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Exam Preview:

1. While coating metal surfaces is the most commonly used method of corrosion control, it cannot be used effectively without interacting with other methods of corrosion control.
    a. True
    b. False

2. Some protective coatings have a high loading of fine ___ particles, so the particles in the cured film are in electrical contact with each other and with the underlying steel.
    a. Carbon
    b. Zinc
    c. Iron
    d. Chromium

3. Which is not a basic category of ingredients for coatings?
    a. Solvent
    b. Activator
    c. Resin
    d. Pigment

4. The solvent is the binder or film-forming part of the coating that is responsible for most of the properties of the coating. Thus, coatings are identified by the generic types of their solvents.
    a. True
    b. False

5. Coatings that cure by chemical reaction are usually the most durable.
    a. True
    b. False
6. ___ make up the solvent portion of coatings.
    a. Volatile organic compounds (VOCs)
    b. Resin
    c. Activators
    d. Zinc mixtures
7. The 300 Series Stainless Steels group of alloys are non-magnetic and have an ____ structure. The basic alloy contains 18% chromium and 8% nickel.
    a. Precipitation hardened
    b. Martensitic
    c. Austenitic
    d. Ferritic
8. Aluminum alloys are resistant to corrosion in many marine environments and are not subject to crevice corrosion, pitting, and in some alloys, stress corrosion cracking.
    a. True
    b. False
9. ____ Series Aluminum Alloys. This series of alloys are alloys of aluminum, magnesium, and silicon. They are relatively high in strength and can be heat treated to obtain higher strengths.
    a. 2000
    b. 3000
    c. 4000
    d. 6000
10. In general, corrosion rates increase with increasing ____. In seawater, this increase is much less than the doubling of reaction rates with each 18°F rise in temperature that would be expected if the reactions were under diffusion control as are many other chemical reactions.
    a. Temperature
    b. Pressure
    c. Relative Humidity
    d. Dew point

Naval Facilities Engineering Command
200 Stovall Street
Alexandria, Virginia 22332-2300

Corrosion Control

PART 2 OF 2

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FOREWORD

Corrosion of shore and waterfront facilities is a common and serious problem. Naval shore establishment losses to corrosion are estimated at over one-half billion dollars annually. Corrosion related costs and the adverse impact on mission readiness are of increasing concern. Additionally a corrosion leak in a POL tank or pipeline could be very expensive for cleanup and could effect the mission adversely. Action to control corrosion or to repair corrosion damage are among the most frequent reasons for performing maintenance on shore and waterfront facilities.

Additional information or suggestions that will improve this manual are invited and should be submitted through appropriate channels to the Naval Facilities Engineering Command, (Attention: Code 1632), 200 Stovall Street, Alexandria, VA 22332-2300.

This publication has been reviewed in accordance with the Secretary of the Navy Instruction 5600.16A and is certified as an official publication of the Naval Facilities Engineering Command.

ERHamm
E. R. HAMM
CAPTAIN, CEC, U. S. Navy
Assistant Commander for
Public Works Centers and Departments

ABSTRACT

The purpose of this manual is to serve as a technical guide for both Naval and civilian personnel in identifying existing or potential corrosion problems, determining the proper corrective actions, and implementing the corrective actions. As corrosion and corrosion control are affected by both original design and construction and maintenance, information is presented regarding all methods for reducing corrosion even though the information is primarily oriented toward maintenance and repair.

This manual describes the mechanisms of corrosion, the types of corrosion commonly experienced in naval shore facilities and waterfront structures, the methods that can be used to control corrosion and methods for implementing an effective corrosion control program. This manual emphasizes methods for determining the most cost effective means of controlling corrosion and practical application of corrosion control to typical problems encountered in the Naval shore establishment.

CHANGE CONTROL SHEET

Document all changes, page replacements, and pen and ink alterations posted in this manual.

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CHAPTER 7. CORROSION CONTROL BY COATINGS

7.1 INTRODUCTION. This chapter presents information on the effective use of organic coatings to protect metal, particularly steel, shore facilities from corrosion. This chapter provides a general understanding of the principles involved in coating operations, so that guide specifications for actual coating of facilities can be used most effectively.

7.1.1 Scope. This chapter covers coating of metal surfaces encountered at Naval shore activities,including their selection, application (and surface preparation), and maintenance in a state of acceptable condition. It does not cover painting of other substrate surfaces or painting of ships or aircraft. The coatings covered are limited to organic paint materials, with the exception of inorganic zinc coatings which are included, because they are most commonly used in conjunction with organic coatings and are applied by spray, like organic coatings. Powder coatings are also described, although their application is somewhat different from typical brush, roller, or spray application.

7.1.2 Coatings as Part of Corrosion Control Program. While coating metal surfaces is the most commonly used method of corrosion control, it cannot be used effectively without interacting with other methods of corrosion control. These include, but are not limited to, designing proper components; selecting proper materials, components, and cathodic protection; and using corrosion inhibitors.

7.2 METHODS BY WHICH COATINGS PROTECT METALS FROM CORROSION. Coatings have three basic mechanisms for protecting metals from corrosion, although more than one of these mechanisms may be used by a coating. These mechanisms are: barrier protection, cathodic protection, and corrosion inhibitors.

7.2.1 Barrier Protection. Most coatings provide corrosion protection by forming a barrier relatively impermeable to moisture and electrolytes necessary for corrosion. Obviously, for optimum protection, the barrier should be as impermeable, thick, and continuous as practical.

7.2.2 Cathodic Protection of Steel. Some protective coatings have a high loading of fine zinc particles, so the particles in the cured film are in electrical contact with each other and with the underlying steel. This permits a type of cathodic protection. Presently, two basic types of zinc-rich coatings are used on steel: organic and inorganic products.

7.2.3 Inhibitive Pigments. Some pigments are added to primers to inhibit corrosion at the coating/metal interface. Red lead is the most common example of an inhibitive pigment.

7.3 COMPOSITIONS AND PROPERTIES OF COATINGS.

7.3.1 Components of Coatings and Their Functions. All ingredients used to formulate a coating can be placed in one of three basic categories: solvent, resin, and pigment. Each of these categories has a special function in the coating's formulation.

Solvent. The solvent is used to dissolve the resin material that actually forms the coating film. It also reduces the viscosity of the product to permit easier application, as well as affecting its leveling, drying, durability, and adhesion. Because the different organic polymers in different resins greatly differ in their solubilities, some resins require much stronger than others to dissolve them. In water-based coatings, the water is a dispersing rather than a dissolving agent.

The emission of virtually all organic solvents in coatings gives rise to photochemical smog. Thus, there is a great pressure to reduce the amount of solvent in coatings or to use water-based coatings.

Resin. The resin is the binder or film-forming part of the coating that is responsible for most of the properties of the coating. Thus, coatings are identified by the generic types of their resins. The resin and the solvent portions of coatings are sometimes called the nonvolatile and the volatile vehicle, respectively, and are sometimes referred to collectively as the vehicle.

Pigment. The pigment constitutes the solid portion of a coating. It is generally heavier than the liquid vehicle portion and may settle out on prolonged standing. Pigments are usually modified or unmodified natural earth materials, although less stable organic pigments are occasionally used. The chief function of the pigment is to provide opacity (hiding) to protect the organic vehicle from degradation by sunlight. Titanium is the pigment most frequently used to give opacity to white paints and light tints.

Pigments also provide color, improve adhesion and weather resistance, decrease moisture permeability, and control gloss. Leafing pigments, such as aluminum, tend to form parallel plates in the film to effectively increase its thickness by increasing the path moisture must penetrate. Other things being equal, the finer the pigment particle size and the less the pigment/resin ratio, the glossier will be the coating.

The pigment and the resin portions are sometimes called the solids portion, since they remain after all the solvent has evaporated. Obviously, the greater the coating solids, the greater will be the dry film thickness received from a given wet film thickness.

There are also many additives or extenders added to coatings to modify gloss or consistency, emulsify components, improve weathering, or obtain some other desirable property. They are considered to be in the resin or pigment part depending whether they exist in the coating as a liquid or solid.

7.3.2 **Mechanisms of Curing.** All coatings cure from one of three basic mechanisms: air-oxidation of drying oils, solvent or water evaporation, or a chemical reaction of components. Coatings that cure by the same basic mechanism tend to be compatible with each other but not with coatings that cure by other mechanisms.

Air Oxidation of Drying Oils. Coatings that cure by air oxidation of drying oils have oxygen from the air react with the unsaturated fatty acids in their drying oils. By this reaction, liquid resins are converted to a solid film.

Examples of coatings that are cured by this mechanism are unmodified drying oils (e.g., linseed oil), alkyds (usually formed by reaction of oils with phthalic anhydride), silicone alkyds, oleoresinous phenolics, and epoxy esters. They wet surfaces very well and generally perform well in mild environments, but they have limited durability in chemical environments, particularly alkaline environments. They cannot be used in water immersion service, except for oleoresinous phenolics. Formulating oil-based coatings with low solvent content presents difficulties and requires unique changes.

Solvent Evaporation. Coatings that cure by simple solvent evaporation are sometimes called lacquers. They are made by dissolving solid resins in an appropriate solvent. After application, the solvent evaporates to deposit the resin in a thin film. No chemical change occurs to the resin. Resins that are softened by solvent or heat are called "thermoplastic."

Examples of coatings that cure by this mechanism are vinyls (polyvinyl chlorides) and chlorinated rubbers. The polyvinyl-butyral resin used in wash primers also belong to this category, as do asphaltic and coal tar coatings. Coatings of this class have limited solvent resistance, since they were deposited from a solvent, but are easy to topcoat and repair because the topcoat solvent bites into the undercoat to bond tightly. Because lacquers are high in solvent (VOC) content, their use will be greatly curtailed.

Water Evaporation. Latex and many other water-borne coatings cure by simple water evaporation. Emulsified particles of solid resin coagulate to form a film as the water is lost. The range of acceptable ambient temperature and humidity values is much more critical for water-borne than for other coatings.

Examples of latex coatings are acrylics and vinyls (polyvinyl acetate). Latex films are quite flexible but tend to be more permeable and less durable than many other films.

Chemical Reaction. Coatings that cure by chemical reaction are usually the most durable. They are generally packaged in two separate containers and mixed to initiate the reaction. Components must be combined in the specified proportions in the manner specified by the supplier to achieve a complete reaction. Sometimes, an "induction period" is required after mixing and before application to permit the reaction to get started. After mixing, there is always a "pot life" during which the coating must be applied, before the reaction has advanced so far as not to permit proper application and curing.

Examples of this class are epoxies, coal tar epoxies, urethanes, and polyesters. Because the chemical reaction is irreversible, they are called "thermosetting" coatings. Although this makes the coating very chemical and solvent-resistant, it also makes the cured coatings difficult to topcoat. Thus, the topcoat is best applied while the undercoat still has some residual tack. After the coating has completely cured, it is necessary to first spray a thin tie coat and then apply a full coat to it when it is still tacky.

Another example of chemically curing coatings is the inorganic zinc coating. They may cure by different types of reaction. Thus, some cure by reaction with water from the air, and thus cure slowly in dry environments. A one-package urethane water-based inorganic zinc coating cures by chemical reaction after evaporation of the water.

Zinc-rich organic coatings may contain different organic resins. Their curing mechanisms are those of the resin-solvent evaporation for zinc-rich vinyls and chemical reaction for zinc-rich epoxies.

7.4 ENVIRONMENTAL, HEALTH, AND SAFETY RESTRICTIONS ON COATINGS.

Environmental restrictions have greatly limited the compositions of coatings, the surface preparation, and the coating application techniques that can be used in many locations. These restrictions can be expected to become even tighter in the near future. Although much general information is provided in this section, personnel concerned with products or procedures described should confer with local authorities to determine what are the prevailing regulations.

7.4.1 <u>VOC Limitations.</u> Volatile organic compounds (VOCs) make up the solvent portion of coatings. Regulations have been enacted in many locations that have not achieved the ozone level established by the Environmental Protection Agency. These regulations cover architectural coatings, coatings for miscellaneous metal parts (shop Painting), aerospace coatings, and architectural coatings. This chapter will concern itself only with VOC restrictions on architectural coatings and coatings for miscellaneous metal parts, since the others are outside the scope of this manual. An architectural coating is for a structure fixed in place, while a miscellaneous metal part is defined as a structural component that can be taken to a shop for coating. Presently, most architectural coatings have a VOC limit of 250 g/liter, while metal part coatings have a VOC limit of 340 g/liter.

The effects of the two regulations of concern are such as to cause reformulation or elimination of virtually all coatings previously used on metals. Only the latex military coatings seldom specified for steel are in conformance. Indeed, use of latex coatings on steel has created many costly problems, because it not only is hard to formulate a high-performance water-based coating for metals, but the range of acceptable temperature and humidity conditions for suitable application is limited.

VOC emissions into the air have been further reduced by regulations restricting the methods of shop application of coatings to those with 65 percent transfer efficiency. For most configurations coated in shops, this effectively means that spray applications must be accomplished by electrostatic spray, or air-assisted airless spray.

7.4.2 Lead and Chromium Concerns. Lead and chromium pigments have been used for many years as corrosion inhibitors for metal primers. Recently, concern has been expressed for possible toxic effects of these pigments in coatings. Thus, lead can no longer be used on housing or other structures where children might come into contact. Probably more important are new regulations concerning the removal of lead-based coatings. They require that removal of existing coatings be preceded by testing the coatings for lead and that lead-containing paint be contained during removal, the air be monitored for lead in the particulates formed during removal, and that the old paint and blasting abrasive be disposed of in a manner required for toxic waste. This great expense, as well as health concerns for children exposed to lead-based paints, has effectively eliminated their use for Navy and Marine Corps facilities. Concern has also been expressed for problems in removing chromium-containing coatings. Thus, using coatings containing lead or chromium is not recommended. When removing old coatings, they should be tested for lead, chromium, and other heavy metals, and then removed and disposed of in accordance with appropriate local regulations.

The corrosion inhibitive pigments commonly used for coatings are listed below in two columns, those considered to be toxic and those considered relatively nontoxic:

Toxic	**Nontoxic**
Red Lead	Zinc Oxide
White Lead	Zinc Phosphate
Zinc Chromate	Zinc Molybdate
Strontium Chromate	Calcium Borosilicate
Basic Lead Silica-Chromate	Calcium Phosphosilicate
	Zinc Phosphosilicate

7.4.3 Mercury. Mercury-containing mildewcides were once routinely added to most oil-based and latex house paints to control the growth of mildew. These compounds used in a low concentration were effective in controlling the growth of most mildew organisms. Recent concern over toxic effects of mercury compounds has restricted the use of mercurials in coatings. Synthetic organic mildewcides approved by the Environmental Protection Agency have replaced mercury mildewcides in most coatings. The products, however, are required in much greater amounts than mercurials to be effective against mildew organisms, some have not shown long term effectiveness, and others may prove to be more hazardous than originally suspected. Investigations are being conducted into determining the most effective and safe use of mildewcides in coatings. In the mean time, these products should be handled such as to limit exposure.

7.4.4 Asbestos. Asbestos fibers were once used extensively to reinforce coatings. They are no longer used, because these fibers pose a health hazard if they get into the air. Thus, old asbestos-containing coatings (e.g., asbestos-filled bituminous coatings) should not be sanded, nor asbestos-cement products be coated, less asbestos fibers be released.

7.4.5 Coal Tar. Coal tar and asphalt coatings were once extensively used. Their use is greatly restricted now because of toxicities of some of their ingredients, because they do not perform well in sunlight, and because of new VOC limitations. One of their chief uses was to line steel potable water storage tanks. Now epoxy coatings, which are considered safer, are used for this purpose.

7.4.6 Organotins. Organotin compounds were found to be very effective in coatings to control the attachment and growth of fouling organisms on the hulls of marine vessels. Concern has greatly limited the use of antifouling paints containing these products. Now the use of such coatings is permitted only on large ships and on aluminum boats, because the other available products containing cuprous oxide will cause galvanic corrosion of aluminum. Cuprous oxide antifouling coatings (e.g., MIL-P-15931) are used routinely elsewhere, where they may be effective for 2 or more years depending on the service.

7.4.7 Urethane Resins. Urethane coatings are of a health concern because of toxic effects of their isocyanate components. To alleviate these concerns, the amount of free isocyanate has been limited, and strict safety procedures have been established for applying urethane coatings.

