.1 JOINING METHODS

Assembly of electronic parts makes use of every joining process common today. Table XL lists the many methods used to seal, bond, and fabricate electronic devices. The selection of the optimum method for each joint (for no one process is suitable for all applications) is most important. (1) The type of connection, and the care with which it is made, is especially critical in integrated circuits. Many failures have been caused by short circuits at interconnections, "purple plague" where gold leads are bonded to aluminum pads, or lack of hermetic seal over the silicon surface. (2) However, a large percentage of operating failures occur at connections outside the integrated circuit itself. (3) It is easy to see why, considering the number and variety of connections. In some microminiaturized devices, there are six levels of interconnections over and above the integrated circuit: (4)

1. Intra-module
2. Module to motherboard
3. Intra-motherboard
4. Motherboard to back panel
5. Back panel wiring
6. Input-output

These bonds may be made by organic adhesives, glass-to-metal seals, soldering, welding, or mechanically. Each type of joint can be a help or a hindrance insofar as deterioration is concerned.

Table XL*
JOINING METHODS

Bonding	Mechanical	Soldering	Welding
Adhesive	Crimping	Hand	Resistance
Thermocompression Bonding**	Solderless Wrap	Dip	Parallel Gap
Glass-to-Metal Bond	Screws	Wave	Ultrasonic
Hermetic Seal	Bolts	Roll	Percussive Arc
	Rivets	Resistance	Electron Beam
			Series
			Laser

*Section 8.1

**Often classed as welding

8.2 BONDING

Although generally chosen for strength, insulation, or thermal or electrical conductivity, adhesives have many attributes of organic coatings. They usually help in preventing corrosion, because they exclude moisture and eliminate dissimilar metal contacts. (5) Any corrosion problems probably arise from the use of acidic activators or poor surface preparation precluding good adhesion, or blind reliance upon the bond without proper process control, or possible dissimilar metal contact with metal-filled conductive adhesives (see Section 9).

Then too, adhesives may be incompatible with the lubricants or cleaning solvents used, as outlined in Reference 6. (See also Sections 5.4.2.5 and 5.4.2.6.) Glass-to-metal bonding producing a hermetic joint is also an important corrosion-prevention technique.

8.2.1 ACID ACTIVATORS. There are many forms of adhesives -- powder, tape, film, paste, liquid; acrylic, cellulose nitrate, epoxy, polyurethane, polyvinylchloride, rubber, silicone, silicone rubber, nitrile-phenolic, vinyl-acetal-phenolic, etc. Except for the polyvinylchloride, none of the resins causes corrosion. The activator, however, may be acidic; it is particularly liable to give trouble in one-part systems. (7) These corrosive vapors can be removed by elevated temperature cures, which increase the bond strength and are, therefore, doubly desirable. The strength of two conductive adhesives cured at room temperature for 7 days was increased 40 percent and 117 percent, respectively, by curing at 55°C (130°F) for 24 hours. (8) If adhesives are cured at room temperature, enough time must be allowed before assembly for complete dissipation of all fumes.

8.2.2 SURFACE PREPARATION. Cleaning prior to bonding is essential. Many plastics (such as fluorocarbons, polyester, polypropylene, polyformaldehyde, polyethylene, and silicone elastomers) require special surface preparation such as etching or priming, to achieve adhesion. The danger of an incomplete seal is not so much the loss of strength, as the fact that moisture can enter the assembly along the glue line.

8.2.3 GLASS-TO-METAL BONDING. Where reliability is important, many manufacturers consider hermetic sealing a necessity. Integrated chip circuitry must be protected from the harmful effects of humidity, even the amount present in normal room air. Passivation, conformal coating and encapsulation have all been used, but hermetic sealing is best. (9) It must be carefully done, to be effective. Out of 146 microminiature logic diodes made with glass-silicon hermetic seal, 4 failed the 10-day moisture test because of imperfections. (10) Semi-conductors may have a glass sealed case, a ceramic body with glass seal, or a ceramic body case with metallized seal. The last system is the most expensive but provides a better seal and higher reliability. (11)

8.2.4 BONDING CHECK LIST. When selecting an adhesive, check the electrical, thermal, and mechanical properties. Also give thought to corrosion prevention:

1. Select adhesives compatible with materials to be bonded.
2. Specify proper surface preparation.
3. Check type of activator and cure required.
4. Beware of dissimilar metal contact (when using metal-filled adhesives).

8.3 MECHANICAL JOINTS

In electronic devices, the mechanical assembly usually involves the chassis, cabinet, housing, supports, etc., and is really a structural application. Electronic devices also use crimped and wrapped leads which are so different from bolted joints that they are considered separately.

8.3.1 BOLTS, SCREWS, RIVETS. The most prevalent type of corrosion occurring at mechanical joints is galvanic corrosion from dissimilar metal contact. General guide-lines for avoidance of galvanic corrosion are listed in Table XIX, Section 6.3.4. Specifically, organic coatings such as polysulfide, epoxy, and zinc chromate primer have proven satisfactory. (12, 13) One caution: where the assembly includes coatings or thermoplastics, check carefully before using liquid locking compounds, as some cause stress-cracking. (14) Vendors of cyano-acrylate sealants warn against allowing the liquid materials to come in contact with varnish, lacquer, acrylics, methacrylates, etc., (see Section 5.3.8) because of this incompatibility.

8.3.2 CRIMPED AND WRAPPED LEADS. Two possible problems with these joints are cracks in the protective plating, and galvanic corrosion. It is difficult to make the sharp bends necessary to get electrical contact, without harming the plated surface. The operation of the circuit, with crimped connectors, depends on the cleanliness of the surfaces and the tightness of the joint. (15) For maximum reliability, the metals should be inherently resistant to corrosion and not dissimilar to each other. (15) It is especially bad when corrosion occurs in crimped joints, because there is little if any way to remove the corrosion products.

8.4 SOLDERING

The soldering process ranks high among the causes of failure and malfunction of electronic devices. This might be expected, because of its wide use by workers with all levels of skill, the variety of solders used and the many types of flux. Basically, deterioration due to soldering may arise from the metallurgy of the process itself, such as the dissolving of gold in solder, or from the flux, the cleaner, or the stripper used. Techniques for preventing corrosion are listed in Table XLI.

Table XLI*
PREVENTION OF DETERIORATION FROM SOLDERING

From Gold-Solder Compounds

Use another metal (not gold) on terminal pads
Abrade or dissolve gold layer before soldering
Use very pure (99.99+ percent) gold
Use thin coat
Use minimum soldering temperature
Use minimum soldering time

From Flux

Use lowest acid content flux practical
Remove flux residues after soldering

From Flux Removal

Select material compatible with components
Do not overclean
Use care in ultrasonic cleaning
Use fresh solvent and rinse material

From Aging

Store in sealed polyethylene bags
Cover joints with moisture-proofing organic coat

*Section 8.4

8.4.1 BRITTLE GOLD-SOLDER COMPOUND. Gold is used extensively to promote solderability, but it dissolves in tin/lead solder to form a brittle intermetallic compound which looks and acts like a cold solder joint. Thicker gold, higher alloy or impurity content, longer soldering times and higher soldering temperatures all promote the pickup of gold by solder. (16) Three ways to eliminate or minimize this problem are (1) to use 99.99+ percent pure gold, which does not dissolve as readily as impure gold; (2) to remove most of the gold by abrasion or solution in molten solder, then wipe off the contaminated layer before soldering, (17); and (3) to use a different metal, not gold, on the terminal pads of circuit boards, plating the pads separately. (18)

8.4.2 CORROSION FROM FLUX. Military specifications usually insist that "no acid or acid salts shall be used in preparation for or during soldering." (19) They permit only "non-corrosive and non-conducting fluxes." (20) But even "neutral" fluxes must have some acidity in order to remove metal oxides and provide a reducing atmosphere to prevent oxide formation, and "non-activated" fluxes can corrode metals. A tinned copper bus bar wire was attacked after 14 days immersion in non-activated rosin flux; activated fluxes produced blue-green corrosion products in as little as two hours. (21) No one intends to leave flux on a conductor for hours or weeks, but it often is trapped under sleeving (21, 22) during normal production operations on circuit boards and stays there.