7.4.8 Abrasive Blast Cleaning. Because abrasive blasting is the preferred method of preparing the surfaces of most metals for coating, it should be considered despite the restrictions and costs in its use.

Particulates. Particulates produced during dry abrasive blasting pose a health threat. Regulations have been imposed to restrict blasting options to such procedures as blasting in closed buildings, using approved abrasives, wet abrasive blasting, and water blasting. The options will be discussed in the section on surface preparation. California's South Coast Air Quality Management District has imposed fees on abrasive blasting related to the amount of particulates produced. Since a much greater quantity of particulates is produced when blasting with sand than with shot or grit, promulgation of this action elsewhere may greatly restrict the use of sand in abrasive blasting.

Silica. Because silica abrasive used in blast cleaning may cause silicosis, its use has been eliminated in Naval Sea Systems Command operations (shipboard use). Because of this and other considerations, use of silica (sand) abrasive is not recommended on shore facilities, unless there is a compelling reason. If this is the case, special precautions should be taken to protect the workers.

Toxic Coatings. Since toxic coatings (e.g., lead-based paints) require special containment and disposal when removed by blasting, it is important to keep the amount of toxic waste (contaminated spent abrasive) as low as possible. This can be done by using the vacuum blasting technique described in the section on surface preparation.

7.5 SELECTION OF COATINGS.

7.5.1 General. Before selecting a coating, four basic questions must be answered:

1. What is the type (e.g., steel) and condition of the substrate?
2. What is the basic function of the coating on the substrate?
3. What is the nature of the environment?
4. What are the desired properties of the coating?

In actual practice answers to the first three questions will normally determine the answer to the fourth question, which in reality dictates what coating system is most appropriate. Another important question may be what methods of surface preparation and application are available, since time, money, accessibility, or environmental restrictions may limit the methods that can be used. Historically, life cycle costing has been the bottom line in selecting a coating system. Now, the cost of coating removal and disposal has become a very important factor. Thus, long-term, high-performance coatings are almost always the coatings of choice for new construction.

Spot repair of coatings is best accomplished with a material similar to that already in place, in order to avoid incompatible products. Because of new environmental restrictions, this may not be possible. Then, special care may be required to insure compatibility. The one exception to spot repairing with a like material occurs with inorganic zinc coatings with organic topcoats. Since inorganic zinc coatings do bond well to organic coatings, zinc-rich organic coatings are used.

7.5.2 General Properties of Differently Curing Coatings. Each of the generic coating types formulated for metal surfaces that are commonly used in Naval shore facilities will be discussed separately.

The advantages and limitations of using the different coatings are listed separately after each discussion.

Oil-Based Coatings. Oil-based coatings were the first coatings used to protect steel from corrosion. They are still used extensively today but have only limited service lives in severe environments. Because the drying oil wets surfaces so well, they are more tolerant of incomplete surface preparation than are other coatings (e.g., they perform reasonably well on steel cleaned by hand or power tools). These coatings deteriorate rather rapidly in water immersion (except for oleoresinous phenolics) or on alkaline surfaces, such as galvanized steel and or concrete. For this reason they are not used in these environments. Oil-based coatings include unmodified drying oils, alkyds, epoxy esters, and oleoresinous phenolics. Unmodified drying oils can be formulated into VOC-conforming coatings more easily than the other resins. It is usually necessary to use the exempt solvent 1, 1, 1-trichloromethane to be VOC conforming. This solvent may be eliminated from exemption in a few years because of toxicity concerns.

Advantages	**Limitations**
Easy to apply, topcoat, and repair	Poor alkali resistance
Moderate cost	Poor immersion service
Good wetting of surfaces (easy surface preparation)	Poor chemical/solvent resistance
Fairly good gloss retention	Poor heat resistance
Can be relatively flexible	Limited weather resistance
Fair exterior durability	
From renewable sources	

Latex Coatings. Latex coatings have been a boom to homeowners because they are easy to apply to a variety of surfaces and are easy to clean up. They are also environmentally acceptable, as they are VOC conforming, even if they may contain compatible organic solvents. Limitations include limited durability, especially on steel and other metals; poor chemical and solvent resistance; and limited acceptable application conditions. Their excellent flexibility is offset by their poor wetting of surfaces. When applied over a smooth enamel, it is necessary to lightly sand the enamel to achieve good topcoat bonding. They are available as acrylics, vinyls (polyvinyl acetates), or copolymers of these resins. Acrylic latexes may be applied over epoxy systems to provide improved exterior weathering.

Advantages	**Limitations**
Low cost	Limited durability
Easy to apply, topcoat, and repair	Poor chemical/solvent resistance
Good flexibility	Poor wetting of surfaces
Environmentally acceptable	Poor immersion service
	Poor heat resistance
	Must apply above 70°F

Bituminous Coatings. Bituminous (coal tar and asphalt) coatings have been used for many years.

Advantages	**Limitations**
Low cost	Poor exterior weathering
Good water resistance	Poor chemical/solvent resistance
Good film build	Available in black only
Easy surface preparation	
Easy to apply	

Lacquers (Vinyls and Chlorinated Rubber Coatings). Vinyl and chlorinated rubber lacquers have excellent water and chemical resistance, but poor solvent resistance. They have a low rate of film build up because they have a high solvent content. However, because of their short drying time, the film can rapidly build up. The high solvent content causes them to exceed VOC limits. This greatly reduces their use. They have relatively good gloss retention and durability if they have enough titanium dioxide content to protect the resins from sunlight. They usually require a greater degree of blast cleaning than the coatings previously described in this section. The first vinyls developed required wash priming of the steel to achieve good adhesion, but later formulations do not.

Advantages	Limitations
Good chemical and water resistance	Poor solvent resistance
Easy to repair and topcoat	Poor heat resistance
Rapid drying and recoating	Low film build up
Applicable at low temperatures	
Has good durability/gloss retention	

Epoxy Coatings. Epoxy coatings have some of the best combinations of chemical, solvent, and water resistance. They form a tightly adhering, hard, slick film with good abrasion resistance and durability. Their shortcomings include inflexibility, poor weathering (chalking and poor gloss retention in sunlight), and difficulties associated with a chemically-curing coating (two- package mixing, limited pot life, and difficulty in topcoating, as described earlier). The surface must be cleaned to a near white finish, but epoxy-polyamide coatings are a little more tolerant of incomplete cleaning. Of the two types of epoxy most commonly used on shore facilities, epoxy-polyamides usually have the better water-resistance and amine-cured epoxies have the better chemical resistance. Epoxies can be formulated to make them high solids (even 100% solids) or water-based to make them VOC conforming.

Advantages	Limitations
Excellent chemical, solvent, and water resistance	Chalks freely in sunlight
Hard, slick, durable film	Poor gloss retention
Excellent adhesion	Curing must be above 50°F
Good abrasion resistance	Clean, blasted surface required
Can be made VOC conforming	Two-package coating; limited pot life
	May be difficult to topcoat

Coal Tar Epoxy Coatings. Coal tar epoxy coatings have coal tar added to the epoxy formulation. This increases the water resistance and film build up per coat while reducing the price. The properties of coal tar epoxies are similar to other epoxies, but they become more brittle (inflexible) in sunlight.

Advantages	Limitations
Good resistance to water and petroleum products	Chalks freely in sunlight
Good film build up	Slow curing
Good abrasion resistance	Clean, blasted surface required
	Two-package coating; limited pot life
	May be difficult to topcoat

Urethane (Polyurethane) Coatings. Chemically curing, two-component urethane coatings have a greater range of properties available than do epoxies. They can be elastomeric or rigid and have excellent or poor exterior weathering (chalk-resistance, discoloration, and gloss retention). They have good resistance to chemicals, solvents, and water. Their chief concern is the highly toxic isocyanate component. Personal protection equipment required during application can make applying this coating more difficult. Urethane coatings do not usually bond to metals as well as epoxy coatings and so are often applied over epoxy primers. On the other hand, aliphatic urethanes are often applied as finish coats to epoxy systems to provide good exterior weathering. Urethanes can be formulated with high solids to make them VOC conforming.

Advantages	**Limitations**
Excellent chemical, solvent, and water resistance	Highly toxic; personal protection required
Applicable at low temperatures	Moisture sensitive; must seal containers tightly; gloss drops with high humidity
Can have excellent gloss retention and chalk resistance	Clean, blasted surface required
Good durability/abrasion resistance	Two-package coating; limited pot life
May be hard or flexible	May be difficult to apply or topcoat
Can be made VOC conforming	

Zinc-Rich Inorganic Coatings. Inorganic zinc coatings are tough, abrasion resistance products that provide cathodic protection to steel. They require the highest level of surface preparation (the cleanest surface) of all generic types of coating and perhaps the greatest skill in applying them successfully. Because the heavy zinc particles tend to settle rapidly to the bottom of wet paint, the paint pot must be kept at the same elevation as the spray equipment (it can only be applied by spraying), the pot must be constantly agitated, and the material hose from the pot to the spray gun should be as short as practical. Inorganic zinc coatings are usually applied at 3 to 5 mils dry film thickness. Applying the inorganic zinc coatings in greater thicknesses may result in mud cracking.

Inorganic zinc coatings require topcoating with organic coatings (e.g., epoxies) for long-term performance in immersion and other severe service. Because they are porous, topcoat solvents or air may penetrate the coating and later emerge though the wet topcoat to form small bubbles and leave holidays in the coating. Thus, tie-coats (1 to 2 mils of wet topcoat) are usually first sprayed on inorganic zinc primers to fill the voids, and a full topcoat is applied while the tie-coat is still tacky. Topcoats must be alkali resistant to avoid alkali degradation by the alkaline zinc corrosion products formed during cathodic protection. As mentioned in Paragraph 7.5.1, topcoated inorganic zinc coatings are repaired using compatible zinc-rich organic coatings.

In new construction, steel is usually abrasively blasted and primed with inorganic zinc primer in a shop under controlled conditions to give high quality application not received so easily in the field. Also, there is less contamination of the environment by the blasting particulates. The preconstruction primer may then be topcoated later after the structure steel has been erected. Welding has been successfully reported through some inorganic zinc coatings. If the primer can be properly maintained, abrasive blasting may not be required later for maintenance painting.

Advantages

Excellent abrasion resistance
Excellent heat resistance
Excellent corrosion resistance
  by cathodic protection of steel
May be shop, weld-through, or
  permanent primer for topcoats

Limitations

High costs
Requires a skilled applicator
Constant stirring required
  during application
Requires careful selection
  and application of topcoats
Stringent surface preparation
  requirements
Unsuitable for acid or alkali
  environments
May have special curing requirements

Zinc-Rich Organic Coatings. Several resins can be used to formulate zinc-rich organic coatings. These include epoxies, urethanes, and vinyls. In each case, the mechanism of curing is that of the apparent resin. These coatings may provide both barrier and cathodic protection to steel. They do not require as clean a steel surface and are easier to topcoat than inorganic zinc coatings.

Advantages

Provides excellent protection

Surface preparation less
  stringent than inorganic zincs
Easier to topcoat than inorganic
  zincs

Limitations

Requires skilled applicator
  to steel under many conditions

High cost
Constant agitation required
  during application
Unsuitable for acid or alkali
  service unless topcoated

7.6 SURFACE PREPARATION FOR PAINTING. Surface preparation is recognized as being one of the most important factors in coating performance and is about 45% of the total painting costs. Preparing a surface includes removing the contaminants that inhibit coating adhesion and providing a surface profile for tight bonding of the coatings.

Grease and oil will prevent tight bonding of coatings, as will loose dirt, dust, rust, scale, and chalk from old paint. Salt remaining on metal surfaces after cleaning may accelerate osmotic blistering. Salt can become trapped in metal pits and crevices where it is difficult to remove.

Mill scale is a bluish, somewhat shiny oxide residue that forms on steel surfaces during hot rolling. Although initially rather tightly adhering, it soon cracks, pops, and disbonds. Unless completely removed before painting, mill scale will later cause the coating to crack and expose the underlying steel.

While smooth surfaces may prevent a tight bonding of coatings, too great a surface profile may present coating difficulties for relatively thin primers. Pinpoint rusting occurs soon when peaks of blasted metal profiles receive only thin films of coating. The surface profile (distance between peaks and valleys) should be that recommended by the coating supplier. For metal structures requiring coating, this is normally 0.5 to 2.5 mils (thousandth of an inch) and never more than one-half the thickness of the primer. The profile height can be varied by changing the abrasive used in blasting.

7.6.1 Preparation Before Cleaning. Before actual cleaning and painting, all welds, edges, bends, and other sharp projections should be ground smooth and all crevices filled. Sharp edges cause coatings to draw thin. Crevices are also difficult to coat and are sources of early corrosion (crevice corrosion). Weld spatter must also be removed because it is loosely held.

All old loose paint must also be removed. A heavy build up of paint can produce a rigid system (“dead paint”) that is poorly bonded to the substrate.

There are many different methods of cleaning metal surfaces. The most commonly used cleaning methods are: solvents, hand and power tools, flames (thermal), steam cleaners, chemicals, abrasive blasting (wet and dry), and water blasting.

Solvent Cleaning. Is used to remove grease and oil that are difficult to remove by other methods. In some cases, solvent containing coatings can dissolve thin deposits of oil and incorporate them in the coating without adverse effects. This is never the case with heavy oil deposits or grease. The solvent is usually applied on rags. Change the rags when they become contaminated. The final rinse is always made with fresh solvent. The organic solvents used should not come into contact with the eyes or skin, be used near sparks or flames, or be inhaled unnecessarily. Solvent cleaned metals may require further cleaning before coating.

Hand and Power Tool Cleaning. Removes only loosely adhering paint, rust, and mill scale. It is slow and produces a burnished rather than a textured surface that permits only limited coating adhesion. Thus, it is used mostly for spot cleaning. Hand tools include scrapers, wire brushes, and sanders.

Power tools (electrical and pneumatic) clean much faster than comparable hand tools and are essentially a duplication of them in power-driven equipment. They include sanders, grinders, wire brushes, chipping hammers, scalers, and needle guns. They clean by impact, abrasion, or both. Cleaning of metal surfaces is less expensive using power tools than using hand tools, and less particulate contamination occurs than when abrasive blasting. Thus, they are used mostly for spot cleaning, where contamination of adjacent areas by abrasive blasting is unacceptable, and when a surface tolerant coating, such as an oil-based paint is used.

Flame (Thermal) Cleaning. Flames and electric heating guns are use only to remove loose scale or rust from metal surfaces. The surface is then cleaned to achieve the desired level of cleanliness. Extreme caution must be used to keep open flames away from flammable materials.

Steam Cleaning. Steam cleaners may be used to clean dirt and grime from coated surfaces, so that repainting may be unnecessary. High temperature and velocity wet steam can also remove heavy oil and grease. Commercial detergents can be added to the wet steam to improve the cleaning power. Steam-cleaned steel is then further cleaned by other methods before coating.

Chemical Cleaning. Chemicals can often be used to clean metals for coating. Alkaline cleaners remove grease, oil, and oil-based coatings from steel but can damage other metals. Solvent strippers are appropriate for removing other coatings. Baths can be used for dip cleaning of some metals. Chemicals can also be used to treat metal surfaces (e.g., phosphating) to promote coating adhesion.

Abrasive Blasting. Abrasive blasting is usually the preferred method of preparing steel and some other metal surfaces for cleaning. The impact of high velocity abrasive particles can completely remove all rust, scale, dirt, and old coating, but not grease or oil. It also roughens the surface to produce a texture that promotes tight coating adhesion. Aluminum and other softer metals require softer abrasives (e.g., plastic beads) for removing old coatings and not damage the metal. Because of the importance of abrasive blasting of steel, it is discussed in considerable detail in Paragraph 7.6.3.

Wet and Water Blasting. Water is sometimes added to the abrasive by using a ring water sprayer at the nozzle to reduce the amount of particulate dust produced in blast cleaning of steel. Chemical corrosion inhibitors such as sodium, potassium dichromate, or phosphate must be dissolved in the water to prevent flash rusting of steel before coating. The possible adverse effects of inhibitor residue on coating performance has not been established.

Water blasting, sometimes called "hydroblasting" is sometimes used to clean metal surfaces for coating. The water may be heated and detergent may be added to help with the cleaning. Power washing with pressures up to about 2,000 psi is effective in removing dirt and mildew on coated metals and is generally safe on adjacent wood and concrete/masonry. Bare steel can be cleaned with water pressures over 30,000 psi and water volumes of only 2 to 15 gallons per minute. Ultrahigh waterblasting begins at 20,000 psi. Abrasives can be added to the stream of water or used separately later to roughen the metal surface to achieve good coating adhesion. Extreme caution must be maintained with these high pressures. Again, corrosion inhibitors must be used in the water.

7.6.2 Recommended Cleaning Methods

Steel. The preferred method of cleaning uncoated steel is washing it with a solvent followed by abrasive blasting. The preferred method of cleaning coated steel is also by abrasive blasting followed by a solvent cleaning, if the coating is to be removed. Other cleaning methods such as hand or power tools are more practical for spot repair of coatings. The standards for different levels of abrasive blasting of steel and for alternative methods of cleaning are discussed in Paragraph 7.6.3.

Galvanized Steel. The recommended method of cleaning galvanized steel varies with the condition of its surface. Simple solvent cleaning is usually adequate for new, clean galvanized steel. If loose zinc corrosion products or coatings are present, they should be removed by bristle or wire brushing only as heavy as necessary for complete removal. If rust is present on older steel, it should be spot removed by abrasive blasting or wire brushing so as not to disturb remaining in-tact galvanizing. A thin coat (0.3 to 0.5 mils) of wash primer (see MIL-P-15328) is often used on new galvanized steel to promote adhesion of oil-based or latex coatings.

Aluminum and Other Soft Metals. New, clean aluminum and other soft metals may be cleaned for coating by solvent washing. Detergent washing may be required for removing dirt. Abrasive blasting with plastic beads or other soft abrasive may be necessary to remove old coatings. These metals, like galvanized steel, are sometimes wash primed to promote adhesion of oil-based or latex coatings.

7.6.3 <u>Standards for Cleaning Steel Surfaces.</u> The most frequently used written standards for cleaning steel surfaces are from the Steel Structures Painting Council (SSPC). They include standards for all common methods of cleaning. Volume I of SSPC's Steel Structures Painting Manual contains all the available standards, as well as other useful information. The National Association of Corrosion Engineers (NACE) has a set of standards for blasted steel surfaces similar to those of the SSPC. Pictorial standards NACE standard steel specimens encased in plastic are also available for determining the level of abrasive blasting. However, the written standards constitute the legal requirements for contract work.

The four grades of blast-cleaned steel are:

White Metal Blast -	100% free of oil, mill scale, rust, and paint SSPC SP-5; NACE Specification 1
Near White Blast -	95% free of residual stain and discoloration SSPC SP-10; NACE Specification 2
Commercial Blast -	Two-thirds free of stain and discoloration SSPC SP-6; NACE Specification 3
Brush-off Blast -	Only tight mill scale, rust, or paint remaining SSPC SP-7; NACE Specification 4

Before using the pictorial standards, you must first determine the grade of steel blasted, since different grades of steel blast cleaned to the same level will not look the same.

Rust Grade A - Adherent mill scale (tight scale with little rust)

Rust Grade B - Rusting mill scale (rusting started; scale flaking)

Rust Grade C - Rusted (mill scale easily removed; little pitting)

Rust Grade D - Pitted and rusted (no mill scale; visible pitting)

SSPC standards for steel surfaces cleaned by methods other than blasting are:

Method	**SSPC No.**	**Intended Use**
Solvent Cleaning	SP-1	Removes oil and grease before further cleaning by another method
Hand Tool Cleaning	SP-2	Removes loose mill scale, rust, and coating
Power Tool Cleaning	SF-3	Removes loose mill scale, rust, coatings faster
Flame Cleaning	SP-4	Preliminary removal of loose mill scale and rust from new steel before further cleaning
Pickling	SP-8	Removed mill scale and rust

Different types of coatings require different levels of cleaning. The most commonly agreed upon levels are:

Coating Type	**Minimum Surface Preparation**
Drying oil	Hand or power tool cleaning
Alkyd	Commercial blast
Coal tar	Commercial blast
Asphaltic	Commercial blast
Latex	Commercial blast
Vinyl lacquer	Commercial or near white blast
Chlorinated rubber	Commercial or near white blast
Epoxy	Commercial or near white blast
Coal tar epoxy	Commercial or near white blast
Urethane	Commercial or near white
Organic zinc	Commercial or near white
Inorganic zinc	Near white or white blast

For immersion or other severe environments, the higher level of two options should be used.

7.6.4 Abrasive Blasting Equipment and Procedures.

Conventional Blasting Equipment. Conventional, abrasive blasting equipment has five basic components: the air compressor, air hose, blasting machine, blast hose, and nozzle.

Air Compressor. The air compressor takes in, compresses, and then releases large volumes of air by piston or rotary action. The continuous and constant supply of high pressures and volumes of air to propel abrasives from the blasting pot and through the blasting hose and nozzle to the metal surface is one of the most critical parts of the blasting operation. The capacity of a compressor as measured in cubic feet per minute (cfm) is directly related to its horsepower rating. A flow of 170 to 220 cfm of 90 to 100 psi nozzle pressure air necessary for blast cleaning steel plate can be obtained with a 50 or 60 horsepower compressor. The rate of blast cleaning is directly related to the nozzle air pressure and volume. Sources of pressure loss include worn compressor parts, small diameter or long hoses (frictional losses), and couplings joining lengths of hose. A 10 psi drop in pressure will reduce the cleaning rate by 15%.

Oil and water traps are used to remove these contaminants originating at the compressor or other components that would otherwise be transferred to cleaned surfaces. These traps need to be inspected and cleaned frequently. Detection of oil and water contaminants cab be achieved with a simple blotter test. A clean, dry, white blotter is held 18 inches in front of the nozzle with only the air flowing for 1 to 2 minutes. Stains on the blotter indicate the presence of contaminants. A simple test to detect for oil contamination of an abrasive is to place a small amount of it in a glass jar, fill the jar with clean water and then shake the jar. A sheen that rises to the surface of the water indicates oil contamination. Such abrasives should be discarded.

Air Hose. The air hose delivering air from the compressor to the blasting machine need not be as durable as the blasting hose, because it is not eroded by abrasives or dragged along the ground. The air hose should have a large diameter (about 1-inch-ID when under 50 feet long) and short length. Exterior couplings are preferred to interior couplings; they effectively reduce hose diameters and increase frictional losses. Use as few couplings as possible to minimize possible air leaks.

Blasting Machine. The blasting machine or “sand pot” holds the abrasive. A valve on the bottom controls the amount of abrasive fed into the blast hose. The chief parts of a gravity-fed blasting machine are the: moisture separator, exhaust valve, filling head, metering valve, and hose/tank coupling. A continuous, uniform flow of abrasive (from an automatic metering valve) is required for efficient cleaning. Blasting machine capacities vary from 50 pounds to several tons of abrasive. Smaller machines require more filling time.

Blast Hose. The blast hose carrying the air and abrasive from the blasting machine to the nozzle must be sturdy, flexible, and treated to prevent electrical shock. A 4-ply blast hose with a 1.25 ID is sold in short, joinable sections to minimize frictional loses.

ID hose called a "whip" is sometimes joined at the nozzle. It is easier to handle, particularly in tight areas, but is not recommended, because its reduced diameter causes frictional losses of pressure.

Nozzles. Nozzles are available with several lengths, designs, sizes of openings (throats), and lining materials. Nozzle lengths of 5 to 8 inches are generally used for removing tightly adhering rust and scale. Shorter nozzles, 3 inches or less, are appropriate for behind beams and in other inaccessible places when a whip might be used.

The tapered shape of the venturi nozzle is more efficient than the cylindrical shape of the straight bore nozzle. The venturi creates a larger, more uniform blast pattern and can increase cleaning rates by 30 to 50%.

The orifice size is chosen according to the available volume of air. The largest practical size that does not permit loss of pressure is usually best. A 1/2-inch nozzle with proper air supply can clean four times the area of a 1/4-inch nozzle.

The lining, particularly at the orifice, is gradually worn away by the abrasive. Since enlarged openings reduce efficiency, the liner is usually replaced after the original diameter has increased by 50%. Tungsten, carbide, and Norbide liners may have service lives of 300, 750 to 1,000 hours, respectively, as compared to 6 to 8 hours for cast iron liners. Dropping or banging the more brittle tungsten, carbide, and Norbide nozzles can reduce their service lives. Nevertheless, they are much more economical to use in the long term.

All nozzles are equipped with "deadman valves" that permit blasting when they are depressed. If the operator drops the nozzle, the flow of air and abrasive is immediately stopped.

A hypodermic needle gage is used to measure nozzle pressure. It is inserted into the blast hose immediately in front of the nozzle in the direction of abrasive flow to minimize damage to it from the flowing abrasive.

Alternative Approaches to Blasting. Automatic cleaning by centrifugal blasting can be achieved in shops in a controlled environment. It utilizes machines with motor-driven, bladed wheels to hurl abrasive at high speed by centrifugal force. Its advantages over conventional blasting include: (1) savings of time, labor, energy, and abrasives; (2)

a superior, more uniform cleaning; (3) reduces blasting waste by recycling the abrasive several times; and (4) protects the environment.

A centrifugal blast cabinet with four 25-hp wheels can throw 2,400 pounds of abrasive per minute. The amount of abrasive throw requires 33 conventional blasters. Portable centrifugal blasting equipment is also available for regular steel surfaces like the decks of ships or sides of storage tanks.

Vacuum blasting systems are now available which collect, clean, and recycle abrasives. Production is slow but very effective in eliminating blasting dust, cleaning welds, and reducing hazardous waste from toxic paints.

Another approach of avoiding contamination of the environment with blasting dust is to conduct the blast cleaning in an enclosed building where particulates are trapped and collected and the abrasive can be cleaned and recycled.

Blasting Procedures

Choosing Abrasives. Abrasives are available in a variety of sizes, shapes, hardnesses, and breakdown characteristics. The proper abrasive for a particular coating is one that provides the necessary cleaning and profile at a good rate, and permits the coating to perform well.

A larger size abrasive will cut deeper than a smaller size abrasive, but the greatest rate of cleaning is achieved with as small a size as possible to give the desired surface. Particles in the 40- to 50-mesh range are commonly used today. Those larger than 16- to 18-mesh have a slow clean rate and may gouge the surface; those 100-mesh or finer may not be able to give the desired profile.

The size and shape of the abrasive is responsible for the type of blasted profile produced. Round shot tends to peen the steel surface to a wavy profile. It is effective in removing brittle deposits, such as mill scale. Grit is angular and so produces a more jagged finish, generally preferred for tight coating adhesion. The variety of grit materials available produces a variety of surface patterns. Sand and slag abrasives are semiangular and produce surface patterns somewhere between those for shot and grit.

Hard abrasives cut faster and deeper than softer or more brittle ones. A hard, but brittle abrasive tends to shatter on impact, which reduces its cleaning rate.

The manner in which abrasive particles fracture and change shape upon impact is called their breakdown characteristic. It limits the number of times recycling is possible, the amount of particulate dust emitted into the air, and the amount of dust that must be removed from the cleaned surfaces before coating.

The four types of abrasives used are:

1. Natural Oxides. Silica, the most widely used oxide, is readily available, cheap, and effective, but health concerns are greatly restricting its use. Starblast, another natural oxide, is fast cutting, has less breakdown and dusting, and may be recycled.

2. Metallic Abrasives. Steel shot and grit abrasives are efficient, hard, and dust free. Care must be taken to keep them dry during storage to prevent rusting. Indeed, all abrasives should be stored in their original sealed bags on pallets off the ground until ready for use. Impacting steel shot may cause small slivers called "hackles" to form on steel surfaces. They may extend up to 6 mils and so must be removed by grinding or sanding before coating to prevent later pinpoint rusting.

3. Slag Abrasives. Copper and nickel slags, by-products of the ore smelting industry, are fast cutting but have a high breakdown and cannot be recycled.

4. Synthetic Abrasives. Aluminum oxide and silicon carbide are non-metallic abrasives with cleaning properties similar to those of metallics but without the rust problem. They are hard, fast cutting, and low dusting but expensive and must be recycled to be economical.

Blast Cleaning Techniques. Some of the important items to remember are:

1. Angle of Attack. The nozzle to surface angle may range between 45 and 90 degrees depending on the work. An 80- to 90-degree angle is suitable for removing rust and mill scale and cleaning pits. A slight downward angle will direct the dust away from the blaster and permit better visibility. A 45- to 60- degree angle is best for peeling away heavy layers of coating or rust. General cleaning is best done at 60 to 70 degrees.

2. Nozzle-to-Surface Distance. The closer the nozzle is to the work, the denser the abrasive will be, but the blast pattern will be smaller. While a close distance (e.g., 6 inches) may be necessary for removing tight scale, 18 inches or more may be more appropriate for removing old paint and for general cleaning.

3. Straight Line Passes. Each pass with the blast nozzle should be in a straight line at the same distance from the surface. Arcing or varying the distance from the work will produce non-uniform cleaning.

4. Coating Cleaned Surfaces. No more steel should be blasted than can be coated that day, since rusting can occur overnight. On hot humid days, flash rusting may

occur in a few hours. If this occurs, the rust must be removed by brush blasting before coating.

It only takes one spray painter to keep up with four blasters, so the work must be properly scheduled.

7.7 APPLICATION OF COATINGS. The basic choices for applying coatings are brush, roller, and spray. Selecting the most appropriate method for a particular job is not so easy today, because the modern high-performance, VOC-conforming coatings are more difficult to apply than coatings previously used. The following considerations must be made before selecting the application method:

Application methods appropriate for the particular coating.

Desired appearance.

Ease and speed of application.

Simplicity of equipment and required operator skills.

Safety/environmental requirements.

Economics of application.

If the coating like inorganic zincs can only be applied by spray, the application choices will be limited. Such coatings are also likely to require highly skilled operators for specialized equipment. Ease and speed of application will affect the ability to provide not only an economical but also a quality, cosmetically acceptable finished product. Safety and environmental restraints may limit the available methods to those with high transfer efficiencies or require safety gear than will slow operations. Some of these factors may be much more important than others.

The relative rates of different application rates are given below:

Application Method	**Square Feet Applied in 8-Hour Day**
Brush	1,000
Roller	2,000 to 4,000
Conventional Air Spray	4,000 to 8,000
Airless Spray	8,000 to 12,000

In contract painting, the contractor is usually given his choice of application method. We, however, should be aware of the problems associated with the particular method he chooses for his work plan and advise him of any concerns we may have about this method.

7.7.1 Brush Application. Brushing is an effective, relatively simple coating application method. It is particularly good for priming, since it works the paint into the surface's irregularities. Because it is slow, brushing is used primarily for touch-ups, small areas (e.g., trim), complex configurations, or where overspray may be a serious problem. It does not produce a very uniform thickness.

Natural brush bristles of good quality are preferred for paint brushes, but synthetic filaments resistant to strong solvents may be also be satisfactory. Bristles that are naturally or artificially flagged (with split tips) are preferred, because they hold more paint. Nylon and polyester filaments are more water resistant than natural fibers and so are preferred for latex paints.

Brushes can leave brush marks in paints that do not level well. They may also leave areas of low thickness. Thus, a second coat should be applied at right angles to the first in order to minimize overlap of brush marks or thin areas. Additional coats should be applied at right angles to the previous coat.

Tips for painting with brushes are:

Shake loose any unattached bristles by spinning the brush between the palms of the hand.

Remove any stray bristles with a putty knife.

Dip the brush to cover one-half the bristle length. Too much paint may wet the heel of the brush and run down the handle.

Remove excess paint by tapping the brush on the edge of the can.

Apply paint with a light touch. Use the bristle tips rather than pressing down hard; this will minimize brush marks.

Work from the dry to the wet surface; this will minimize lap marks.

Hold the brush at a 75-degree angle to the surface; this produces the best results.

7.7.2 Roller. A roller is best used on large, relatively flat areas that do not require the smooth surface or uniformity received from spraying and in interior areas where overspray may present a masking or cleaning problem. The nap fiber length normally varies between 1/4 to 3/4 inch. A longer nap holds more paint but does not give as smooth a finish. Thus, it is used on rougher surfaces. Rollers with extra long naps (1-1/4 inches) are used to coat chain link fences. Handle extensions 10 feet or longer allow the painter to reach high areas but usually at a reduction in application quality.

The roller cannot penetrate pores, cracks, or other surface irregularities as well as a brush. Also, rolling can mix air into the paint to permit moisture to penetrate the cured film. Lacquers are difficult to apply by roller because of their rapid solvent evaporation, particularly on warm days.