8.4.2.1 Preventing Corrosion from Flux. Soldering fluxes with low acid numbers are less corrosive than those with higher acid. (21) Use the lowest acid content flux which gives good results, and remove flux residues after soldering. For printed circuit boards, a new flux developed for NASA (perfluorooctavoic hydrazide) is a water-soluble acid which leaves a corrosion resistant coating. After soldering, a water wash removes the acid and leaves hydrazine which aids in corrosion prevention. (23) This flux cannot be used on aluminum. No matter what the flux, remove all residues by thorough cleaning. Flux residues may be conductive as well as corrosive, and are often "tacky", collecting dust which increases the resistance of the joint. (20)

8.4.3 CORROSION FROM FLUX REMOVAL. Deterioration can result from incomplete removal of residues after soldering (sec 8.4.2), from contaminated cleaners, from too much cleaning, or from reaction between the cleaner and components. Contaminated cleaners obviously cannot do the job; fresh solvent and fresh rinse are required to prevent drag of contaminants. Many companies rely upon abrasive scrubbing, or stiff brushing with perchloroethylene, or ultrasonic cleaning. Scrubbing or brushing techniques have two disadvantages: (1) they may roughen board surfaces or harm delicate components, and (2) they are completely dependent on the skill of the individual worker. Ultrasonic cleaning can damage diodes. Many common solvents attack plastics, darken solder, stain gold, remove marking from components, or accelerate corrosion by flux residues. (22) Clean with care.

8.4.3.1 Preventing Corrosion from Flux Removal. Any material used to remove flux residues must, in addition to dissolving the residues completely, be harmless to other materials and components, and be easily removed itself. Regardless of method or material used, do not overclean. Over-zealous cleaning may do more harm than the presence of a small amount of flux residue, especially if the whole assembly is later covered with a moisture-proofing coating. One company (22) recommends the following procedures:

1. Where ultrasonic cleaning and total immersion is permissible, use it, followed by alcohol (IPA) and Freon rinses.
2. For printed circuit board assemblies where total immersion is permissible, use automated chemical cleaning
 - a. 3 to 5 minutes in solvent, 206K
 - b. 2 to 4 minutes in rinse, alcohol (IPA)
 - c. 2 to 4 minutes in solvent, 206K, fresh
 - d. 2 to 4 minutes in rinse, alcohol (IPA) fresh
 - e. 2 to 4 minutes in rinse, Freon
3. If immersion is not permissible, apply solvent with stiff bristle brush, followed by alcohol (IPA) and Freon rinses.

8.4.4 DETERIORATION FROM AGING. There is no question that solderability of contacts deteriorates with time, but there is much disagreement over what coating or metal provides best solderability after storage, and even over what short-duration test best simulates the effect of time. (24) Some tests indicate that thick tin plate withstands aging best; (25) in

other applications, heavy deposits of gold seem better. Since solderability does decrease with time, parts should be marked with the date of plating and stored in sealed polyethylene bags to minimize contamination. Even then, many metals (i.e., silver) will need a brightening or cleaning dip before soldering.

8.4.5 COATING SOLDER JOINTS. Specifications requiring overcoating solder joints with moisture or fungus-proofing varnish are often questioned in industry. Experience in the tropics shows that this moisture-proofing is definitely needed; without it, solder joints were severely corroded. (26)

8.5 WELDING

Welding, like soldering, requires careful selection of materials and close process control. But resistance and electron beam welding, the technique most in use for electronic devices, need no flux or filler, (27) and therefore avoid some of the deterioration problems inherent in soldering. Furthermore, welding the can forms a hermetic seal for future protection. (28) The plating on leads must be considered for both weldability and corrosion prevention. While less plating would suffice for welding, it was necessary to use 50 microinches nickel, 400 microinches silver and 50 microinches of gold in order to withstand 48 hours of salt spray. (29) A review of about 600 publications on interconnections, with special emphasis on welding, is given in Reference 30. A comparison of EB (electron beam) and laser welding processes in 1966, together with a list of metal combinations which may be ultrasonically welded, is given in Reference 33.

8.6 PURPLE PLAGUE

"Purple plague," the gold-aluminum compound formed in the presence of silicon, is very brittle and often cracks, causing open circuits. Purple plague is a special problem in silicon transistors and integrated circuits, where it is sometimes necessary to remove the gold plate from the post to keep purple plague from forming. (31) Use silver or copper pads instead of gold, or deposit aluminum on the gold. (11)

8.7 OTHER JOINING METHODS

Thermocompression and ultrasonic bonding are finding more use today in microelectronics. Reference 32 reviews thermocompression bonding, soldering, conductive adhesives and resistance welding of modules.

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SECTION 9 ELECTRICAL BONDING AND SHIELDING

9.1 NEED FOR BONDING AND SHIELDING

Electronic systems are constantly becoming more sensitive, so more attention must be paid to rendering them less susceptible to externally generated electromagnetic interference (EMI), and preventing the emanation of electromagnetic energy. To achieve these aims, the designer must provide the proper grounding, and electromagnetic shielding. Many designers, concerned only with circuitry, do not realize that commonly used bonding and shielding techniques introduce a hazard - corrosion - which can ruin performance. This is due both to the requirements of "bare metal" for bonding, and to the frequent joints of dissimilar metals.

9.1.1 BONDING AND CORROSION. In electrical bonding, it is necessary to provide an electrical path to ground, or to obtain a continuous electrically conductive path, as for electromagnetic shielding. Since most paints, sealants, and organic finishes are electrically insulating, they cannot be used for corrosion prevention in areas of bonding. Although bare metal-to-metal bonds may be satisfactory immediately after manufacture, they deteriorate in moist or corrosive environments, resulting in corrosive attack and degraded performance. A unit may be acceptable today, but later on, when performance is required, it may not function.

9.1.2 DISSIMILAR METALS. When leads are soldered or joined to a dissimilar metal, there is an immediate possibility of galvanic corrosion. The joint should be completely coated by epoxy or other organic thermosetting moisture barrier to prevent moisture from reaching the dissimilar metal joint. (1)

9.2 BONDING METHODS

9.2.1 SURFACE FINISH. The first requirement for a good bond is that the metal surfaces be clean and free from contamination, oxide, or insulants. Unfortunately, few metal surfaces will remain this clean for very long. Immediately prior to bonding, all oxide and other contaminants must be removed by chemical treatment or abrasion. (1) Recommended finishes are listed in Table XLII.

9.2.1.1 Aluminum. There is a great deal of difference in the electrical resistance of various chemical film treatments; also, the resistance (although low when first applied) can increase markedly with time. One engineer found that MIL-C-5541 from two different sources had similar initial resistance, on bare 2024 aluminum; but after 1000 hours humidity test, source 1 had 100 milliohms resistance, while source 2 showed only 4.5. (2) Moreover, the chemical film treatment is very soft and cannot withstand abrasion. (3, 4) See Section 6.6.3.1. Tin plate and nickel-cadmium plate have been recommended for aluminum. (3)

9.2.1.2 Bare Metals. Bare metal to be bonded must be well cleaned. After bonding, the area around the bond should be coated with epoxy or polyurethane or other organic sealant to exclude moisture. When bare copper was bonded to itself, resistance went from 0.05 milliohm initially to 8.1 milliohms after 1000 hours in a humidity chamber (2), so even metals which show low initial resistance need protection against future environments.

Table XLII***
FINISHES FOR ELECTRICAL BONDING

Metal*	Finish
Aluminum	If clad, bare Chemical Film Treatment, MIL-C-5541 Cadmium Plate, QQ-P-416 **Tin Plate, MIL-T-10727 Nickel-Cadmium Plate, AMS 2416 If rest of surface is anodized: 1. mask bond areas before anodize, or 2. spot-face bond areas after anodize
Brass, Copper	Bare Cadmium Plate, QQ-P-416 **Tin Plate, MIL-T-10727 Gold Plate, MIL-G-45204
Cadmium	Bare
Iron and Steel	Cadmium Plate, QQ-P-416 **Tin coat, MIL-T-10727
Magnesium	Bare; clean immediately before bonding and coat area immediately afterward
Nickel, Stainless Steel	Bare; difficult to bond because of adherent oxide
Silver	Bare
Solder	Bare
Tin	Bare

*Use care to prevent galvanic corrosion

**Preferred

***Section 9.2.1

9.2.2 CONDUCTIVE ADHESIVES. Bonds are frequently made by use of conductive adhesives which usually contain silver as the conducting metal. Since silver is quite dissimilar to aluminum, steel, cadmium, etc., care must be taken to prevent galvanic corrosion. Conductive adhesives and caulking materials are discussed at more length in 9.6.3.