Tips for painting with a roller are:

For thick-bodied coatings, dip the roller directly in the paint container; for thin-bodied coatings, use a roller tray.

Load the roller uniformly for even application at the desired thickness. Too little or too much coating may cause tracking or skidding.

Do not apply heavy pressure to the roller.

Apply the second coat at right angles to the first to avoid areas of low thickness or holidays.

7.7.3 Spray.

Conventional Air Spray. Air spray features the finest atomization and finish and the greatest versatility. The basic parts of conventional air spray equipment are: air compressor, paint tank, hoses for air and fluid, and spray gun.

The air compressor powers the conventional air spray equipment. It must continuously supply both adequate air pressure for paint atomization and uniform flow of paint to the spray gun. Air pressure and flow are directly related to each other. If one drops, so does the other. The air flow, measured in cfm, must be great enough that the pressure does not drop during triggering to give short bursts rather than a continuous stream of atomized paint. Pulsation indicates an inadequate air supply. The air supply must also provide power for agitators or other accessories. Data sheets of paint suppliers provide information on recommended spraying pressures (and thus necessary compressor capacities), air caps, and fluid tips. Oil and water in the air supply must be removed by separator or extractor attachments to provide clean air.

The tank that holds the paint material (usually in a paint pail) has an air compressor to control the operational pressure. Some tanks have agitators that continuously mix the paint to prevent settling of heavy pigments. When large quantities of material are required, a pressure pump can be used directly in the paint container.

The air hose carries the compressed air, and the fluid hose carries the paint to the gun. An air hose with too small an ID can cause the air line pressure to drop and starve the gun. As with blasting hoses, frictional losses of pressure can be minimized by using relatively large diameter and short hoses. Avoid kinking or compressing these hoses. A large diameter may be necessary on a long hose to maintain adequate air pressure. The ID of the hose from the compressor to the pressure tank is usually at least 3/8 inch and the ID of the hose from the pressure pot to the gun should be at least 5/16 inch.

The ID of the fluid hose is determined by the necessary volume and pressure of the particular paint at the gun. Heavy paint may require as large an ID as 1/2 or 3/4 inch. Small guns often use a 1/4 inch ID fluid hose. The hoses must be resistant to the paints and solvents that flow through them.

The conventional spray gun is relatively complex and requires a great deal of skill to operate. The basic parts of a spray gun are: air nozzle or cap, fluid nozzle or tip, fluid needle, trigger, fluid adjustment valve, air valve, side port control, gun body and handle, air inlet, and fluid inlet. Supplier instructions provide much information on their operation.

Most spraying problems are related to improper or inadequate cleaning of guns. Recommended maintenance items include:

Lubricate the air gun daily.

Wash the gun body with a rag dipped in solvent. (Only wet the front end of the gun with solvent. The solvent will remove lubricants and dry out the packing.)

Unclog nozzle by washing it separately in solvent. Use only a pipe cleaner, broom bristle, or match in cleaning the hole to prevent damage.

Never use oils or lubricants containing silicone.

With conventional air spray, outer jets of air atomize the paint. The external mix air nozzle is almost always used. The external mix nozzle is used for production work that does not require a fine finish. They are not used with catalyzed or fast drying paints, these paints tend to clog the nozzle.

A proper spray pattern when the trigger is fully depressed may be round or “fan” shaped (a long oval). As long as the fluid and air pressure remain the same, the amount of sprayed paint will remain the same. Increasing the pattern size decreases the paint thickness and vice versa. The ideal spray pattern for production work is a long oval with clearly defined edges and little overspray or rebound. The individual particles of atomized paint should be uniform in shape, size, and distribution. Spray pressures should be kept as low as possible for such a pattern.

Special spray equipment may be designed to apply thick paints. This includes heating accessories to reduce paint viscosities and components for mixing of metered components at the gun. Guns on extension arms permit spraying in difficult to reach places. It is considered a better technique to use scaffolding to get to such areas, if at all possible.

Airless Spray. Airless spray features the greatest production rate and consequently the greatest economy. The basic parts of airless spray equipment are: high-pressure paint pump, fluid hose, and airless spray gun.

A high pressure pump forces paint from the container to the spray gun and atomizes it into a spray. It is rated according to the ratio of paint pressure produced to the air pressure that produced it. Thus, a pump that delivers a paint pressure of 30 psi for each psi of air pressure from the compressor has a 30:1 ratio. There must be sufficient pressure and material flow to produce a constant spray of paint.

The fluid hose must be able to withstand the high pressures necessary to deliver the paint to the gun and atomize it. While pressures of 1,800 to 3,500 psi are commonly used, most air hoses can handle pressures as high as 5,000 psi. A 1/8- to 1/4-inch ID hose is used for medium viscosity paints, and 3/8- to 1/2-inch ID for high viscosity paints.

The airless spray gun is basically a fluid nozzle with a valve. **A** spray tip filter screens out particles that might clog the tip. Each spray tip is designed for a particular spray pattern. Indeed, changing tips is the only way to change the spray pattern. The orifice size (0.007 to 0.0072 inch) controls the atomization and the amount of fluid delivered. The tip angle (10 to 80 degrees) controls the fan width. Tips with the same orifice size but different angles will deliver the same amount of paint but at different fan widths and thicknesses. A large spray pattern is required for a high application rate. Paint viscosity is the chief factor in selecting a particular tip.

Airless spray guns may be powered by electricity, gasoline, or compressed air. As with conventional air spray, a good pattern will have a smooth oval outline, clearly defined edges, and a uniform distribution of paint particles. However, a round pattern is not acceptable. To correct a faulty airless spray pattern tips, filters, or atomization pressures may need to be replaced or adjusted.

Air-Assisted Airless Spray. Air-assisted airless spray uses compressed air to assist in the atomization of paint from an airless system. It makes it easier to apply heavy products.

Electrostatic Spray. Electrostatic spray can apply coatings to hard-to-coat conductive surfaces with minimum loss of paint. This ability to paint "around corners" permits a painter to coat very complex configurations. It can be used for airless or conventional air application. A charged probe is used for external ionization of the atomized paint, which is attracted to a grounded surface. It presents no safety hazard to properly trained personnel. Electrostatic spray has the following features: ability to wrap around edges and irregular surfaces; increased transfer efficiency (lower material usage), more uniform paint application, and less overspray.

Thermal Spray of Metals. Equipment and techniques are available for the thermal (flame or electric arc) spraying of metal coatings on steel. The metals are melted, and the molten metal is sprayed to produce a porous coating that protects by cathodic protection. For longer protection, they may be sealed with a thin conventional organic coating or silicone. Aluminum and zinc are the most frequently used thermal sprayed metals. Zinc presents a health hazard and so is seldom sprayed by the Navy. A very clean steel surface is required for coating. Metal spray coatings are normally very abrasion resistant.

Powder Coatings. Organic polymers (e.g., epoxies and acrylics) in powder form can be applied to a conductive (usually metal) surface and fused to it by heating in an oven at a predetermined temperature to form a tough, corrosion resistant coating. Application is done by electrostatic spray to a preheated metal component to permit the powder to stick to it before fusing. Application can also be done in a fluidized bed. In addition to being free of organic solvent, the system has a high transfer efficiency. Any powder not sticking to the metal surface can be collected and blended with virgin powder and used again.

7.7.4 **Recommended Spraying Procedures.** The recommended aspects of paint spraying, for both airless and conventional air spray are described below.

Stroking. Stroking during spraying should be done with the gun, wrist, arm, and shoulder at right angles to the work and moving parallel to it. This prevents "'arcing," varying the distance of the gun to the work, which results in variation of the paint thickness. For large, flat surfaces, each stroke should overlap the previous one by 50%. This produces a relatively uniform surface and eliminates holidays at the ends of the fan.

The stroke length should be from 18 to 36 inches, depending on the sprayer's arm length and comfort. Long areas should be divided up into smaller sections of appropriate length. Each section should slightly overlap the adjacent ones.

Triggering. The stroke of the spray gun should begin before the gun is triggered and continue briefly after releasing the trigger. This produces a smooth, continuous film without a heavy build up of paint at the start and end of each stroke. It also helps keep the fluid nozzle or airless tip clean.

Distance. The amount of material delivered and the atomization pressure determine the proper gun-to-surface distance for a uniform, wet film. It is usually about 6 to 12 inches for conventional air spraying and 12 to 15 inches for airless spraying. If the gun is held too close to the surface, the paint can sag or run. If the gun is held too far from the surface, a dry spray with a sandy finish and holidays (pinhole or skip areas) may result.

Corners. Each side of inside corner should be sprayed separately. A vertical stroke on one side, followed by a short horizontal stroke on the other will usually result in a relatively uniform coating. Spraying directly into the corner will produce a film of varying thickness, thinner in the corner and heavier on the sides.

An outside corner is sprayed directly when the sides are sprayed. This results in uniform paint thickness, without lap marks.

7.7.5 Storing and Mixing of Coatings Before Application.

Storing Coatings. Proper storage of coatings will protect these costly products from premature deterioration and minimize fire hazard. Long term storage should be in a room or building isolated from other work areas. The room or building should be dry, well-ventilated, and protected from sunlight, sparks, and flames. Shelves or pallets should be used to keep the cans up away from the dampness of floors. Labels should be kept in tact and free of paint to permit easy identification. Material safety data sheets (MSDSs) should be available for each coating and solvent stored, as required by law. Stocks of coating should be rotated and used so that old ones are used first, and no coating should be kept more than 1 year after manufacture. Once opened, the contents of a can should be used before opening up another can of the same coating. Coatings stored for more than 1 year should be checked for quality, as described in Paragraph 7.8, before using.

No more coating should be taken to the job site than is actually required. It should also be protected from the weather. Water-borne coatings can freeze in cold weather and can be damaged permanently.

Mixing Coatings. During storage, the coating's heavy pigments tend to settle and cake at the bottom of cans. These coatings must be reblended to their original uniform consistency before applying to obtain complete curing and satisfactory film properties. Mixing of coatings may be done either manually or mechanically, the latter usually being preferred, especially with volumes of 5 gallons or more, in order to insure thorough blending.

1. Mixing Single-Component Coatings. Single-package coatings are mixed as follows.

Pour the thin upper portion of settled paint into a clean container the same size as the original can.

Stir the settled portion of paint with a strong, clean paddle to break up the pigment and lift it from the bottom.

Break up paint clumps by rubbing them against the inside wall of the can.

Use a “figure 8” movement to mix the paint thoroughly.

Change the mixing to a lifting and beating motion.

Gradually return the thin, upper portion of paint to the original container, stirring continuously.

When the paint appears to be well mixed, “box” the paint by pouring it back and forth between the two containers until it reaches a smooth, uniform consistency.

Avoid excessive mixing of latex paints. Excessive mixing may entrap air and cause foaming.

No more paint should be mixed than can be used that day. Unused portions of paint should be combined and stored in a single, covered container. It should be mixed again before using.

2. Mixing Two-Component Coatings. Two-component coatings must be mixed in the correct proportions and in the manner specified by the supplier in order to achieve optimum film properties. Most suppliers package the kits in the correct mixing ratio. The chemical reaction that starts when the two components are mixed and continues long after curing to a solid film. Some two-component products require an induction period, such as 30 minutes, to allow the reaction to achieve a necessary reaction stage before applying the coating. The curing reaction is greatly accelerated by higher temperatures thus greatly reducing the pot life (the time period during which the coating can be successfully applied). The larger the batch size mixed, the greater will be the exotherm (temperature rise), and the shorter will be the pot life. If pot life is exceeded,

the coating may harden in the pot, lines, or gun. Mixed coatings not used at the end of the day cannot be kept over night. The mixed coatings must be discarded.

Two-component are mixed as follows.

Stir the base component (usually Package A) with a clean paddle to disperse pigment lumps that may have settled. (Five minutes is usually adequate.)

While continuing to stir, slowly add all of Package B (usually called the catalyst, co-reactant, or curing agent) which is frequently unpigmented. (The mixing container must be large enough to hold both components.)

Agitate the two mixed components with a manual or power stirrer until smooth.

Note: Vary these instructions if specified by the supplier.

Environmental Conditions and Thinning (Reducing) Mixed Coatings. Properly formulated coatings seldom require mixing when applied in the recommended temperature range. Most coatings should be applied between 50 and 90°F. However, the best temperature range for conventional spraying is 60 to 80°F, and airless spraying can be used at 90°F. Lacquers such as vinyls and chlorinated rubbers can be applied at temperatures as low as 35°F. The coating's temperature being applied should always be as high as that of the surface being coated but not significantly higher, unless formulated for hot application.

The coating being applied should have a viscosity level for proper application. Three factors may affect viscosity: (1) solvent/solids ratio; (2) coating temperature: and (3) mixing of thixotropic coatings.

The solvent/solids ratio is established by the coating supplier, so that no thinning is usually necessary. The colder the coating, the greater will be its viscosity. Thus, it is generally best to warm cold paints rather than thin them to achieve proper application viscosity. Should thinning be necessary, the type and amount of thinner specified by the supplier should be used. The amount is not ordinarily more than 1 pint per gallon of coating and should not cause the coating to exceed the VOC limits discussed in Paragraph 7.4.1. With two-component coatings, viscosity of the mixed products is important, not the viscosities of the original components.

Some coatings called "thixotropic" or "false-bodied" reach the desired viscosity after being stirred or agitated. They seem very thick in the can but when stirred become more fluid, so that they can be applied. On further standing, the viscosity will increase until the coating reaches its previous gel-like stage. Thus, thixotropic coatings may require continual agitation during application.

In order to prevent condensation of moisture from the air on wet paint, it should be applied only when the temperature is at least 5°F above the dew point and rising. Also, coating should never be applied when the prevailing wind is blowing 15 mph or greater or when the temperature is expected to fall below freezing, before the coating is fully cured.

7.8 INSPECTION OF PAINTING. Inspecting contract painting work is done to verify that the requirements of the specification are met in full and that a quality product has been obtained. Obviously, the latter requires that the specification has been properly prepared. Any apparent errors, omissions, or potential problems should be brought to the attention of the contract officer. Before work has begun, there should be a pre-construction conference to be sure that there is a complete understanding of what is expected. At this time, the inspector should become aware of the times when critical items of inspection must be made and that the areas to be inspected will be accessible and checked before the work proceeds further. The inspector's daily reports must be complete and clearly written, since they may become legal evidence. Any field changes must be written and approved by the contracting officer.

7.8.1 Inspection of Materials. The coating materials must be inspected before work is started to insure that there are sufficient quantities of each product to fulfill all requirements and that they are of the specifications or brands required. The amount of each material required can be determined from the coverage rate given on the supplier's data sheet or by calculation. Use the 16,000 ft^2/gal as the wet film covering rate of paints, if the volume of solids in the wet paint is known. Along with the data sheet and label identification, each material must have a material data safety sheet. The material should be stored off the ground or floor, protected from the weather, and away from a source of sparks or flame. If laboratory testing of products is required, it should be verified that each product meets its specification requirement. If testing was not required, two l-quart authentic samples of each product should be taken and stored during the warranty period, normally 1 year, to be tested should a problem arise.

7.8.2 Inspection of Surface Preparation. Industrial standards should be used for surface preparation, whenever they are available. For steel surfaces, the standards are normally those of the Steel Structures Painting Council (SSPC). These include:

SSPC-SP 1 - Solvent Cleaning
SSPC-SP 2 - Hand Tool Cleaning
SSPC-SP 3 - Power Tool Cleaning

SSPC-SP 5 - White Metal Blast Cleaning
SSPC-SP 6 - Commercial Blast Cleaning
SSPC-SP 7 - Brush-Off Blast Cleaning
SSPC-SP 8 - Pickling
SSPC-SP 10 - Near-White Blast Cleaning

The standard chosen should be the one appropriate for the coating and the environment, as recommended by the coating supplier or by the guide specification used. SSPC-SP 5 or 10 are normally specified for high-performance coatings. All four blast cleaning standards require solvent cleaning (SSPC-SP 1) to remove grease and oil before blasting. Visual standards are available from SSPC and others to assist in verifying the level of blast cleaning. Different visual standards are available for different conditions (extent of rusting) of the steel. Hand and power tool cleaning are most frequently used for touch-up or when abrasive blasting cannot be used.

The supplier of the primer or the guide specification may also recommend a particular abrasive for blasting or a particular profile for the blast cleaned surface. The latter is obtained by selecting an appropriate abrasive. To verify that the specified profile height has been received, it will be necessary to use a comparitor, profilometer, or test paper.