9.2.3 BOND LATER. If an electrical bond is to be made in the field or at some later date, the bond area may be protected by a strippable plastic coating (MIL-C-16555) or tape, until the bond is made. Or "brush" selective plating may be employed, using portable equipment.

9.2.4 PREFERRED TECHNIQUES. From the viewpoint of corrosion, the best way to get an electrical ground is by bus strap. If bus strap is not practical, a shear-splice joint, adequately insulated on the exterior, is recommended.⁽⁴⁾ If neither of these methods can be used, take precautions to prevent deterioration and galvanic corrosion (Section 6.3.4). The bond area must always be clean and free from contaminants before bonding, and it should be sealed against corrosion after bonding.

9.3 BONDING CHECKLIST

1. Do not use steel star washer on aluminum unless cadmium or tin plated; the steel penetrates the aluminum and concentrates the entire corrosive attack on the small aluminum pits. (4)
2. Remember that corrosion products add electrical resistance and degrade reliability to an unacceptable level.
3. Have metal surface clean before bonding, free from oil, dirt or contaminants.
4. Use bus strap or shear splice joint wherever possible.
5. Protect against galvanic corrosion at dissimilar metal joints. (6.3.4)
6. Take special care when bonding magnesium, whatever method is used. (6.3.4.2)
7. When using strippable coating, test first for compatibility.

9.4 WHY USE ELECTROMAGNETIC SHIELDING

Today, the electromagnetic energy which is all around us can seriously interfere with the proper operation of electronic equipment. The source of interference may not be hostile; it may come from commercial transmitters such as television and radio stations, or communications media; or it may originate in civilian equipment such as garage doors, portable hand tools, office machines, or microwave ovens; or it may result from military facilities such as radar, missile launch sites, or test equipment. It is necessary to shield electronic devices so that they will neither emanate, nor be susceptible to, unwanted electromagnetic energy.

9.4.1 TODAY'S PROBLEMS. The need for shielding is much more important today than even ten years ago, because of (1) the high density of electrical and electronic equipment in the systems; (2) the number and kinds of systems operating simultaneously; (3) the high sensitivity of individual pieces of equipment; (4) the increased complexity of modern electronic equipment and systems; and (5) higher power levels. Shielding and filtering, once considered the last resorts of the designer, often prove the most practical and reliable ways to assure freedom from undesired response or malfunction caused by RFI. (5) Shielding is, therefore, required today in magnetic, radio and microwave frequencies, from a few Hertz to 10 GHz. (6) See Table XLIII. There is every reason to believe it will be needed even more in the future.

9.5 TYPES OF SHIELDING

9.5.1 ELECTROSTATIC. To prevent damage from static electricity, electronic components are often wrapped in conductive films or painted with conductive coatings. (A stationary electrostatic field can be shielded by a conductive barrier (7), magnetic or non-magnetic). Graphite is frequently used as the conductor; and so far as corrosion is concerned, graphite acts like a metal close to silver in the galvanic series. Whether the carrier is polyethylene, rubber, or other resin, the graphite can still form a galvanic couple with aluminum or magnesium, and must be treated as a dissimilar metal contact.

9.5.2 MAGNETIC. Electronic parts such as klystrons, magnetrons, relays, magnetic tapes and pickups, are especially subject to damage from magnetic field interference. A stationary magnetic field can be shielded only by a magnetic metal. This may be foil or tape for fair attenuation of high flux densities, or an 8.0 percent nickel-steel for maximum attenuation at lower flux densities, or a laminated shield. Laminates may be iron-nickel steel with the iron layer on the outside to reduce the field to a level at which the nickel-steel is a more efficient shield (8), or they may be laminates of copper and nickel-steel foil. Or a

Table XLIII**
SHIELDING TECHNIQUES

Material	Electrostatic*	Magnetic	Electrical	Plane
Metal Shield				
Iron	X	X		
Nickel Steel	X	X	X	
Laminates	X	X	X	
Coatings				
Graphite	X			
Silver	X	X	X	X
Silver-Plastics, Adhesives, Gaskets	X		X	X
Conductive Rubber, Silver	X		X	X
Conductive Rubber, Graphite	X			
Conductive Glass	X		X	
Wire Mesh	X		X	X

*If Grounded

**Section 9.4.1

nickel-iron coating may be sprayed on irregular shaped parts, providing shielding from 60 Hz to 10 KHz. (9) Other metal foils and tapes are also available. The magnetic shields also provide electrostatic shielding, and are very effective where a wide frequency band interference has both magnetic and electrical field components.

9.5.2.1 Iron and Steel Shields. Designers must remember that iron and steel need protection from oxidation and corrosion, even when used as magnetic shields. Tin, either electroplated or hot dipped, is a good way to prevent corrosion. (8) Organic coatings are electrically insulating, and should not be used.

9.5.3 RADIO FREQUENCY AND PLANE WAVE SHIELDING. Much equipment operates in a wide frequency band of electromagnetic interference, and many of the metallic materials used to wrap and shield electronic components are useful throughout the entire range from 25 Hz to 10 GHz. Some typical attenuations of various materials are given in Table XLVI. Note that bare threads are not the best. The shielding efficiency achieved depends upon the design, the frequency, the power level, and many other factors; the shielding material is not the main factor. Attenuations as high as 135 db have been achieved by proper design and use of proper gasket material. There are so many kinds, sizes, and shapes of RF gaskets available that the designer can get exactly the right one for each specific application, if he will only investigate the possibilities as part of the initial design.

9.6 SHIELDING METHODS

9.6.1 METAL-TO-METAL CONTACT. Sometimes electromagnetic compatibility is assured through initial design, filters, and the use of shielded components. Metal-to-metal contact is theoretically an ideal way to provide shielding, but practically, there are some

disadvantages; for instance (1) the high cost of machining to the close tolerances necessary for adequate contact; (2) the RF leakage around mechanical joints such as screws and bolts, see Table XLIV; (3) the problem of protecting the mating surfaces from corrosion; (4) the fact that housings must have some means of access, so cannot form the completely continuous envelope desired.

9.6.1.1 Spring Contacts. Spring contact fingers, usually phosphor bronze or beryllium copper, are often used on closures to assure conductivity. In many instances wire mesh gaskets are needed to assure electrical continuity. The metals are selected primarily for their electrical properties and are nearly always dissimilar to the aluminum or magnesium chassis, or the steel structure.

Table XLIV*
EXAMPLES OF ATTENUATION

Attenuation db					
Field	Metal Foil	Conductive Plastic		Glass	Bare Threads (Screw Assemblies)
		(A)	(B)		
Magnetic - 60 Hz	25				
Magnetic - 10 KHz	50		75		23
Magnetic - 200 KHz	70	70		60	
Electric - 200 KHz	100	100	90	110	75
Electric - 1 MHz	100	100	100	100	80
Electric - 10 MHz	100	100	90	90	75
Plane - 400 MHz	100	100		60	
Plane - 10 GHz	100	100		30	

NOTE: Value depends upon design, thickness, etc.

*Section 9.5.3, 9.6.1

9.6.2 CONDUCTIVE GASKETS

9.6.2.1 Selection. The choice of conductive gasket depends on the field (low or high impedance, frequency, strength) as well as on the part to be shielded, space available, and environments anticipated. Designers should check the manufacturers of EMI gaskets for suggestions, prior to freezing design, to be sure to get maximum shielding at minimum cost. Designers should also keep in mind that corrosion products are usually poor conductors with a very adverse effect on reliability. Attention to corrosion prevention in the design stage is insurance of good performance later on.

9.6.2.1.1 Types. Modern EMI gaskets fall into five major groups:

1. Metal, usually wire mesh;
2. Metal attached to, or wrapped around, an elastomer;
3. Metal wire or mesh embedded in an elastomer;
4. Metal balls, powder (occasionally, flakes) integrally mixed into a resin or elastomer;
5. Graphite carried in an elastomer. This is much poorer and can be used only in special situations.

Assuming that adequate EMI shielding can be attained by any type of gasket listed in Table XLV, and that the structure is aluminum or magnesium, then from the corrosion point of view, preference should be given to those forms which provide both environmental and EMI shielding,

Table XLV*
COMMONLY USED** EMI GASKET MATERIALS

	Monel Wire	Silver Balls or Powder	Silver Plated Brass	Tin Plated Steel or BeCu	Aluminum Wire	18-8 Stainless
Wire Mesh	X		X	X	X	X
Mesh Bonded to:						
Neoprene	X		X	X	X	
Silicone Rubber	X		X	X	X	
Molded in:						
Neoprene	X				X	
Silicone Rubber	X	X		X	X	X
Butyl or BunaN	X					

*Section 9.6.2.1.1

**Many other metals, plastics, and elastomers are available.

and which do not form a dissimilar metal couple. The following would be equally good for corrosion resistance: (1) mesh molded into elastomer so that no metal is open to the environment; (2) molded gaskets containing silver metal, with resin coating the outside; (3) mesh bonded to an elastomer, with the elastomer on the exterior to prevent moisture from reaching the metal mesh. The type and design of gasket, and mating surfaces, especially whether the area is exposed to, or protected from, environments such as moisture, are more important to corrosion than the choice of metal. Designers should provide a groove or channel, but be careful that it is not a water trap.

9.6.2.1.2 Aluminum. Although theoretically the most compatible with aluminum or magnesium structures, aluminum is not always the best choice. Its poor strength and low wear resistance, coupled with its insulating oxide film, lead many EMI specialists to reject it as a gasket material. (10)

9.6.2.1.3 Silver. Whether solid metal or plated over brass, silver is subject to surface oxidation. It is non-compatible with cadmium, zinc and tin, as well as with aluminum and steel. However, some gaskets contain silver balls supported in resin; the assembly pressure breaks through the insulating resin on the contacting spheres and produces high metal-to-metal contact, but does not remove the insulating resin around the silver spheres at the sides of the gasket. Salt spray tests of chemical-film-treated aluminum, joined by these conductive gaskets, showed no corrosion problems. (11)

9.6.2.1.4 Monel. Monel is used for about 75 percent of the EMI gaskets today, because of its combination of corrosion resistance, shielding effectiveness, and mechanical properties. Like silver, it is incompatible with aluminum, steel, etc. Like silver, when encapsulated in silicone rubber or other plastic, it does not cause corrosion.

9.6.2.1.5 Tin. Tin is more compatible with aluminum and magnesium than would appear from the EMF table. Tin plated copper or steel wire is good in corrosion resistance and electrically, and is becoming much more popular as a shielding material, especially for lower frequencies.

9.6.2.1.6 Resin. The carrier resin can be corrosive. Polyvinylchloride is sometimes needed for fuel resistant gaskets, but it may liberate hydrochloric acid. Silicone rubber, butyl, buna N, or neoprene, inert carriers, are preferred.

9.6.2.1.7 Choice of Forms. Gaskets which are formed, extruded, molded, etc., and which therefore have an insulating coating over the conducting metal, offer less problems in corrosion. Mesh is rather hygroscopic; moreover, the wires are very fine and provide an extremely large surface area for oxidation. Sponge often absorbs moisture, thus contributing to corrosion.

9.6.2.2 Gasket Checklist. To prevent corrosion when providing for EMC, observe the following rules:

1. Provide for EMC in the original design; this is more efficient and cheaper than trying to add it later. (12)
2. Use materials which are compatible; i.e., cadmium or tin plate on steel, copper, or aluminum.
3. If bonding dissimilar metals is unavoidable, then coat the joint area after bonding with organic sealant such as epoxy or polyurethane.
4. Similarly, seal the dissimilar metal joint when using a gasket with monel or silver, on aluminum.
5. A combination RF-environment seal prevents corrosion because moisture is kept out. This type of seal is available in many materials and shapes; including oriented wire in silicone rubber, wire mesh in elastomer, silver powder or balls in rubber, etc., but be careful when using sponge rubber.
6. When using wire mesh, provide a suitable channel or an additional environmental seal to exclude moisture.

It is true that corrosion can and does result from the use of dissimilar metals unless: (1) one metal is entirely encased in resin so that no dissimilar metal contact is possible; or (2) the junction of dissimilar metals is completely sealed by an insulating coating, so that no moisture can reach the two metals. By using the proper groove dimensions, gasket and design, one can achieve shielding without danger of corrosion.

9.6.3 CAULKING COMPOUNDS AND ADHESIVES

9.6.3.1 Applications. Conductive caulking compounds are often used to fill in gaps around threads, to seal RF shielded compartments, to provide electrical continuity at joints. The conductive adhesives may be used for these purposes, and also for bonding ferrities, making lead terminations, and many other bonds where solder is not desirable.

9.6.3.2 Types. Conductive cements are, basically, high viscosity, metal-filled adhesives achieving low resistivity and high strength with a room temperature or relatively low temperature cure. (13) They may be thermosetting adhesives, putty or nonhardening resin. (14) While they might be rendered conductive by use of graphite, aluminum, copper, or gold, the metal most used is silver. It has high electrical and thermal conductivity, is not too expensive, and even silver sulfides and chlorides are good conductors. (15)

9.6.3.2.1 Variety. Conductive cements are available in many different compositions, from polysulfides with maximum volume resistivity of 500 ohm-cms to silver-epoxy adhesives, with resistivity under 1×10^{-3} ohm-cms. No matter what the service requirements, there is some commercially available conductive cement which will meet it. Many are on the market today: one- or two-part; epoxy or silicone resin; room-temperature or 200°C cure; expensive or fairly cheap; paste or cream. Factors which the designer should consider are listed in Table XLVI.

Table XLVI*
PROPERTIES OF INTEREST
IN CONDUCTIVE ADHESIVES

Essential	Important
Electrical Conductivity	Pot Life
Cure Temperature	Ease of Mixing
Cure Time	Base of Application
Bond Strength	Cost
Maximum Service Temperature	
Water Absorption	

*Section 9.6.3.2.1

9.6.3.3 Advantages. Conductive sealants, caulking compounds and adhesives have several advantages:

1. Easy to apply.
2. Cure at room temperature or a relatively low temperature (much cooler than soldering).
3. Relatively inexpensive.
4. Wide choice of types.

9.6.3.4 Corrosion Problems of Conductive Cements. Because they are so easy to use, designers tend to forget that conductive adhesives may bring corrosion problems, such as galvanic corrosion, attack from acids, and short circuits due to silver migration.

9.6.3.4.1 Galvanic Corrosion. The action of dissimilar metals in contact, and consequent galvanic corrosion, is the same with the use of conductive cement as with gaskets. In order to have conductivity, metal-to-metal contact is necessary; and the most-used metal, silver, is quite dissimilar to steel, aluminum and magnesium. (See Section 6.3.)

9.6.3.4.2 Acid Activators. Some adhesives employ activators or curing agents which liberate acidic fumes, attacking both metals and non-metals.

9.6.3.4.3 Silver Migration. The phenomenon of silver migration (see Section 6.4.2) can occur if there is high humidity and a voltage differential, either AC or DC⁽¹⁶⁾ regardless of whether the silver is massive, plated, or carried in a resin. Tests of 65 hours at 95 percent RH at 95°F, with 400V DC, resulted in silver adhesives migrating on 80 percent of the ceramic and glass substrates, but on only one glass-epoxy substrate.⁽¹⁵⁾ Silver migration causes short circuits.

9.6.3.5 Conductive Cement Checklist. To minimize corrosion problems while getting the maximum bonding or shielding efficiency, be careful to:

1. Have surfaces clean and free from contaminants before applying cement.
2. Check pot life to be sure adhesive is in best condition.
3. Mix thoroughly - this cannot be over-emphasized.
4. Allow cement to dry tack-free before curing at elevated temperature, unless otherwise instructed by manufacturer.
5. Cure thoroughly before storing or packaging in next assembly.
6. Maintain absolute cleanliness - do not handle silver-epoxy adhesive joints.
7. Overcoat dissimilar metal contacts with insulating organic coating.
8. Keep lids and caps on resin and hardener even if next use is expected within 10 minutes and even if the system has 100 percent solids.

9.6.4 CONDUCTIVE COATINGS. For both magnetic and electrical shielding of such items as encapsulated modules, a conductive envelope is required — perhaps a metal potting cup, sprayed metal, foil wrap, or a conductive coating applied to the exterior surface. Conductive coatings, like adhesives, may contain copper, gold, etc., but are usually silver. They may be applied by dipping, spraying or brushing. The same precautions should be observed; careful surface preparation prior to coating, drying between coats, and complete curing before further assembly. One additional recommendation: to obtain continuity around a foamed module, put on one coat of epoxy or polyurethane to seal the pores of the foam before applying the conductive coating.

9.7 DESIGN RECOMMENDATIONS

The designer of electronic equipment is urged to consult "Interference Reduction Guide for Design Engineers"⁽¹⁷⁾ copyrighted by Filtron Company, Inc., New York, but also available from the Department of Defense. This report discusses in detail the techniques for the reduction of electromagnetic interference.