7.8.3 Inspection of Coating Application. It is customary to test for appropriate weather conditions before starting to apply any coating. Temperature can easily be checked with a thermometer and humidity with a sling psychrometer to determine if they meet specification requirements. The temperature should always be at least 5°F above the dew point and rising, to prevent condensation of moisture on the wet paint. Also, exterior spray painting should not be started, if the wind affects the spray’s pattern.

By determining the wet film thickness of a coating, you can determine if the specified dry film thickness will be received. Several types of wet film gages are available. Since such measurements disturb the wet film, it will have to be repaired before continuing.

Several types of magnetic gages are available for determining if the dry film thickness meets specification requirements. They should all be checked for calibration before using. The Tooke gage is a destructive gage (cuts into the coating film) for determining dry film thickness on any substrate surface.

Electrical holiday detectors are used to locate holidays or other imperfections in coatings on metal or other conductive surfaces. The low holiday detector (e.g., 67 volts) is normally used on coatings less than 10 mils thick, and the high voltage detector on thicker coatings such as those used on underground piping.

7.8.4 Final Acceptance Inspection. A thorough inspection should be made to determine if all specification requirements have been met before final acceptance. All previously noted deviations should be corrected.

7.9 PREMATURE COATING FAILURES. All coatings eventually fail. Of great concern are those that occur within the warranty period (normally 1 year) or well before expected. Obviously, problems should be corrected as soon as found to minimize the extent of damage. There are two general types of early failures: those that affect the surface coating only and those that expose the underlying substrate surface.

7.9.1 Topcoat Failures. Topcoat failures may be only cosmetic, if they occur on the surface of the coating. Examples of such failures are blushing, bleeding, and fading. They can be corrected by properly applying an additional coat of the topcoat.

Failures that completely penetrate the topcoat are more serious. Examples of these are intercoat peeling and blistering. If the failure is not extensive, the areas of damage may be removed and the spot repaired.

7.9.2 Failures That Expose Substrate Surface. Failures that expose the underlying metal are very serious, since the metal may corrode and undercut the surrounding film. Examples of this failure are cracking and peeling to the metal.

Corrective actions depend on the severity of the problem. For limited or localized damage, spot cleaning and repair may be suitable. Cleaning is best accomplished by abrasive blasting but hand or power tool cleaning may be adequate. For extensive damage (e.g., 20% or greater), it is ordinarily best to remove all the existing coating by abrasive blasting and completely recoat.

7.10 MAINTENANCE PAINTING. Most painting operations consist of maintenance painting. Because of the great expense of total repainting and disposal of old paint, it is best to use and maintain high-performance coating systems as long as possible. Coating systems should be selected for easy maintenance.

7.10.1 Compatibilities. The maintenance painting of existing coated metal structures requires that a compatible coating be applied. If it is incompatible, early coating failure may occur. Cause of incompatibility include strong topcoat solvents lifting existing coatings, strong topcoat solvents causing bleeding of existing bituminous coatings, and inability of new rigid topcoat to expand and contract with flexible undercoat. It is best to topcoat existing paint with the same type of coating as already on the structure. If this is not possible, the topcoat should be of the same generic type or cure by the same mechanism. The one exception to this rule is repair of inorganic zinc systems. Zinc rich-organic coatings are used to obtain good adhesion to both exposed steel and surrounding organic topcoat. If there is any concern about incompatibility of the new coating, it is wise to apply a test patch about 1 ft^2 in size over the existing paint and check for incompatibility problem that should occur within a few days.

7.10.2 Spot Repairing. Spot repairs require cleaning of exposed metal and surrounding tightly adhering topcoat(s). The coating edges at damaged areas should be "feathered" (beveled) to achieve good adhesion of the patch and provide an attractive finish. Primer and topcoats used in these repairs should completely cover the metal and overlap onto the existing coating system to prevent weak joints of new to old coating.

7.11 PAINTING SPECIAL STEEL STRUCTURES.

7.11.1 Fuel and Water Storage Tanks.

Interiors. Interiors of steel fuel and water tanks should be cleaned for coating by abrasive blasting to a white or near white metal finish (i.e., SSPC-SP 5 or 10). The cleaned steel should then be coated with three coats of the epoxy-polyamide (see MIL-P-24441) each applied at 3 mils dry film thickness. Formula 150 green primer should be followed by Formula 156 red intermediate coat (Formula 151 gray is also suitable for fuel tanks but not potable water tanks) and Formula 152 white finish coat.

Exteriors. Exteriors of steel fuel and water tanks should be coated as described for their interiors except that the finish coat of Formula 152 should be replaced by 1-1/2 mils dry film thickness of white (see MIL-C-85282) aliphatic polyurethane. The latter provides good exterior weathering.

7.11.2 Piping.

Underground. Underground piping can be coated with a variety of thick coatings or wraps. These include extruded and fusion-bonded coatings and plastic and heat-shrinkable tapes. Coal tar and asphalt materials are not applied very much any more because of health and safety concerns. They are best applied in a shop under controlled conditions. They should be checked for holidays both immediately after application and above the ditch before burial. Required properties include: good electrical insulation, good moisture (barrier) resistance, easy application and field repair, good adhesion, resistance to damage during handling, and resistance to cathodic disbonding.

Above Ground. Coating piping located above ground should be done as previously described above for steel fuel and water tank exteriors.

Underwater. Coating piping located underwater, should be done as previously described for steel fuel and water storage tank interiors.

7.11.3 Waterfront Structures.

Steel waterfront structures (e.g., piling and other pier structures) are normally coated with the epoxy-polyamide system previously described for steel fuel and water tanks interiors. An alternative system is two coats of SSPC Paint 16 (coal tar epoxy-polyamide) applied to a total of 16 mils dry film thickness over a near-white (SSPC-SP 10) abrasively blasted surface.

7.11.4 Antenna and Other Tall Towers and Supporting Equipment.

Towers. Because of the extreme expense of repainting steel antenna towers, it is best to apply and maintain a high-performance coating system. If possible, the primer or the total system should be applied in a shop under controlled conditions and touch up the damaged coating areas after erection in the field. A recommended coating system consists of one coat of zinc-rich epoxy (SSPC Paint 20, Type II), one coat of epoxy-polyamide (MIL-P-24441) Formula 150 green primer, and one coat of white aliphatic polyurethane (MIL-C-85285).

Anchors and Guys. Anchors and guys can be protected by applying a petrolatum paste that encapsulates the metal. A special applicator has been developed for remote application of steel guy lines with petrolatum paste. Alternatively, anchors may be coated as described for the exteriors of steel fuel and water storage tanks.

7.12 PAINTING GALVANIZED SURFACES. Because new galvanized steel is smooth and may contain oil to protect it during storage, it is difficult to get coatings to bond well to it. Weathered galvanizing that has developed a surface texture is much easier to coat. Historically, galvanizing has been wash primed and coated with two coats of alkyd or latex coating. Because wash primer and the recommended alkyd coating are no longer considered environmentally acceptable, this method is no longer applicable. Latex coatings may, however, be applied to weathered galvanizing. A much better performance will be received from one coat of epoxy-polyamide Formula 150 green primer and one coat of aliphatic polyurethane (MIL-P-85285). New galvanizing should always be solvent washed (SSPC-SP 1) before coating. Weathered galvanizing should be washed to remove all loose surface contamination before coating.

7.13 PAINTING ALUMINUM AND OTHER NONFERROUS METALS. In the past, aluminum and other nonferrous metals were frequently wash primed and coated with alkyd. Because this system is no longer environmentally acceptable, a two or more coat epoxy (MIL-P-24441) is recommended.

7.14 PAINTING SAFETY. Because coating operations are frequently hazardous, special safety precautions must be taken. Local safety offices can provide detailed information and safety equipment.

7.14.1 High Places (Scaffolding, Lifts, Nets, and Lines). Workers in high places should be protected by life lines or nets. Scaffolding should be the required design, and instructions on their use should be followed.

7.14.2 High Pressures.

Abrasive Blasting Respirators/Training/Physicals. Abrasive blasters should have the necessary safety training, equipment, and physical examinations to meet all prevailing safety requirements.

Waterblasting. Waterblasting equipment must have a safety certificate and must be used as described in the instructions.

Airless Spraying. Airless spray guns should always be used with safety guards. Back flushing with solvents should be done only when special adapters for this purpose are used.

7.14.3 Flammable Materials. Flammable paint materials should be stored in accordance with local safety requirements and used in enclosed areas only with grounded equipment and structures and with nonsparking electrical fixtures. Proper ventilation of vapors is required.

7.14.4 Toxic Materials. Toxic paint materials must be stored in accordance with local safety requirements. Clothing and respirators should be used to avoid contact and inhalation. Exposure time should be limited as much as practical.

7.14.5 Caustic Materials (Acids, Alkalis, Steam). Acids, alkalis, and steam can cause serious burns. Gloves, face shields, and protective clothing should be used when working with them.

7.14.6 Safety Plan. All shops conducting cleaning or application operations should have a safety program. This program should include first-aid and safety training related to these operations to keep all workers aware of hazardous conditions and methods to provide protection from the hazards.

CHAPTER 8. CORROSION RESISTANT METALS

8.1 SELECTING METALS FOR CORROSION RESISTANCE. Selecting metals for their resistance to corrosion should be considered as a part of the overall material selection process. Corrosion resistance as well as strength, ductility, fabricability, availability, and cost are all factors that must be considered in selecting a material. In this chapter, the corrosion resistance and applications of many of the metals that are commonly used in shore facilities will be described. However, in order to make specific materials selections, detailed information on the corrosion properties as well as other materials properties must be obtained and evaluated.

8.2 APPLICATION OF CORROSION PERFORMANCE DATA TO SELECTION OF MATERIALS. Materials performance data, whether based on the analysis of previous successful or unsuccessful application or on corrosion testing must be carefully integrated into the design process. Only through an understanding of how the type and amount of corrosion that is likely to occur in specific locations in a system will affect the function of the system can corrosion failures be avoided.

8.2.1 Materials Selection as Part of the Design Process. Material selection is often performed only toward the end of the design process. In some cases, due to material availability, fabrication problems, or even after initial use or test has shown that the originally specified material is unsatisfactory, the first attempt to solve the problem is to change the material without changing the design. This often results in a less than optimum match between material properties and the requirements of the application. In some cases, this process results in a materials “overkill” that has an adverse impact on cost, fabrication difficulties, and use of non-standard components with attendant problems in obtaining spares.

8.2.2 Designing to Fit Available Materials. In many cases, it is appropriate to identify those materials that have suitable corrosion properties for a specific application, then design a system based on the properties of the available materials. This is often more effective than selecting materials that have the properties required by a given design.

8.2.3 Use of Corrosion Data. Corrosion data. whether from experience or from testing, must be used in a systematic manner. Corrosion data are used to quantitatively predict the amount and distribution of corrosion that will occur on a given component in a given application. Whether the design is performed in a “materials first” or “design first” manner, some quantitative corrosion data must be used. It is important to understand how the data were obtained in order to best apply it to design.

8.2.4 Definition of Required Material Properties. In order to select materials, limits for material performance must be established. While requirements for such properties as strength and ductility are relatively easy to define, requirements for such properties as corrosion resistance and fabricability are often less easy to define quantitatively. For corrosion resistance, high levels of resistance to certain forms of attack such as crevice corrosion, can be identified as a specific requirement with resistance to other forms of attack being less important. A list of specific critical properties for a specific application with "desirable" and "acceptable or threshold" requirements for these critical properties is often useful in selecting materials for specific applications.

8.2.5 Determination of Acceptable Performance. In many cases, a material will be selected that will perform adequately for a given service life but will deteriorate significantly during that service period and will either have to be repaired or replaced if the application is repeated. In this case, the performance could be considered adequate but not desirable. In many cases this is appropriate. In cases where repetitive or extended application is anticipated, select a more corrosion resistant material that will not require repair or replacement for re-use.

8.2.6 Sources of Corrosion Data. Corrosion data are available from a wide variety of sources. However, it is not available from any single source. Data from similar service performance, corrosion testing, or corrosion theory can all be used if properly interpreted and applied.

Service Performance. Data from previous service performance often address many of the anticipated corrosion related factors but are often qualitative in nature. As discussed in Chapter 3 of this manual, in-service material performance must be properly evaluated in order to be useful in design.

Corrosion Testing. Data from corrosion tests are usually very quantitative in nature but often does not address many of the factors anticipated in a given application. Most marine corrosion data are obtained from the exposure of small samples of isolated materials. Information on galvanic interactions and the effects of crevices is more limited and is often semi-quantitative or qualitative. Care must be taken to verify that the quantitative data presented are appropriate to the form of corrosion that was experienced. Corrosion rates based on weight loss should not be used to assess non-uniform corrosion attack. Corrosion data are usually more useful in comparing the performance of materials with similar performance than in comparing the performance of materials with widely different corrosion behavior. In many cases, data from corrosion testing are difficult to use in the quantitative prediction of long term system performance of complex systems.

Corrosion Theory. Corrosion theory is useful in evaluating the causes of corrosion damage but is difficult to apply to the prediction of corrosion performance. If there are no data from either corrosion testing or from in-service performance of a given material it is likely that some aspect of its performance has made it unfit for marine service. The market for marine materials is highly competitive and if a material has not been used or tested in the marine environment it should be used only with great caution.

8.3 GENERAL CATALOG OF CORROSION DATA. The following can be used as a general guide for preliminary evaluation of materials for marine service. Additional details on material properties and performance should be obtained for design purposes.

8.3.1 Irons and Steels. Irons and steels are the most commonly used materials for shore facilities. They are subject to uniform corrosion at a low rate and can be protected by protective coatings and/or cathodic protection. Due to the experience with using irons and steels in a wide variety of environments, there are large amounts of data from corrosion testing and much in-service performance data available for the irons and steels. Irons and steels are low in cost and are easy to form and fabricate.

Carbon Steels. Steels with a total alloy content less than 3% corrode uniformly in a wide variety of environments including atmospheric and immersion service. The corrosion of carbon steels in marine environments varies widely and is dependent on local conditions. Rates as low as 1 MPY and as high as 250 MPY have been experienced. For immersion service in seawater, the rates of uniform attack are less dependent on local conditions and rates from 5 to 10 MPY are common. Carbon steel is seldom exposed to aggressive environments without coatings or cathodic protection. It is the performance of these systems rather than the corrosion rates of the unprotected material that govern the life of carbon steel marine equipment. Temporary localized failure of protective systems does not result in high rate localized attack. Carbon steel is anodic with respect to most other materials.

High Strength-Low Alloy Steels. High strength-low alloy steels show improved corrosion resistance over carbon steels in rural and mild industrial environments. In marine atmospheres and in immersion services, however, the difference in performance between carbon and low-alloy steels is minor. The primary advantage of these materials is their higher strength. But remember that the same amount of material loss will usually have a greater impact on the load carrying capacity of a high strength material than on a low strength material. The high strength-low alloy steels should be protected when used in marine environments. They are somewhat more cathodic than carbon steels.

8.3.2 Alloy Steels. Steels with a higher alloy content are more susceptible to pitting attack than steels with lower alloy content. Pitting is common in alloys with more than 5% total alloy content. Corrosion rates are similar to carbon and low alloy steels with pitting being only three to five times the rate calculated from weight loss. Alloy steels are selected for their higher strength but can be susceptible to hydrogen embrittlement or stress corrosion cracking at yield strengths in excess 100 ksi. The alloy steels are somewhat more cathodic than carbon steels.

Cast Irons. "Cast iron" refers to a wide variety of materials. Commonly, they are ferrous alloys that contain more than 2% carbon that is found in the alloy such as graphite or large carbide aggregates. These alloys are used primarily for their formability by casting rather than their mechanical properties or corrosion resistance. Many of the low alloy cast irons are subject to graphitization. This occurs fairly uniformly with a penetration rate of 0.010 to 0.020 inches per year in seawater immersion or in many soil environments. Alloy cast irons containing 20% nickel have improved corrosion resistance and corrode uniformly at a low rate. The potential of graphitized cast iron can be very cathodic with respect to most other materials and can approach that of graphite. Thus, when graphitized, cast irons can cause corrosion when electrically coupled to most other metals. Alloy cast irons are somewhat more cathodic than carbon steels.