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SECTION 10 SPECIFIC PARTS

10.1 STRUCTURAL

The structural elements of electronic equipment include the housings, covers, supports brackets, cabinets, chassis, and the like — parts which are necessary for their mechanical properties but are not intended to carry or resist electrical current. Rust or slight corrosion may not affect the structural integrity of the equipment. But the corrosion products may drop onto a nearby surface where they can cause a short, attack the surface, or clog up an intricate mechanism. Deterioration of structural parts (except seals) is not so immediately harmful as in electronic components, but it is dangerous and should be prevented.

10.1.1 GENERAL CAUTION. Spacers, knobs, and the like are often plastic; see Sections 7.4 and 7.5. In the use of metal parts, keep in mind the following cautions:

1. Avoid low areas where moisture can collect;
2. Protect with at least three coats of paint;
3. Do not use wrinkle or rough finishes (they hold dust, moisture and contaminants);
4. Do not deform on installation, or otherwise contribute to stress corrosion (see 6.2.4.3);
5. Do not plate high-strength steels (see 6.2.5.1);
6. Do not try to paint or plate porous castings (see 6.2.6);
7. Avoid dissimilar metal contact (see 6.3.4);
8. Insulate at joints (see 5.4.2, 6.3.4, 8.3.1);
9. Provide groove or channel for gaskets.

10.1.2 HOUSINGS, BRACKETS, CABINETS, COVERS. Such items are usually metal, either cast or welded. Special attention should be paid to the design, to preclude any collection of moisture, inaccessible crevices, or narrow spaces which cannot be adequately protected. Parts need coatings which withstand abrasion and handling abuse, as well as provide corrosion resistance. Steel or aluminum also need protection from dissimilar metals; see Section 6.3. Magnesium is hard to protect adequately. If it must be used because of its light weight, use every care to provide impervious multicoat organic protection; see Section 6.10.6.

10.1.3 CHASSIS. The chassis is generally aluminum, occasionally magnesium. For enclosed protected equipment not subject to scratches or abrasion, the MIL-C-5541 chemical film treatment is adequate for aluminum; magnesium always needs full protection.

10.1.4 HARDWARE. Nuts, bolts, and similar attaching hardware should be of stainless (corrosion-resistant) steel, passivated; brass or bronze, nickel or tin plated; or steel, cadmium plated and chromate treated (except when organics are present in the assembly).

10.1.5 KNOBS, CONTROLS, AND SPACERS. The thermosetting plastics with mineral fillers are used for many small pieces of hardware. When specifying plastic parts, check the moisture absorption and the tendency towards stress cracking (see 7.2.6) in common solvents.

10.2 ELECTROMECHANICAL

Such items as switches, relays, potentiometers, motors, generators and synchros, are considered electromechanical rather than purely electronic, because motion is an integral

part of their operation. Any dust, condensate, or corrosion can put the performance of these parts out of tolerance. The design of this type of device is of the utmost importance, and must incorporate seals such as O-rings, chevron-type, etc., to minimize entrance of moisture and other contaminants. It is impossible to encapsulate completely or to hermetically seal the entire part, because movement is necessary, but these techniques should be used as much as possible. Moreover, all parts should be corrosion-resistant or adequately protected, and compatible with the other materials used. There is always a possibility of corrosives entering in time. This situation cannot be met by desiccating the final assembly for two reasons: (1) no one knows how long a time may elapse between initial manufacture and final use, (2) extremely dry atmospheres lead to "dusting." Care in design, in fabrication, and in handling prior to assembly, is essential. Such precautions as the use of toggle boots and flexible seals are well worth while.

10.3 ELECTRONIC

The biggest enemy of acceptable performance of electronic devices is moisture. Two years ago, it was recognized that there is a "pressing need to ensure that military electronic equipment is capable of functioning properly in humid environments."⁽¹⁾ Moisture is even more of a problem today with the greater use of microminiaturized parts - the close proximity of various components enables moisture to bridge conductors, cause leakage or shorts, and create havoc. Temperature, corrosive fumes and chemicals, microbes and animals, are other enemies of high reliability electronics.

10.3.1 CAPACITORS. Moisture has a very bad effect on fixed capacitors. The dielectric loses insulation resistance and dielectric strength, the metal cases corrode, and fungus-nutrient materials like paper are attacked by mold, in conditions of high humidity.⁽²⁾ Some prefer ceramic capacitors for tropical service⁽³⁾ but they, too, pick up moisture. In tests in the Panama jungle, ceramic capacitors showed the greatest degradation during the rainy season.⁽⁴⁾ While direct correlation between amount of fungal attack and electrical degradation has not been established,⁽⁵⁾ it is still undesirable to have any component affected by microbes. Fixed capacitors should be of moisture-resistant plastic or glass or mica, with corrosion-resistant coating on the case (epoxy-dipped mylar, or polystyrene case and dielectric, for example). Tuning capacitors should be hermetically sealed.⁽³⁾

10.3.2 COILS. Ferromagnetic inductance coils show better resistance to humidity when encapsulated;⁽⁶⁾ most specifications for military usage require resistance to high temperature, temperature cycling and moisture, so encapsulation is necessary. However, potting can result in a rigid assembly which limits the magnetostrictive action of the core, so the encapsulant must be carefully selected. The thermosetting resins are most used.⁽³⁾

10.3.3 CONNECTORS. Of the four most frequent causes of failure of printed circuit connectors, two are chemical: moisture condensation and contact corrosion.⁽⁷⁾ New designs have complete environmental sealing, using silicone rubber as the dielectric, when connectors are mated. They should be protected by plastic covers until assembled.⁽⁸⁾

10.3.4 CONTACTS. The major cause of degradation of contacts is air pollution⁽⁹⁾ because the oxides, sulfides, and other products formed, have poorer conductivity than the pure metal. Sliding contacts have an advantage in that friction removes corrosion products after a few wipes. However, military electronic devices may be stored for years, then required to operate without any warming-up or preliminary operation. To assure good contact the first time, work is under way on monolayer boundary lubricants such as octadecylamine hydrochloride^(10, 11) but as yet, none has been generally used. Therefore, corrosion-resistant metals such as gold or rhodium are employed where maximum reliability is required. Even these metals are not entirely free from degradation; problems encountered in gold plating are discussed in Section 6.7.4.4.

10.3.5 DIODES AND INTEGRATED CIRCUITS. See Solid State Devices, Section 10.3.9.

10.3.6 MODULES, POTTED OR ENCAPSULATED. Problems arising from the encapsulating process are discussed in Section 7.10. A special problem area lies in the RF shielding of encapsulated modules, often accomplished by spraying with copper, wrapping in metal foil, or coating with conductive resin; see Section 9. A good review of module design and materials is given in Reference 12.

10.3.7 PRINTED CIRCUITS. Among the major causes of printed circuit failures are the contamination or damage of the plastic laminate, and corrosion of the conductors.⁽¹³⁾ These difficulties are often caused by solder flux, or overcleaning to remove flux residues. The importance of sealing cut edges of printed circuit laminates, and coating the assembly with moisture proofing organics such as polyurethane or epoxy has already been discussed in Section 7. Uncoated boards suspended in a test cabinet in a shore area in the Canal Zone, all corroded beyond any use.⁽⁴⁾ One possible danger should be mentioned: the possibility of damage to delicate components by contraction of the conformal coating. In one series of tests, thermal cycling caused breakage of diodes, as shown in Figure 5⁽¹⁴⁾.

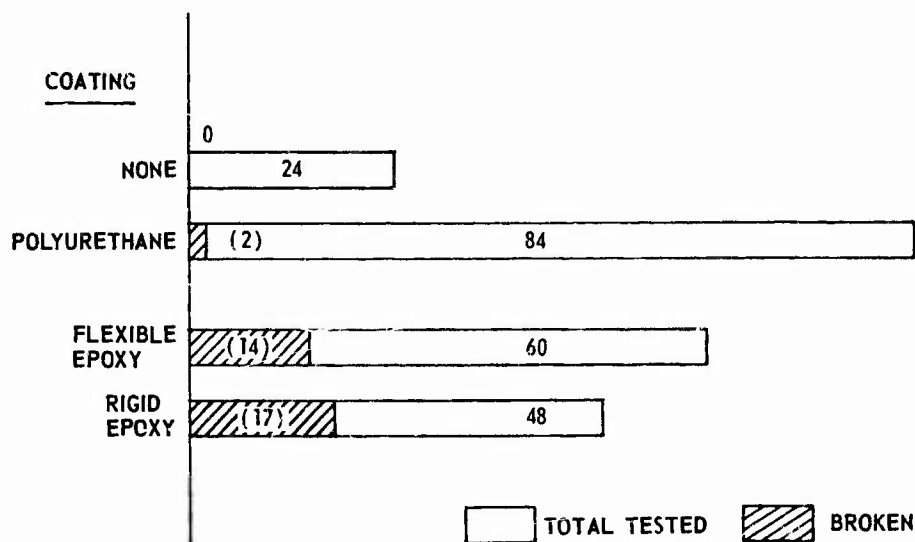


Figure 5. Breakage of Conformal Coated Diodes by Thermal Cycling.

10.3.7.1 Plating Printed Circuits. There is a difference of opinion on optimum plating for printed circuits. For some types of contacts - the spring type - gold performs better, but in the bellows type, gold and solder give equivalent service, although the solder degrades more in humidity tests.⁽¹⁵⁾ Modern practice in printed circuit production is discussed in Reference 16; see also Sections 6 and 8.

10.3.8 RESISTORS. Because of the bad effect of moisture on molded composition resistors,⁽¹⁷⁾ most military resistors are encapsulated or impregnated. Moisture on the body of a resistor forms a leakage path equivalent to a variable resistance in parallel with the resistor.⁽²⁾ On wirewound resistors, when a ceramic core and coated wire are used, the weakest point is at the terminal end caps. Hermetically sealed, molded or encapsulated resistors are required to meet stringent moisture resistance tests. Silicone, epoxy and diallyl phthalate⁽¹⁸⁾ are among the encapsulants used. On certain precision resistors of palladium and silver, changes greater than 0.1 percent were caused by coating with epoxy, silicone, and silicone rubber. A polyester coating proved satisfactory.⁽¹⁹⁾

10.3.9 SOLID STATE DEVICES. This general term includes diodes, transistors, and integrated circuits. Generally, it is believed that hermetic sealing is necessary,⁽²⁾ although there are some who believe encapsulation is sufficient for environmental protection.⁽²⁰⁾ Materials and processes are discussed in detail in Reference 21.

10.3.10 TRANSFORMERS. Like other metallic parts, transformers must be coated for protection against corrosion. Impregnation with varnish or encapsulation is the usual technique.

10.3.11 WAVE GUIDE. Metal wave guide can often be protected against environments by one of the very thin organic coatings mentioned in Section 7, which are only 0.1 mil, or less thick. If uncoated, the elements may attack and roughen the wave guide surface, degrading performance.

10.3.12 WIRE, CABLE, HARNESSSES. Certain problems with silver-plated Teflon insulated wire ("red plague") were mentioned in Section 6: these can be eliminated by using nickel under the silver. Attempts to use polyvinylchloride insulation over the silver plated copper wire resulted in severe corrosion.⁽²²⁾ Other coatings used for wire were discussed at the Fourteenth Annual Wire and Cable Symposium at Atlantic City, New Jersey, 1-3 December 1965.⁽²³⁾ One problem with fluorocarbon-insulated wire is the difficulty of getting adhesion when potting or encapsulating.⁽²⁴⁾ Polyimide coating with semi-flexible silicone varnish is rated best for elevated temperature magnet-wire, if processes are carefully controlled to prevent solvent crazing.⁽²⁵⁾

10.4 MARKING

The retention of identification on components after cleaning an assembly, is a real problem. Many marking inks are soluble in chlorinated hydrocarbons. A baked enamel, a stable epoxy, varnish, or a transparent shrinkable film, have proved useful in different applications.

10.5 RADOMES

Although they perform both structural and electrical duties, the environmental protection of radomes is determined by the electrical requirements. Radomes and other external parts often require protection from rain erosion, but the coating must be one which does not interfere with transmission. Plastic radomes may require sealing to enable them to withstand pressure differentials; the sealant is usually the same resin, to assure compatibility and uniform properties.

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SECTION 11 PACKAGING, PRESERVATION AND TRANSPORT

11.1 HAZARDS

Of all types of equipment, electronic devices are most likely to be damaged during shipment and storage unless properly protected. Physical breakage such as bent pins in connectors, or broken leads on welded modules, are common causes of failure. Of 170 Minuteman connector failures, 24 percent were due to bent pins and 6.5 percent to broken pins.⁽¹⁾ Also, the environment affects electronic components. Time produces some change in properties of encapsulants. Temperature changes cause outgassing of organic materials or thermal expansion of encapsulants which can break fragile parts. Silver terminals are tarnished by sulfurous gases (see Section 11.3.4). It has well been said that "Storage screens out or precipitates latent manufacturing defects."⁽²⁾

11.2 IN-PROCESS PROTECTION

Sometimes parts are seriously damaged during manufacture, even before final assembly. Many "air-conditioned" factories do not have controlled humidity, and condensate appears after a cool night. Careless workmen harm delicate surfaces by handling, contaminating them with fingerprints. It takes special care all the way to fabricate high reliability electronic devices. Items to remember are listed in Table XLVII.

Table XLVII*
QUALITY IN MANUFACTURING

1. Check manufacture date, shelf life, time container was open, and pot life of materials.
2. Clean surfaces before coating, joining, potting, or encapsulating.
3. Avoid dust and contamination by using protective bags, caps, sleeves, and containers.
4. Keep fingerprints off, or remove thoroughly.
5. Do not overclean in removing soldering flux; do not roughen plastic laminates.
6. Select cleaners and strippers with care, considering all the materials in the assembly.
7. Replenish cleaners frequently; keep them uncontaminated.

*Section 11.2

11.2.1 CONTAINERS. For transfer and in-process storage in the factory, use cushioned containers. For maximum protection, separate small, fragile or intricate components and store them in individual boxes or polyethylene bags.

11.2.2 CAPS. Where waveguides, for example, are open to the atmosphere, plastic caps exclude dirt and dust; connectors, too, need protective caps. Almost any desired size and shape can be bought from stock.

11.2.3 BAGS. Polyethylene bags are used for most electronic items. These bags should be sealed; if rubber bands or adhesive tape are used to close the bags, they often corrode copper. If staples are used, contaminants can get in at the staple holes.⁽³⁾ Sometimes polyethylene coated paperboard cartons and separators are preferred because of lower cost.⁽⁴⁾ These bags and cartons have proved effective barriers to corrosive fumes; they keep silver from tarnishing, keep dust out, prevent fingerprints, and keep items clean.

11.2.4 TREATED PAPER. Although used more for long-time storage protection, film or paper treated with volatile corrosion inhibitor is equally good for short-time storage. There are special products for specific metals. One, a polyester film coated on one side with VCI, is heat sealed around silver items to prevent tarnish. Another VCI paper which has polyethylene wax on the outside is good for protection of iron and steel, copper, brass, bronze and aluminum, but must not be used on cadmium, magnesium, lead or zinc. Some plastics are said to react with certain VCI chemicals; tests made some 10 years ago showed damage to unplasticized polyvinylchloride, cellulose acetate, modified polystyrene, and cellulose acetate butyrate,⁽⁵⁾ while polyamide and polytrifluorochloroethylene were not affected. It is wise to check all materials present before storing any assemblies in VCI treated wrappings.

11.2.5 TEMPORARY COATINGS. The thin-film coatings mentioned in Section 7.13.1 are very useful in preventing tarnish on parts before final assembly. Even in thicknesses of 0.1 mil, these coatings are quite effective.⁽⁶⁾ Moisture-displacing coatings or oils (see Sections 7.7.5, 7.13) effectively prevent rust on iron, and remove fingerprints.

11.2.6 LOCATION OF STORAGE AREA. Storage areas should be well ventilated, kept at low relative humidity, and not near any process creating harmful fumes. Acid vapors from plating tanks, or ozone from welding machines, quickly deteriorate nearby parts. Wood is another potent source of attack; oak, chestnut and cedar are the worst for emitting corrosive vapors.⁽⁷⁾ Assemblies should not be placed on bare wooden shelves.

11.2.7 FINGERPRINTS. Contamination of electronic components is caused by fingerprints, which contain acid, oil, and many types of bacteria. Delicate parts should be thoroughly cleaned with fingerprint-remover before storage.