8.3.3 Stainless Steels. Stainless steels can be defined as a ferrous alloys that contain more than 11% chromium and are resistant to general rusting in mild atmospheric conditions. They are generally subject to non-uniform attack in chloride containing environments with crevice corrosion and pitting attack being common on many alloys. Due to the high rate of localized attack that occurs at the start of the attack, the incubation time for attack is often a more significant measure of corrosion resistance than penetration rates. The stainless steels exhibit two potential states: (1) active and (2) passive. The passive state is substantially cathodic to the active state. It is this potential difference that drives non-uniform attack, such as pitting and crevice corrosion on these alloys. For purposes of evaluating possible galvanic corrosion between the stainless steels and other alloys, the potential of the passive state should be used. As these alloys polarize readily, their potentials can have a wide range in some conditions and may be of little value in assessing galvanic corrosion problems based on field measurements.

200 Series Stainless Steels. This group of alloys is similar to the more common 300 Series alloys described below as they are non-magnetic and have an austenitic structure. The basic alloy contains 17% chromium, 4% nickel and 7% manganese. Although these alloys are somewhat more resistant to attack than the more common 300 series stainless steels, their overall performance is similar. Some proprietary grades related to the 200 series, have performance equal or superior to the best 300 series stainless steels. These alloys are, however, not immune to attack and are very susceptible to concentration cell and pitting attack. When corrosion starts they usually corrode rapidly and non-uniformly. In seawater immersion, the incubation time for these alloys is in the range of 1 to 3 months with some of the Nitronic grades having incubation times of up to 1 year.

300 Series Stainless Steels. This group of alloys are non-magnetic and have an austenitic structure. The basic alloy contains 18% chromium and 8% nickel. These alloys are subject to crevice corrosion and pitting. They have a range of incubation times in seawater ranging from essentially zero in the case of the free machining grades, such as Type 303, to 6 months to 1 year for the best alloys, such as Type 316. They have been widely used in facilities with mixed results. If used in an application where chloride levels are low or where concentration cell corrosion has been prevented through design, they are likely to perform well. When chloride levels are high and where concentration cells can occur, the performance of these alloys is often poor. They must always be selected with care for a specific application and the effect of potential non-uniform attack on system performance must be addressed.

400 Series Stainless Steels. This group of alloys are magnetic and have a martensitic structure. The basic alloy contains 11% chromium and 1% manganese. These alloys can be hardened by heat treatment but have poor resistance to corrosion. They are subject to both uniform and non-uniform attack in seawater. The incubation time for non-uniform attack in chloride containing environments is very short, often only hours or a few days. Unless protected, using these alloys in seawater or other environments where they are susceptible to corrosion is not recommended.

600 Series Stainless Steels. This series of stainless steels is commonly referred to as “Precipitation Hardening” stainless steels. These steels can be heat treated to high strength levels. They are subject to crevice corrosion and pitting in chloride containing environments and are also subject to stress corrosion cracking and hydrogen embrittlement. The incubation time for crevice corrosion and pitting in seawater is relatively short, often only a few days. The incubation time for stress corrosion cracking can be very short, sometimes measured in hours. The use of these alloys in chloride containing environments is not normally recommended unless they are carefully selected, their heat treatment is carefully specified and controlled, and the effect of pitting and crevice corrosion is properly addressed.

Miscellaneous Cast and Wrought Stainless Steels. Alloy 20, a proprietary cast and wrought stainless steel has superior corrosion resistance to Type 316 stainless steel. Many newly developed proprietary stainless steels have given good service in many applications and have corrosion resistance superior to Type 316 stainless steel. The use of these alloys must be evaluated based upon their specific corrosion properties. While the resistance of these alloys is superior to many other grades of stainless steels, the benefits of using these alloys in critical applications instead of more corrosion resistant or corrosion immune alloys must be balanced against the consequences of failure.

8.3.4 **Aluminum Alloys.** Aluminum alloys are used primarily because of their low weight, the ease with which they can be formed and fabricated, and their corrosion resistance in many atmospheric and immersion environments. They are not, however, resistant to corrosion in many marine environments and are subject to crevice corrosion, pitting, and in some alloys, stress corrosion cracking. The alloys are also very subject to galvanic corrosion as they have an anodic potential with respect to most other metals.

1000 Series Aluminum Alloys. This series of alloys are essentially unalloyed aluminum. While they have fairly good corrosion resistance as compared to other aluminum alloys, they have relatively low strength. They are subject to crevice corrosion and pitting.

2000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and copper. These alloys are relatively high in strength and are widely used in the aerospace industry. The corrosion resistance of these alloys is inferior to most other aluminum alloys.

3000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and manganese. Their corrosion performance is roughly comparable to the 1000 series alloys.

5000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and magnesium. The are relatively low in strength and cannot be heat treated to obtain higher strengths. Their corrosion performance in most environments is superior to other aluminum alloys with the exception of the 1000 series. They are, however,, subject to both pitting and crevice corrosion, particularly in marine applications.

6000 Series Aluminum Alloys. This series of alloys are alloys of aluminum, magnesium, and silicon. They are relatively high in strength and can be heat treated to obtain higher strengths. Their corrosion performance in most environments is somewhat inferior to the 5000 series alloys but is acceptable in many applications. They are subject to both pitting and crevice corrosion.

7000 Series Aluminum Alloys. This series of alloys are alloys of aluminum and zinc. They are heat treatable to obtain high strengths. Their corrosion performance in chloride containing environments application is inferior to other aluminum alloys. If they are used, care must be used to control crevice and pitting attack unless the effects of these forms of attack are not functionally significant. Some of the 7000 series alloys are subject to stress corrosion cracking when heat treated to high strength levels.

Cast Aluminum Alloys. Of the cast aluminum alloys, alloy A-356 has the best overall balance between mechanical properties, castability, and corrosion resistance and is the most commonly used aluminum casting alloy for corrosion service. Its corrosion performance is comparable to the 6000 series wrought alloys.

8.3.5 Copper. Although copper has a relatively low strength, its electrical and thermal conductivity make it an appropriate material for some marine applications. Copper corrodes uniformly at a low rate in many environments. Copper is subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices. Copper and copper alloys are cathodic to steel and many other commonly used alloys.

Bronzes. Bronzes are copper-tin, copper-aluminum, or copper-silicon alloys. Many of these alloys corrode uniformly at a relatively low rate. Some of the alloys, particularly the aluminum bronzes with aluminum contents in excess of 10%, are subject to dealloying and should not be used if this form of attack is functionally significant. Nickel-aluminum bronzes are widely used as casting alloys and, if properly heat treated, can give excellent service. Most bronzes are subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices.

Brasses. Brass is a copper-zinc alloy. Unless the zinc content is below 10% or inhibitors are added to the alloy, brasses are subject to dealloying in immersion service, particularly in seawater. The use of other copper alloys such as the aluminum bronzes or copper-nickel alloys in lieu of brass is recommended for most applications where resistance to corrosion in immersion conditions is important.

Copper-Nickel Alloys. The nickel content of the most common copper-nickel alloys ranges from 10% to 30%. They are most commonly used for heat exchanger tubes. The resistance of the alloys to velocity attack is good with the limiting velocity for the 10% nickel alloy being about 8 feet per second and for the 30% nickel alloy being about 20 feet per second. They also have good resistance to low flow conditions. The alloys corrode uniformly below their limiting velocities. Both alloys are subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices.

Beryllium Copper. Beryllium copper alloys can have very high strengths of up to 200 ksi. They corrode uniformly at a low rate. Beryllium copper is subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices. Beryllium copper is widely used as a spring and electrical contact material.

8.3.6 Nickel Alloys. Many nickel alloys have been developed specifically for their high resistance to corrosion. The alloys in this group are among the most corrosion resistant materials in many environments and some of the alloys are essentially immune to attack.

Nickel. Nickel, as usually applied as a plating material, is resistant to corrosion in mildly corrosive environments but is not resistant to corrosion in chloride containing environments. Except in chemical processing, nickel is seldom used as a structural material.

Nickel-Copper Alloys. The most common nickel-copper alloy is Monel 400, which is nominally 70% nickel and 30% copper. Monel 400 is highly resistant to corrosion in many environments but is not totally resistant to corrosion in seawater. It is subject to pitting attack in seawater if exposed without coupling to other metals. The incubation time for pitting in seawater is rather long and ranges from 1 to 2 years. Monel 400 is subject to metal ion concentration attack and the corrosion of this alloy is usually reduced within crevices. Monel is cathodic to most other common alloys. Monel K-500 is an age hardenable nickel-copper alloy and has higher strength than Monel 400 but has comparable corrosion characteristics.

Other Nickel Alloys. Nickel alloys such as Inconel 625 and Hastelloy C-276 are essentially immune to corrosion in many environments. Inconel alloy 718 has high strength in the order of 150 ksi and has good resistance to corrosion in many environments and usually only exhibits small amounts of crevice attack. A-286 is a nickel-chromium-titanium-molybdenum alloy that is widely used as a high strength fastener alloy. While subject to crevice corrosion with initiation times and propagation rates similar to Type 316 stainless steel, it has been successfully used in many applications. Its practical corrosion resistance is improved due to its cathodic potential with respect to many materials and the significant improvement in its corrosion resistance when coupled to more anodic materials.

8.3.7 Titanium Alloys. Titanium alloys are high in cost and difficult to form and fabricate. Many of the alloys are, however, essentially immune to corrosion in a wide variety of environments.

General Corrosion Performance. Titanium alloys are essentially resistance to general corrosion in most environments at ambient temperature. They are essentially immune to crevice attack and pitting. At elevated temperatures they can be subject to pitting and crevice corrosion in some environments.

Stress Corrosion Cracking. Some of the titanium alloys are subject to stress corrosion cracking. The commercially pure (CP) alloys and Alloy 6Al-4V are the most commonly used alloys and are resistant to stress corrosion cracking in most environments. Use of these alloys is recommended unless higher strength is specifically required. Other alloys may be resistance to stress corrosion cracking but must be evaluated for each specific application.

8.3.8 Other Alloys and Materials. Several materials that are either effectively immune to corrosion in many environments or have other unique properties are available for use in special applications.

Cobalt Alloys. Stellite 6 is a cobalt based alloy that is widely used for a combination of abrasion and corrosion resistance. It is difficult to form and fabricate but can be used when its relatively high yield strength (90 ksi), abrasion resistance, and immunity to corrosion are required. MP-35N is another cobalt based alloy that is widely used as an aerospace fastener material. Its combination of extremely high yield strength (285 ksi) and immunity to corrosion are unique. The potential of cobalt alloys are cathodic to most other metals.

Noble Metals. Gold and platinum are essentially inert in most environments. Gold is sometimes used as a plating on copper alloys to improve electrical contact resistance. Platinum is primarily used as an anode material for impressed current cathodic protection. It is either used as wire anodes or is bonded to titanium or niobium supports. Platinum and gold are cathodic to most other metals.

Lead Alloys. Lead and lead alloys corrode uniformly at a low rate in many environments where the protective film of corrosion products formed on their surface is insoluble. However, in the presence of nitrates, acetates, or chlorides, lead alloys can corrode non-uniformly as the corrosion products formed are not protective. Lead-tin solder corrodes in a similar manner.

CHAPTER 9. SYNTHETIC ORGANIC MATERIAL (PLASTICS) AND ORGANIC MATRIX COMPOSITES (REINFORCED PLASTICS)

9.1 GENERAL PROPERTIES OF PLASTIC MATERIALS.

9.1.1 Definition. A plastic is any one of a large and varied group of materials that contain, as an essential ingredient, an organic resin substance of large molecular weight. Although the material is solid in the finished state, at some stage in its manufacture it has been or can be formed into various shapes by flow, usually through application or together with heat and pressure.

An organic matrix composite or reinforced plastic is any one of a large and varied group of materials that use a plastic or combination of plastics as the matrix material combined with any number of reinforcing materials to provide a composite with improved properties over the individual parts.

9.1.2 Classification. Organic plastic materials may be classified into four groups:

Thermoplastic - can be physically transformed and change shape by heat, repeatedly.

Thermosetting Plastic - chemically transformed by heat, chemical action, catalysts or ultraviolet light or other forms of radiation leading to a relatively infusible state.

Elastomers - synthetic polymerized, stretchable, rubber-like properties.

Thermoplastic Elastomers - has the characteristics of both plastics and elastomers.

9.1.3 Physical Properties. All corrosion-resistant materials must be selected on the basis of their ability to out perform all other products when evaluated under identical conditions. High molecular weight organic materials are used to advantage by forming into useful shapes. The physical properties listed should be considered when selecting plastic materials:

Stress/strain characteristics under service conditions
Creep
Strength (tensile, impact, flexural, compressive)
Heat distortion
Specific gravity
Flammability

Resistance to weather
Resistance to sunlight
Hardness

9.1.4 Chemical Resistance Versus Molecular Structure. Natural macromolecules frequently have some inconvenient or undesirable properties. This problem has been approached on the basis of: (a) modification of the natural macromolecules; and (b) the synthesis of other new types, often from natural macromolecules. In selecting a plastic material, the following characteristics should be considered: Polar and nonpolar classification, resistance to specific environments, resistance to specific chemicals, service tests under specific conditions, and toxicity.

9.1.5 Laboratory Tests. Methods of testing plastics are outlined in the following specifications:

Plastics, Organic: General Methods of Testing. Federal Specification L-P-406

Rubber: Sampling and Testing, Federal Test Method. Standard No. 601

Paint, Varnish, Lacquer, and Related Materials: Methods of Inspection, Sampling, and Testing. Federal Specification TT-P-141

1988 Book of ASTM Standards. ASTM Volumes 08.01, 08.02, 08.03, 08.04, 09.01, 09.02, and 10.01

Tentative specifications. Society of the Plastics Industry

9.1.6 Organic Matrix Composites (Reinforced Plastics). Composites have high tensile strength and impact resistance. The reinforcement can be embedded in the matrix or external. The composites design structure can be fiberglass, honeycomb, single to multiple plys, or any number of other construction designs.

The majority of organic matrix composites uses the first two types of plastics as the matrix material but there are still many uses for the elastomers where flexibility may be a requirement, as in flexible fuel hoses.

9.1.7 Fiber Reinforced Plastics (FRP). A broad group of composite materials composed of fibers embedded in a plastic resin matrix. In general, they have high strength-to-weight ratios and excellent corrosion resistance compared to metals. They can be formed economically into virtually any shape and size.

In size, FRP products range from tiny electronic components to large boat hulls. In between these extremes, there is a wide variety of FRP gears, bearings, bushings, housings, and parts used in all product industries.

Glass is by far the most used fiber in FRPs. Glass-fiber-reinforced plastics are often referred to as GFRP or GRP. Asbestos fiber has some use, but is limited in applications where maximum thermal insulation or fire resistance is required. Other fibrous materials used as reinforcements are paper, sisal, cotton, nylon, and Kevlar. For high performance parts and components, fibers, such as boron and graphite, can be used.

Although a number of different plastic resins are used as the matrix for reinforced plastics, thermosetting polyester resins are the most common. The combination of polyester and glass provides a good balance of mechanical properties as well as corrosion resistance, low cost, and good dimensional stability. In addition, curing can be done at room temperature without pressure, thus making for low processing equipment costs. For high volume production, special sheet-molding compounds are available in continuous sheet form. Resin mixtures of thermoplastics with polyesters have been developed to produce high quality surfaces in the finished molding. The common thermoplastics used are acrylics, polyethylenes, and styrenes.

Other glass-reinforced thermosets include phenolics and epoxies. GRP phenolics are noted for their low cost and good overall performance in low strength applications. Because of their good electrical resistivity and low water absorption, they are widely used for electrical housings, circuit boards, and gears. Since epoxies are more expensive than polyesters and phenolics, GRP epoxies are limited to high performance parts where their excellent strength, thermal stability, chemical resistance, and dielectric strength are required.

Initially, GRP materials were limited to thermosetting plastics. Today, however, more than 1,000 different types and grades of reinforced thermoplastics are commercially available. Leaders in volume use are nylon and styrenes; others include sulfones and ABS. Unlike thermosetting resins, GRP thermoplastic parts can be made in standard injection-molding machines. The resin can be supplied as pellets containing chopped glass fibers. As a rule, a GRP thermoplastic with chopped fibers at least doubles the plastic's tensile strength and stiffness. Glass-reinforced thermoplastics are also produced as sheet materials for forming on metal stamping equipment.