11.3 PACKAGING AND PRESERVATION

11.3.1 PACKAGING METHODS. The standard packaging and preservation techniques for all kind of materials are detailed in the 457 page manual of the Joint Military Packaging Training Center⁽⁸⁾ and in MIL-P-116. Method II of MIL-P-116 requires an impervious moisture barrier wrap, plus a desiccant inside the package. It is effective but expensive, and other techniques are being investigated.⁽⁹⁾ Test programs show that Methods IIa, IIc and IId of MIL-P-116 provide, even under very adverse conditions, a relative humidity not over 10 percent.⁽¹⁰⁾

11.3.1.1 Electronic Components. A packaging specification specifically for electronic parts and components, published by NASA,⁽¹¹⁾ has five main kinds of packages: (1) plastic blister for individual components, (2) plastic box with two-piece cushion of expanded polystyrene or flexible polyurethane foam; (3) transparent plastic tube with polyethylene foam cushions and removable end-caps, for semiconductors; (4) polyethylene skin package for connectors; and (5) molded plastic for sturdy bulk items. NASA specifically bars the use of contact preservatives in electronic packaging. Some manufacturers protect nearly all electronic items in sealed polyethylene bags, including sheets of anti-tarnish paper with silver plated parts, and cushioning these bags with cellulosic material inside the shipping box or carton.⁽¹²⁾

In one case, the part is enclosed in a polyethylene envelope with a ripcord to open it. This envelope is supported in the container (which has activated silica as desiccant) by foam-in-place polyurethane.⁽¹³⁾ Polyethylene is the most widely used film, but even it does not have all the desired properties, such as zero moisture vapor transmission rate. Composite films of more than one plastic offer several advantages as moisture barriers.⁽¹⁴⁾

11.3.2 CLEANING. It is essential that parts be clean, free from fingerprints, grease, dust, oil, dirt or other contaminants before preservation is attempted. Desiccants cannot prevent corrosion, vapor corrosion inhibitors cannot work, and protective coatings are useless unless the part is thoroughly clean. The effect of a contaminated surface may explain contradictions in various reports on protection methods.

11.3.3 EFFECT OF TIME. Among materials which change properties with time are the rubbers. (See 7.6.1.) Recent tests show that the lubricants used with O-rings can cause softening and excessive volume change; when molybdenum disulfide in a solvent is the lubricant, both styrenebutadiene and silicone rubbers give good service after years of storage. There are losses in strength but not enough to lower performance.⁽¹⁵⁾ However, when elastomeric foams ordinarily used as cushioning materials are exposed to tropical heat, many lose their impact-absorbing characteristics. Neoprene is satisfactory, but polyurethane foam becomes useless after 8 months in the moist tropics. Foamed latex and rubberized hair are good only 5 to 9 months in dry tropical heat.⁽¹⁶⁾ Of course, the passage of time also contributes to the seriousness of chemical attack from fumes, etc., and damage from the variations in temperature.

11.3.4 ATTACK BY PACKAGING MATERIALS. Many commonly used packaging materials are actually harmful to electronic components. Cushioning materials often give off sulfurous fumes which attack silver, or acidic vapors which contaminate other metals. A review of the effect of 55 packaging materials on seven common metals - aluminum, brass, cadmium, iron, magnesium, silver and zinc - is given in Reference 17. The deterioration of cadmium by organic vapors has already been discussed (Section 5.3.7) but merits further mention. Shipping in wooden boxes, for instance, corrodes both cadmium and magnesium if any vapors can reach the metals. Materials inert in themselves, such as polyamide-cured epoxy and alkyl, promote this corrosive attack on cadmium.⁽¹⁸⁾ Paper and cardboard tarnish silver, copper and brass even when dry, if they contain as much as 0.006 percent free sulfur, or over 2.5 percent sodium sulfide.⁽¹⁹⁾ Paper and cardboard generally hold moisture and provide food for fungi, detrimental to the electronic items wrapped therein.

11.3.5 HELPFUL PACKAGING MATERIALS. Paper and cardboard can be treated so that they do not tarnish silver, by impregnating with copper-sodium chlorophyllin.⁽²⁰⁾ The use of stable non-volatile chemicals as impregnants provides years of anti-tarnish storage for silver. Paper and cardboard can also be fungus-proofed with sodium pentachlorophenoxide, 8-quinolinol or salicylanilide.⁽²¹⁾ By reinforcing with fiberglass and impregnating with a fungicide and vapor corrosion inhibitor, paper can be made resistant to water, fungus, and rust.⁽²²⁾ Polyethylene provides excellent protection for electronic items, whether used as a bag or envelope (preferably heat sealed), as a box or tube, or as a coating for paper or board.^(4, 11, 12)

11.3.6 VAPOR CORROSION INHIBITORS. The vapor corrosion inhibitors are volatile materials which condense on near-by surfaces and render moisture non-corrosive to many metals. These inhibitors may be impregnated into paper (see 11.2.4) or films, carried in oil or grease, or used as powder. For maximum efficiency, the VCI coated paper or film should completely envelope the material; be not more than 12 in. from the metal concerned; have no other packaging between it and the metal; and be used on absolutely clean metal.⁽²³⁾ While special VCI papers have been developed to protect silver, copper, and aluminum, the VCI never helps cadmium or zinc⁽²⁴⁾ and may even attack some plastics.⁽⁵⁾

11.3.7 DESICCANTS. Desiccants maintain relative humidity at the desired level, low enough to prevent condensation of moisture at the minimum temperature anticipated. The total humidity inside any package comes not only from outside, but also includes any moisture in the air when the container was packed, plus any in the cushioning or packing materials, plus that in the component or part. The amount of desiccant, usually silica gel, is established by considering the volume of air in the container, the degree of humidity permissible, and the time involved. Neither vaporproof packing nor desiccant is enough by itself to keep parts from damage by moisture; both are needed, to keep moisture out and to maintain humidity within the package at a safe low level.

11.4 SPECIAL PROBLEMS IN THE TROPICS

Parts which are transported or stored in the tropics require special procedures because of the severity of the environment. Moisture, fungi, insects, rodents and sunlight cause deterioration in any climatic zone, but reach a peak in the tropics.⁽²⁵⁾ Animal and insect attack is much worse there; thicker wrapping films are required, and the polyethylene bag so favored in temperate zones may be eaten by rats⁽²⁶⁾ or by insects⁽²⁷⁾ unless over 0.005 in. thick. All the precautions already mentioned, such as cleanliness, moistureproofing, avoidance of corrosive materials, use of fungicides and the like, must be strictly observed to keep equipment in good condition in tropical storage.

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APPENDIX II GOVERNMENT DOCUMENTS

NOTE: Following are typical and selected Government documents on the particular subject. For others, consult the Department of Defense Index of Specifications and Standards

GENERAL CONDITIONS AND REQUIREMENTS

Army Regulation AR 705-15 Operation of Material Under Extreme Conditions of Environment

MIL-STD-171 Finishing of Metal and Wood Surfaces

MIL-STD-186 Protective Finishing Systems for Rockets, Guided Missiles, Support Equipment and Related Materials

MIL-STD-210 Climatic Extremes for Military Equipment

MIL-STD-443 Environments for Electronic Parts, Tubes, and Solid State Devices

MIL-STD-454 Standard General Requirements for Electronic Equipment

MIL-STD-808 Finishes, Protective and Code for Finishing Schemes for Ground and Ground Support Equipment

MIL-B-5387 Bonding, Electrical and Lighting Protection for Aerospace Systems

MIL-E-5400 Electronic Equipment, Aircraft, General Specification For

MIL-E-8189 Electronic Equipment, Guided Missile, General Specification For

MIL-E-11991 Electrical-Electronic Equipment, Surface Guided, Missile Weapons Systems, General Specification For

MIL-E-16400 Electronic Equipment, Naval Ship and Shore, General Specification For

MIL-F-14072 Finishes for Ground Signal Equipment

MIL-HDBK-132 Protective Finishes

TEST METHODS

MIL-STD-169 Extreme Temperature Cycle

MIL-STD-170 Moisture Resistance Test Cycle for Ground Signal Equipment

MIL-STD-202 Test Methods for Electronic and Electrical Component Parts

MIL-STD-810	Environmental Test Methods for Aerospace and Ground Equipment
MIL-STD-826	Electromagnetic Interference Test Requirements and Test Methods
MIL-E-5272	Environmental Testing, Aeronautical and Associated Equipment
MIL-T-5422	Testing, Environmental, Aircraft Electrical Equipment

METALS - TREATMENT

AMCP-706-311	Corrosion and Corrosion Protection of Metals
ORDP-608-OW- RIA3	Protective Coating and Plating
MIL-HDBK-205	Phosphatizing and Black Oxide Coating of Ferrous Metals
MIL-STD-276	Impregnation of Porous Nonferrous Metal Castings
QQ-P-35	Passivation Treatment of Austenitic, Ferritic and Martensitic Corrosion Resisting Steel
TT-C-490	Cleaning Methods and Pretreatment of Ferrous Surfaces for Organic Coatings
MIL-F-495	Finish, Chemical Black for Copper Alloys
MIL-M-3171	Magnesium Alloy, Processes for Pretreatment and Prevention of Corrosion On
MIL-S-5002	Surface Treatments and Metallic Coatings for Metals Surfaces and Weapons Systems
MIL-C-5541	Chemical Films and Chemical Film Materials for Aluminum and Aluminum Alloys
MIL-I-6869	Impregnants for Aluminum Alloy and Aluminum Alloys
MIL-T-12879	Treatments, Chemical Prepaint and Corrosion Inhibiting for Zinc Surfaces
MIL-C-13924	Coating, Oxide, Black, for Ferrous Metals
MIL-M-45202	Magnesium Alloy, Anodic Treatment Of

METALS - COATINGS

QQ-C-320	Chromium Plating, Electrodeposited
QQ-N-290	Nickel Plating (Electrodeposited)
QQ-P-416	Plating, Cadmium (Electrodeposited)

QQ-S-365	Silver Plating, Electrodeposited
QQ-Z-325	Zinc Coating, Electrodeposited
MIL-C-8837	Coating, Cadmium, Vacuum Deposited
MIL-T-10727	Tin Plating, Electrodeposited or Hot Dipped
MIL-L-13808	Lead Plating, Electrodeposited
MIL-C-14550	Copper Plating, Electrodeposited
MIL-C-23217	Coating, Aluminum, Vacuum Deposited
MIL-P-23408	Plating, Tin-Cadmium
MIL-C-26074	Coating, Nickel-Phosphorus, Electroless Nickel
MIL-G-45204	Gold Plating, Electrodeposited
MIL-R-46085	Rhodium Plating, Electrodeposited

METALS - SOLDERING

QQ-S-571	Solder, Tin Alloy, Lead-Tin Alloy and Lead Alloy
MIL-S-6872	Soldering Process, General Specification For
MIL-S-45743	Soldering, High Reliability, Electrical Connections
MIL-S-46844	Solder Bath Soldering of Printed Wiring Assemblies

NON-METALLICS - ADHESIVES

MIL-HDBK-691	Adhesives
MIL-A-3920	Adhesive, Optical Thermosetting
MIL-A-8576	Adhesive, Acrylic Base, for Acrylic Plastic
MIL-A-25457	Adhesive, Air-Drying Silicone Rubber
MIL-A-52194	Adhesive, Epoxy (for Bonding Glass Reinforced Polyester)
MIL A-81236	Adhesive, Epoxy With Polyamide Curing Agent

NON-METALLICS - ENCAPSULANTS AND POTTING COMPOUNDS

MIL-I-16923	Insulating Compound, Electrical Embedding
MIL-M-24041	Molding and Potting Compound, Chemically Cured, Polyurethane (Polyether Based)

MIL-P-46076	Plastic, Polyurethane, Flexible, Potting and Molding Compound
MIL-R-46092	Rubber, Silicone, Encapsulating Compound
MIL-P-46847	Plastic Material, Foamed Polyurethane for Encapsulating Electronic Components

NON-METALLICS - GASKETS, SEALANTS, TAPE

MIL-HDBK-212	Gasket Materials (Non-Metallic)
MIL-HDBK-695	Rubber Products, Shelf Storage Life
MIL-S-7124	Sealing Compound, Elastomeric, Accelerator Required, Aircraft Structures
MIL-S-8516	Sealing Compound, Synthetic Rubber, Electric Connectors and Electric Systems, Accelerator Required
MIL-S-11031	Sealing Compound, Adhesive (Polysulfide Base)
MIL-S-22473	Sealing, Locking and Retaining Compound, Single Component
MIL-I-23053	Insulation Tubing, Electrical, Heat Shrinkable
MIL-T-23142	Tape, Pressure Sensitive Adhesive for Dissimilar Metal Separation
MIL-S-23586	Silicone Rubber Compound, Room Temperature Vulcanizing
MIL-T-23594	Tape, Pressure Sensitive Adhesive, Electrical, High Temperature Insulation, Polytetrafluoroethylene
MIL-R-46846	Rubber, Synthetic, Heat Shrinkable

NON-METALLICS - ORGANIC COATINGS

MIL-V-173	Varnish, Moisture and Fungus Resistant
MIL-V-1137	Varnish, Electrical Insulating
MIL-C-8507	Coating, Wash Primer (Pretreatment) for Metals, Application Of
MIL-P-8585	Primer Coating, Zinc Chromate, Low Moisture Sensitivity
MIL-V-13497	Varnish, Impregnating, Electrical Insulating
MIL-P-15328	Primer, Pretreatment (Formula No. 117 for Metals)
MIL-C-16555	Coating Compound, Strippable Sprayable
MIL-C-22627	Coating Conformal, Resin
MIL-C-22750	Coating, Epoxy-Polyamide

MIL-P-27316	Primer Coating, Epoxy, for Metal Surfaces
MIL-I-24092	Insulating Varnish, Electrical Impregnating
MIL-P-46056	Primer Coating, Polyamide Epoxy
MIL-C-46057	Coating, Polyurethane
MIL-I-46058	Insulating Compound for Electrical, for Coating Printed Circuit Assemblies
MIL-P-52192	Primer Coating, Epoxy
MIL-C-52210	Coating, Epoxy, Spray Type for Printed Circuitry

NON-METALLICS - PLASTICS

MIL-HDBK-700	(MR) Plastics
MIL-M-14	Molded Plastics and Molded Plastic Parts, Thermosetting
MIL-P-79	Plastic Rods and Tubes, Thermosetting, Laminated
MIL-P-8013	Plastic Material, Polyester Resin, Glass Fiber Base, Low Pressure Laminated
MIL-P-13949	Plastic Sheet Laminated, Copper Clad, (for Printed Wiring)
MIL-P-15047	Plastic Material, Laminated, Thermosetting Sheets, Nylon Fabric Base, Phenolic Resin
MIL-P-19833	Plastic Molding Material and Plastic Molded Parts, Glass Fiber Filled, Diallyl Phthalate Resin
MIL-M-21347	Molding Plastic, Polystyrene, Glass Filled
MIL-M-21470	Molding Plastic, Polychlorotrifluoroethylene
MIL-P-25518	Plastic Material, Silicone Resin, Glass Fiber Base, Low Pressure Laminated
MIL-P-27538	Plastic Sheet, FEP-Fluorocarbon (Unfilled) Copper Clad (for Printed Wiring)

NON-METALLICS - TREATMENTS

MIL-T-152	Treatment, Moisture and Fungus Resistant, of Communications, Electronic and Associated Equipment
MIL-T-12664	Treatment, Fungus Resistant, Paranitrophenol, for Cork
MIL-T-13867	Treatment, Moisture and Fungus Resistant for Fire Control Electrical and Electronic Instruments and Equipment

MIL-T-21330	Treatment, Insect Repellant, for Paper
MIL-M-46032	Mildew Resistant Treatment for Fabrics, Copper Processes
T-W-571	Wood Preservation, Treating Practices

PACKING, PACKAGING, AND PRESERVATION

MIL-P-116	Preservation, Methods Of
MIL-P-3420	Packaging Materials, Volatile Corrosion Inhibitor Treated, Opaque
MIL-D-3464	Desiccants, Activated, Bagged. Packaging Use and Static Dehumidification
MIL-B-5423	Boot, Dust and Water Seal (for Toggle and Push Button Switches and Rotary-Actuated Parts) General Specification For
MIL-C-5501	Cap and Plug, Protective, Dust and Moisture Seal
MIL-P-9969	Polyurethane Foam, Rigid or Plastic, for Packaging
MIL-B-13239	Barrier Material, Water Vaporproof, Flexible, All Temperature
MIL-T-22085	Tape, Pressure Sensitive Adhesive, Preservation and Sealing
MIL-P-22241	Plastic Film, Polytetrafluorethylene, TFE Fluorocarbon Resin

NASA-MSFC-STD

343/3	Electronic Parts and Components: Protection, Handling and Packaging Of
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