9.1.8 Polymerization. Most synthetic organic materials (plastics) are produced by adding small unsaturated molecules together to form long chains that can be straight or branched and with or without cross-linking. This process is usually carried out under pressure, under heat, chemical action, radiation, or any combination of these catalysts known as curing agents.

9.2 THERMOPLASTIC APPLICATIONS.

9.2.1 Acetal Resins. Highly crystalline resins that have the repeating group $(OCH_2)_x$. The resins are polyformaldehyde. The natural acetal resin is translucent white and can be readily colored. There-are two basic types: homopolymer (Delrin) and copolymer (Ceclon). In general, the homopolymers are harder, more rigid, and have higher tensile flexural and fatigue strength, but lower elongation. The copolymers are more stable in long term, high temperature service and have better resistance to hot water. Special types of acetals are glass filled, providing higher strengths and stiffness, and tetrafluoroethylene (TFE) filled, providing exceptional frictional and wear properties.

Acetals are among the strongest and stiffest of the thermoplastics. Their tensile strength ranges from 8,000 to about 13,000 lb/in.^{2} (55 to 89 MPa), the tensile modules of elasticity is about 500,000 lb/in.^{2} (3,445 MPa), and fatigue strength at room temperature is about 5,000 lb/in.^{2} (34 MPa). Their excellent creep resistance and low moisture absorption (less than 0.4%) give them excellent dimensional stability. They are useful for continuous service up to about 220°F (104°C). Acetals’ low friction and high abrasion resistance, though not as good as nylon’s, rates them high among thermoplastics. Their impact resistance is good and remains almost constant over a wide temperature range. Acetals are attacked by some acids and bases, but have excellent resistance to all common solvents. They are processed mainly by molding or extruding. Some parts are also made by blow and rotational molding. Parts and products made of acetal include pump impellers, conveyor links, drive sprockets, automobile instrument clusters, spinning reel housings, gear valve components, bearings, and other machine parts. Delrin, of DuPont, is used for mechanical and electrical parts. It has a specific gravity of 1.425, a tensile strength of 10,000 lb/in.^{2} (68 MPa) with elongation. of 15%, dielectric strength of 500 volts per mil (19.6 x 10^6 volts per meter), and Rockwell hardness of M94. It retains its mechanical strength close to the melting point of 347°F (175°C). Celcon, of the Celeanese Corp., is a thermoplastic linear acetal resin produced from trioxane, which is a cyclic form of formaldehyde. The specific gravity is 1.410, flexural strength of 12,000 lb/in.^{2} (82 MPa), Rockwell hardness of M76, and dielectric strength of 1,200 volts per mil (47 x 10^6 volts per meter). It comes in translucent white pellets for molding.

9.2.2 Acrylic Resins. Colorless, highly transparent, thermoplastic, synthetic resins made by the polymerization of acrylic derivatives, chiefly from the esters of acrylic acid, CH_2:CH"COOH, and methacrylic acid, CH_2:C(CH_3)"COOH, ehtyl acrylate and methyl acrylate. Glacial acrylic acid is the anhydrous monomer with less than 2% moisture. It can be esterified directly with an alcohol. Vinyl acrylic acid, CH_2:CHCH:CHCOOH, with a melting point of 80°C, is made from acrolein and malonic acid. It polymerizes on heating.

The resins vary from soft, sticky semi-solids to hard, brittle solids, depending on the constitution of the monomers and on the polymerization. They are used for adhesives, protective coatings, finishes, laminated glass, transparent structural sheet, and molded products. Acrylic resins, or acrylate resins, are stable and resistant to chemicals. They do not cloud or fade in light when used as laminating material in glass and are used as air-curing adhesives to seal glass to metals or wood. Water-based acrylics are also used for caulks and sealants. They have better adhesion and weather resistance than butyl rubbers and dry more quickly. The sealants usually contain about 80% solids.

Most acrylic plastics are based on polymers of methyl methacrylate, which can be modified by copolymerizing or blending with other monomers. Noted for excellent optical properties, they have a light transmission of about 92%. Besides the transparent grades, they come in translucent or opaque colors as well as the natural water white color. Moldings have a deep luster and high surface gloss, and for this reason are widely used for decorative parts. Acrylic plastics have excellent weathering characteristics. Because they are hardly affected by sunlight, rain, and, corrosive atmospheres, they are well suited for outdoor use. In general, the majority of grades can be used up to about 200°F (100°C). Thermal expansion is relatively high.

Acrylic plastics are hard and stiff. They are a relatively strong plastic; their tensile strength ranges from 5,000 to about 11,000 lb/in.^{2} (34 to about 75 MPa). However, regular grades are somewhat brittle. High impact grades are produced by blending with rubber stock. The high strength is useful only for short term loading, For long term use, to avoid crazing or surface cracking, tensile stresses must be limited to about 1,500 lb/in.^{2} (10 MPa).

Acrylic plastics are available as cast sheets, rods, tubes, and blocks. They are also processed by injection or compression molding. Sheets are produced in thicknesses from 1/8 to 3/8 inch (0.32 to 0.95 cm) and in sizes up to 10 by 12 feet (3 by 4 meters). A special process that produces molecular orientation in the cast product is used to make crack-resistant aircraft cabin windows and fighter plane canopies. Acrylic moldings as large as 1 yd^2 (1 m^2) have been produced. A lead-filled acrylic sheet, produced by Kyowa Gas Chemical Industry Co., Japan, is used as a radiation shielding material. It is transparent and has better impact strength and fabricability than leaded glass. Moldings include knobs, handles, escutcheons, parts for vending machines, and a wide variety of lenses for light control, signal lamps, etc. the like.

Tough molding resins are made by copolymerizing methyl methacrylate with styrene.

Product	**Manufacturer**	**Remarks**
Zerlon 150	Dow Chemical Co,	A molding resin with a flexural strength of 17,600 lb/in.^{2} (123 MPa).
Thiacril	Thiokol Chemical Corp.	An acrylate rubber having a tensile strength of 2,500 lb/in.^{2} (16 MPa) and an elongation of 350%. Used for gaskets, wire insulation, and hose.

Allyl methacrylate is a liquid of the empirical formula $C_7H_{10}O_2$ boiling at 145°F (63°C), and insoluble in water. It can be polymerized to form liquid or hard solid resins, but is used chiefly as a cross-linking agent for other resins to raise the softening point and increase hardness.

Product	**Manufacturer**	**Remarks**
Gafite	General Aniline & Film Corp.	A polymethyl alphachloroacrylate $(CH_2CClCOOCH_3)_x$. A transparent and crack-resistant resin used for aircraf windows. The heat distortion point is 260°F (127°C), and has higher tensile and flexural strength than other acrylics. Cyclohexyl methacrylate has optical properties similar to crown glass, and is used for cast lenses, where its softness and low softening point, 160°F (71°C), are not objectionable.
Lucite	E.I. du Pont de Nemours & Co., Inc.	A methyl methacrylate marketed as molding powder and in rods, tubes, and cast and molded sheets. Lucitone, which is this material, is used for making dentures (pink) and can be translucent.
Lucite HM-140	E.I. du Pont de Nemours & Co., Inc.	A Lucite material compounded for high temperature injection molding.

Product	**Manufacturer**	**Remarks**
Acrylic syrup	E.I. du Pont de Nemours & Co., Inc.	A liquid Lucite for use as a low pressure laminating resin. Produces strong, stiff tough laminates adaptable to translucent or bright colors. Reinforced with glass fibers, a panel with contact cure has a flexural strength of 25,000 lb/in.^{2} (172 MPa), elongation 1.5%, distortion point at 233°F (112°C), Rockwell hardness of R121, and light transmission up to 65%.
Crystalite	Rohm & Haas Co.	An acrylic molding powder used for aircraft windows.
Plexiglas	Rohm & Haas Co.	A transparent methyl methacrylate in sheets and rods. Also used for aircraft windows.
Perspex	Rohm & Haas Co.	A similar English acrylic resin used for aircraft windows.
Plexiglas V	Rohm & Haas Co.	An injection molding.
Plexiglas VM	Rohm & Haas Co.	A molding powder that resists heat distortion to 174°F (79°C).
Vernonite	Rohm & Haas Co.	An acrylic denture resin.
Acryloid Resins	Rohm & Haas Co.	Acrylic copolymer solid resins, and the acrysol resins are solutions for coatings.
Plexene M	Rohm & Haas Co.	**A** styrene-acrylic resin for injection molding. The specific gravity of the molded resin is 1.08, the dielectric strength is 350 volts per mil (14 x 10^6 volts per meter), and tensile strength 15,000 lb/in.^{2} (103 MPa).
Rhoplex Resin	Rohm & Haas Co.	Acrylic resin emulsions for paints, textile finishes, and adhesives.
Crilicon Resin	Jersey State Chemical Co.	Acrylic resin emulsions for paints, textile finishes, and adhesives.

Product	**Manufacturer**	**Remarks**
Polyco 296	American Polymer Corp.	A water-soluble acrylic copolymer used for thickening natural or synthetic rubber latex for paper and textile coatings.

Coatings made with acrylics have good adhesion and gloss, are resistant to oils and chemicals, and have good dielectric strength.

Product	**Manufacturer**	**Remarks**
Carboset 511	B.F. Goodrich Chemical Co.	A water solution of acrylic resin for protecting polished metal surfaces and precision parts against scratching. It is resistant to water, but can be washed off with soap and water.
Cavalon	Du Pont	A polyacrylic resin for coatings that has high hardness and resistance to abrasion.

9.2.3 Cellulosic Resins. Cellulose is the main constituent of the structure of plants, which when extracted, is used for making paper, plastics, and in many combinations. Cellulose is made up of long chain molecules in which the complex unit $C_6H_{10}O_5$ is repeated as many as 2,000 times. It consists of glucose molecules with three hydroxyl groups for each glucose unit. These OH groups are very reactive, and an almost infinite variety of compounds may be made by grafting on other groups, either repetitively or intermittently, such as reaction with acetic or nitric acids to form acetates or nitrates, reaction with ethylene oxide to form hydroxyethyl cellulose, reaction with acrylonitrile to form cyanoethylated cellulose, or reaction with vinyls.

Ethyl Cellulose. A colorless, odorless ester of cellulose resulting from the reaction of ethyl chloride and cellulose. The specific gravity is 1.07 to 1.18. It is nonflammable, very flexible, stable to light, and forms durable alkali-resistant coatings. It is used as a thin wrapping material, for protective coatings, as a hardening agent in resins and waxes, and for molding plastics. Ehtyl cellulose plastics are thermoplastic and are noted for their ease of molding, light weight, and good dielectric strength, 400 to 520 volts per mil (15 to 20.5 x 10^6 volts per meter), and retention of flexibility over a wide range of temperatures from -75 to 150°F (-57 to 66°C), the softening point. They are the toughest, lightest, and have the lowest water absorption of the cellulosic plastics. But they are softer and lower in strength than cellulose-acetate plastics.

Product	Manufacturer	Remarks
Lumarith EC	Celanese Corp.	An ethyl cellulose in the form of sheets, films, and molding powder. Celcon is a name applied by Celanese to ethyl cellulose plastics.
Hercocel E	Hercules, Inc.	A compounded ethyl cellulose molding powder in several formulations to give tensile strengths from 3,750 to 7,400 lb/in.^{2} (26 to 51 MPa), with elongation from 6 to 16%.
Ethocel	Dow Chemical Co.	An ethyl cellulose. Stripcoat is a solution of ethyl cellulose used for dipping automotive and aircraft parts or other metal products to form a thin, waterproof protective coating to prevent corrosion. The coating strips off easily when the part is ready to use.

The same material is marketed by a number of other companies for the same purpose under a variety of trade names.

Cellulose Acetate. An amber colored, transparent material made by the reaction of cellulose with acetic acid or acetic anhydride in the presence of sulfuric acid. In Germany it was made by treating beechwood pulp with acetic acid in the presence of an excess of zinc chloride. It is used for lacquers and coatings, molding plastics, rayon, and photographic film. Cellulose acetate may be the triacetate $C_6H_7O_2(OOOCCH_3)_3$, but may be the tetracetate or the pentacetate, or mixtures. It is made in different degrees of acetylation with varying properties, Unlike nitrocellulose, it is not flammable, and it has better light and heat stability. It has a refractive index of 1.47 to 1.50, and a sheet 1/8-inch (0.32 cm) thick will transmit 90% of the light. The specific gravity is 1.27 to 1.37, hardness 8 to 15 Brinell, tensile strength 3,500 to 8,000 lb/in.^{2} (24 to 55 MPa), compressive strength up to 20,000 lb/in.^{2} (137 MPa), elongation 15 to 80%, dielectric strength 300 to 600 volts per mil (12 to 24 x 10^6 volts per meter), and softening point 122 to 205°F (50 to 96°C). It is thermoplastic and is easily molded. The molded parts or sheets are tough, easily machined, and resistant to oils and many chemicals. In coatings and lacquers the material is adhesive, tough, and resilient, and does not discolor easily.

Cellulose acetate fiber for rayons can be made in fine filaments that are strong and flexible, nonflammable, mildewproof, and easily dyed. Standard cellulose acetate for molding is marketed in flake form.

Cellulose triacetate, with 60 to 61.5% combined acetic acid, is more insoluble, has higher dielectric strength, and is more resistant to heat and light than other types. It is cast into sheets and is also used for resistant coatings and textile fibers.

Cellulose acetate lacquers are sold under many trade names. They are the acetate in solvents with plasticizers and pigments.

Product	**Manufacturer**	**Remarks**
Vimlite	Celanese Corp.	Saran screen filled with cellulose acetate. Transmits ultraviolet light and is used for glazing.
Miramesh	National Research Corp.	Material with one side coated with a film of aluminum. Used for light diffusers and radiant-heat reflectors.
Masuron	John W. Masury & Son	Cellulose acetate material.
Nixonite	Nixon Nitration Works	Cellulose acetate material.
Plastacele	Du Pont	Cellulose acetate material.
Acele	Du Pont	Du Pont’s name for acetate yarns.
Celanese	Celanese Corp.	Cellulose acetate yarns and fabrics.
Celairese	Celanese Corp.	Fluffy acetate fiber used for interlinings.
Lanese	Celanese Corp.	Fine fluffy acetate fiber used to blend with wool.
Fortisan	Celanese Corp.	Specially processed strong acetate fiber of extreme fineness [0.0001 inch (0.00025 cm) in diameter], originally developed for parachutes, but now also used in fine fabrics.

Product	**Manufacturer**	**Remarks**
Forticel	Celanese Corp.	Cellulose propionate plastic used in injection molding. Has a flow point at (161°C), has high impact resistance, and requires less plasticizier than cellulose acetate.
Arnel	Celanese Corp.	Cellulose tricetate fiber resistant to shrinkage and wrinkling in fabrics.
Arnel 60	Celanese Corp.	Cellulose acetate fiber with a circular cross section instead of the normal crenelated cross section for higher strength and better spinning qualities.
Hercocel A	Hercules, Inc.	Cellulose acetate molding powder that will produce moldings with tensile strengths from 4,000 to 7,000 lb/in.^{2} (27 to 186 MPa) and elongations from 14 to 22%. The flow temperatures ranges from 285 to 355°F (140 to 179°C), depending on the form.
Avcovel	American Viscose Corp.	By-product of cellulose production used as a filler in plastics to increase impact strength. It contains 50% cellulose and 50% white cotton.

Cellulose acetate butyrate is made by the esterification of cellulose with acetic acid and butyric acid in the presence of a catalyst. It is used for coatings, insulation, varnishes, and lacquers. Called butyrate or CAB, is somewhat tougher, has lower moisture absorption, and a higher softening point than acetate. Special formulations with good weathering characteristics plus transparency are used for outdoor applications, such as signs, light globes, and lawn sprinklers. Clear sheets of butyrate are available for vacuum-forming applications. Other uses include: transparent dial covers, television screen shields, tool handles, and typewriter keys. Extruded pipe is used for electric conduits, pneumatic tubing, and low pressure waste lines.

Cellulose acetate propionate is similar to butyrate in both cost and properties. Some grades have slightly higher strength and modulus of elasticity. Propionate has better molding characteristics but lower weatherability than butyrate. Cellulose acetate propionate is used to make steering wheels, fuel filter bowls, and appliance housings. Transparent sheeting is used for blister packaging and food containers.

Product	Manufacturer	Remarks
Tenite III		A cellulose acetate propionate used for extrusion rod and moldings of high impact strength.
Hercose C	Hercules, Inc.	A cellulose acetate butyrate used for cable coverings and coatings. It is more soluble than cellulose acetate and more miscible with gums. It forms durable and flexible films.
Ester EAB-171	Eastman	A liquid cellulose acetate butyrate for glossy lacquers, chemical-resistant fabric coatings, and wire-screen windows. Contains 17% butyl with one hydroxyl group per four anhydroglucose units. Transmits ultraviolet light without yellowing or hazing and is weather resistant.

9.2.4 Chlorinated Polyether. A high priced, high molecular weight thermoplastic used chiefly in the manufacture of process equipment. Crystalline in structure, it is extremely resistant to the thermal degradation at molding and extrusion temperatures. The plastic is resistant to more than 300 chemicals at temperatures up to 250°F (120°C) and higher, depending on environmental conditions.

Along with the mechanical capabilities and chemical resistance, chlorinated polyether has good dielectric properties. Loss factors are somewhat higher than those of polystyrenes, fluorocarbons, and polyethylenes, but are lower than many other thermoplastics. Dielectric strength is high and electrical values- show a high degree of consistency over a range of frequencies and temperatures.

The material is available as a molding powder for injection molding and extrusion applications. It also comes in sheets, rods, tubes, pipes, and blocks for lining tanks and other equipment, and for machining gears, plugs, etc. Rods, sheets, tubes, pipes, blocks, and wire coatings can be extruded on conventional equipment and by normal production techniques. Parts can be machined from blocks, rods, and tubes on conventional metal working equipment.

Sheets can be used to convert carbon steel tanks into vessels capable of handling highly corrosive liquids at elevated temperatures. Using a conventional adhesive system and hot gas welding, sheets can adhere to sandblasted metal surfaces.

Coatings of chlorinated polyether powder can be applied by several processes. Using the fluidized bed process, pretreated and preheated metal parts are dipped in an air-suspended bed of finely divided powder to produce coatings, which after baking are tough, pinhole free, and highly resistant to abrasion and chemical attack. Parts clad by this process are protected internally and externally against corrosion.

9.2.5 Fluoroplastics (also known as fluorocarbon resins and fluorine plastics). A group of high performance, high price engineering plastics. They are composed basically of linear polymers in which some or all of the hydrogen atoms are replaced with fluorine, and are characterized by high crystallinity and molecular weight. All fluoroplastics are natural white and feel waxy. They range from semi-rigid to flexible. As a class, they rank among the best of the plastics in chemical resistance and elevated temperature performance. Their maximum service temperature ranges up to about 500-F (260°C). They also have excellent frictional properties and cannot be wet by many liquids. Their dielectric strength is high and is insensitive to temperature and power frequency. Mechanical properties, including tensile creep and fatigue strength, are only fair, although impact strength is high.

There are three major classes of fluoroplastics. In order of decreasing fluorine replacement of hydrogen, they are: fluorocarbons, chlorotrifluoroethylene, and fluorohydrocarbons. There are two fluorocarbons: tetrafluoroethylene (PTFE or TFE) and fluorinated ethylene propylene (FEP). PTFE is the most widely used fluoroplastic. It has the highest useful service temperature, 500°F (260°C), and chemical resistance. FEP's chief advantage is its low melt viscosity, which permits it to be conventionally molded.

Product	**Manufacturer**	**Remarks**
Teflon	Du Pont	A tetrafluoroethylene of specific gravity up to 2.3. Tensile strength: up to 3,500 lb/in.^{2} (23.5 MPa). Elongation: 250 to 350%. Dielectric strength: 1,000 volts per mil (39.4 x 10^6 volts per meter). Melting point: 594°F (312°C). Is water and chemical resistant.

Product	**Manufacturer**	**Remarks**
Teflon S	Du Pont	A liquid resin of 22% solids. Can be sprayed by conventional methods and is curable at low temperatures. Gives a hard, abrasion-resistant coating. Temperature service range is up to 400°F (204°C). Is used as conveyors and chutes.
T-film	Eco Engineering Co.	A thin Teflon film for sealing pipe threads.
Teflon Fiber	Du Pont	Plastic in extruded monofilament, down to 0.01 in. (0.03 cm) in diameter. Oriented to give high strength. Used for heat- and chemical-resistant filters.
Teflon Tubing	Du Pont	Made in fine sizes down to 0.10 inch (0.25 cm) in diameter with wall thickness of 0.01 in. (0.03 cm).
Teflon 41-X	Du Pont	A colloidal water dispersion of negatively charged particles of Teflon. Used for coating metal parts by electrodeposition.

Teflon FEP is fluorinated ethylenepropylene in thin film, down to 0.0005 inch (0.001 cm) thick, for capacitors and coil insulation. The film has a dielectric strength of 3,200 volts per mil (126 x 10^6 volts per meter), tensile strength of 3,000 lb/in.^{2} (20 MPa), and elongation of 250%.

Chlorotrifluoroethylene (CTFE or CFE) is stronger and stiffer than the fluorocarbons and has better creep resistance. Like FEP and unlike PTFE, it can be molded by conventional methods.

There are two kinds of fluorohydrocarbons: polyvinylidene fluoride (PVF_2) and polyvinyl fluoride (PVF). While similar to the other fluoroplastics, they have a lower heat resistance, and considerably higher tensile and compressive strength.

Except for PTFE, the fluoroplastics can be molded, extruded, and formed by other conventional methods. However, processing must be carefully controlled. Because PTFE cannot exist in a true molten state, it cannot be conventionally molded. The common method of fabrication is by compacting the resin in powder form and then sintering.

Product	Manufacturer	Remarks
Whitcon	Whitford Chemical Corp.	A fluorocarbon powder of 1-m particle size. Used as a dry lubricant or added to rubbers, plastics, and lubricating greases.
Plaskon Halon (Grade G80)	Allied Chemical Co.	A tetrafluoroethylene powder 25 to 30 m fine particles. Molded parts have tensile strengths to 6,500 lb/in.^{2} (44.5 MPa).
Fluorothene Plastic	Union Carbide	Has the formula $(\mathrm{CF_2}\text{"}\ \mathrm{CFCl})_n$, which is different from Teflon. It has one chlorine atom on every unit of the polymer chain, replacing the fourth fluorine atom. It is transparent and molded parts have a specific gravity of 2.1, a tensile strength of 9,400 lb/in.^{2} (65 MPa), a high dielectric strength, and will withstand temperatures to 300°F (149°C).
KEL-F	3M	A chlorotrifluoroethylene used for moldings, gaskets, seals, liners, diaphragms, and coatings. The molded parts have high chemical resistance. The compressive strength is 30,000 lb/in.^{2} (210 MPa), but can be heat treated to increase the compressive strength to 80,000 lb/in.^{2} (560 MPa). The tensile strength of the molded material is 5,000 lb/in.^{2} (34 MPa), but oriented fibers have a tensile strength to 50,000 lb/in.^{2} (344 MPa).
Fluorocarbon Rubber	3M	A saturated fluorocarbon polymer containing 50% fluorine. Is used for tubing, gaskets, tank linings, paints, and protective clothing. Clothing has a tensile strength of 3,000 lb/in.^{2} (20 MPa), elongation of 600%, heat resistance to 400°F (204°C), and a high resistance to oils and chemicals.

Product	Manufacturer	Remarks
Aclar	Allied Chemical Co.	A chlorotrifluoroethylene transparent packaging film that is exceptionally resistant to oils and chemicals, has a moisture-barrier efficiency 400 times that of polyethylene film, has good strength to 390°F (199°C), and retains its flexibility to -300°F (-184°C). It is also used for wire covering.

9.2.6 **Polyamide Resins (Nylon).** A group of polyamide resins that are long-chain polymeric amides in which the amide groups form an integral part of the main polymer chain and have the characteristic that when formed into a filament, the structural elements are oriented in the direction of the axis.

Nylon was originally developed as a textile fiber, and high strengths (above 50,000 lb/in.2 (344 MPa)) are obtainable in the fibers and films. But this high strength is not obtained in the molded or extruded resins because of the lack of oriented stretching. When nylon powder, which has been precipitated from the solution is pressed and sintered, the parts have high crystallinity and very high compressive strength, but they are not as tough as molded nylon.

Nylons are produced from the polymerization of a dibasic acid and a diamine. The most common one of the group is that by the reaction of adipic acid with hexamethylenediamine. The nylon molding and extruding resin of Du Pont’s Elvamide 8042, formerly Zytel 42, has a tensile strength of 12,500 lb/in.^{2} (106 MPa) with elongation above 100%, a flexural strength of 13,800 lb/in.^{2} (95 MPa), Rockwell hardness of R118, a flow temperature of 480°F (249°C), and a dielectric strength of 350 volts per mil (14 x 10^6 volts per meter).

All of the nylons are highly resistant to common solvents and to alkalies, but are attacked by strong mineral acids. Molded parts are light weight, with a specific gravity of about 1.14, good shock-absorbing ability, good abrasion resistance, very low coefficient of friction, and high melting point, up to about 482°F (250°C). One disadvantage of nylon is its high water absorption and the resulting dimensional changes in moldings in service. Nylon is used to make gears, bearings, cams, and linkages. The electrical characteristics are about the same as those of the cellulosic plastics. As a wire insulation, nylon is valued for its toughness and solvent resistance.

Nylon fibers are strong, tough, elastic, and have a high gloss. The finer fibers are easily spun into yarns for weaving or knitting either alone or in blends with other fibers, and they can be crimped and heat set.

Product	**Manufacturer**	**Remarks**
Nyloft Fiber	Firestone Tire & Rubber Co.	Is used in carpets. The nylon is staple fiber, lofted, or wrinkled to give the carpet a bulky texture resembling wool.
Caprolan Tire Cord	Firestone Tire & Rubber Co.	Made from Nylon 6 of high molecular weight, has the yarn drawn to four or five times its original length to orient the polymer and give one-half twist per inch.
Nylon Film	Du Pont	Made in thicknesses down to 0.002 in. (0.005 cm) for heat-sealed wrapping, especially for food products where tight impermeable wrap is needed.
Nylon Sheet	Du Pont	Comes in colors or is transparent in thicknesses from 0.005 to 0.06 in. (0.013 to 0.152 cm). Is used for gaskets and laminated facings
Nylon Monofilament	Du Pont	Filament and fiber, when stretched, have a low specific gravity down to 1.068, and a tensile strength above 50,000 lb/in.^{2} (344 MPa). Is used for brushes, surgical sutures, tennis strings, and fishing lines. Nylon fibers made by condensation with oxalic acid esters have high resistance to fatigue when wet.
Nylon 6	Du Pont	Is made from caprolactam, which has the empirical formula $(CH_2)_5NH\dot{C}:O$, with a single 6-carbon ring. Molded parts have a tensile strength of 11,700 lb/in.^{2} (79 MPa) elongation 70%, dielectric strength 440 volts per mil (17.3 x 10^6 volts per meter), and a melting point of 420°F (216°C).

Product	Manufacturer	Remarks
Nylon Foam or Cellular Nylon	Du Pont	Is made from Nylon 6 and comes in slabs, rods, and sheets. Densities range from 1 to 8 lb/ft^3 (16 to 128 kg/m^3). The low density material is flexible, but the high density material is rigid with a load carrying capacity about the same as balsa wood. The foam is used in light weight buoys and flotation products.
Nylon 6/10	Du Pont	Is tough, heat resistant, and has a very low brittleness temperature. Can absorb about one-third as much moisture as Nylon 6 and half as much as Nylon 6/6.
Nylon 9	Du Pont	Is made from soybean oil by reacting with ozone. It has better water resistance than other nylons and is used for coatings.
Nylon 11	Du Pont	Is a polycondensation product of aminoundeconoic acid which is made by a complex process from the recinoleic acid of castor oil. This type of nylon has superior dimensional stability and is used for injection moldings. Nylon 11 was originally marketed in France as Rilsan.
Nylon 12	Du Pont	Is similar to Nylon 11. Is a lauro lactam synthesized from butadiene. Has a low water absorption and good strength and stability. Is used for packaging film, coatings for metals, and moldings.
Nylon 4	Du Pont	Is a polypyrrolidine used for textile fibers. The molecular chain has more amide groups than do the chains of other nylons. Its ability to absorb moisture is about the same as cotton. Fabrics made from this nylon do not have the hot feel that is common with other synthetic fibers, and they press better and are static free.

Product	**Manufacturer**	**Remarks**
Alrac Nylon	Radiation Research Corp.	Is Nylon 4.
Nylon 6/6	Du Pont	Has a specific gravity of 1.14 and a tensile strength of 11,500 lb/in^2 (78 MPa). Is used for gears and mechanical parts, and its physical properties can be further enhanced by adding glass fibers or spheres as fillers.
Nylatron G	Polymer Corp.	Graphite-impregnated nylon in rods and strips for making gears, bearings, and packings.
Nylasint	Polymer Corp.	Sintered nylon impregnated with oil. Used for bearings
Flalon	Burgess-Berliner Assoc.	Nylon flanned of 15-denier crimped fibers carded on both faces. Looks like cotton flannel, but is superior in heat and wear resistance.
Raynile	Hewitt-Robbins, Inc.	Rayon-nylon fabric with nylon traverse threads. Is flexible and has about twice the strength of cotton fabric.
Fiberthin	U.S. Rubber Co.	Thin waterproof fabric used to replace heavier tarpaulins for protective coatings. Is woven of nylon and coated with plastic. Weighs 5 oz/yd^2 (0.17 kg/m^2) and has a tensile strength of 175 lb/in. (31 kg/cm) of width.
Facilon	Sun Chemical Corp.	Caprolan nylon fabric impregnated with vinyl resin. Used for facing wall panels and flexible floor coverings. Comes in colors and embossings.

9.2.7 Polycarbonate Resins. Made by reacting bisphenol and phosgene, or by reacting a polyphenol with methylene chloride and phosgene. The monomer may be $OC_6H_4C(CH_3)_2C_6H_4OC{:}O$. The molecular structure is in double-linked zigzag chains that give high rigidity. The resin is thermoplastic. It is crystalline with rhombic crystals.

Polycarbonate is a linear, low crystalline, transparent, high molecular weight plastic. It is considered the toughest of all plastics. In thin sections, up to 3/16 inch (0.478 cm) thick, its impact strength is as high as 16 ft"lb (24 kg"m). In addition, polycarbonate is one of the hardest plastics. It also has good strength and rigidity, and because of its high modulus of elasticity, is resistant to creep. These properties, along with its excellent electrical resistivity, are maintained over a temperature range of -275 to 250°F (-170 to 121°C). It has negligible moisture absorption, but it has poor solvent resistance, and, in a stressed condition, will craze or crack when exposed to some chemicals. It is unaffected by greases, oils, and acids. Polycarbonate plastics are easily processed by extrusion, by injection, blow, rotational molding, and vacuum forming. They have very low and uniform mold shrinkage. With a white light transmission of almost 90% and high impact resistance, they are good glazing materials. They have more than 30 times the impact resistance of safety glass. Other applications are safety shields and lenses. Besides glazing, polycarbonate's high impact strength makes it useful for air-conditioner housings, filter bowls, portable tool housings, marine propellers, and housings for small appliances and food-dispensing machines.

Product	**Manufacturer**	**Remarks**
Lexan Resin	General Electric	Has a molecular weight of 18,000, a tensile strength of 10,500 lb/in.^{2} (71 MPa), with an elongation of 60%, dielectric strength to 2,500 volts per mil (98 x 10^6 volts per meter), and a Rockwell hardness of M70. The deformation temperature under load is 290°F (143°C), and the specific gravity is 1.20. Is transparent and the 1/8-inch (0.318-cm) transmits 85% of the light. This material is called Makrolon in Germany.
Merlon	Mobray Chemical Co.	Polycarbonate resin.
Plestar Film	Ansco	Polycarbonate.

Product	Manufacturer	Remarks
Lexan 145	General Electric	Polycarbonate powder for use in emulsion coatings that have high strength, are tough, and nontoxic. When this resin is compounded with 40% glass fiber, its tensile strength is doubled and its coefficient of thermal expansion is greatly reduced.
Lexan FL 1800	General Electric	Structural foam resin with high resistance to combustion, meets both service performance requirements and flammability standards for materials used in enclosures for large data process systems.
Cycolac KM	Borg-Warner Corp.	A carbonate resin that is used in mixtures with an acrylonitrile-butadiene-styene copolymer with copolymerization. It retains the general characteristics of the carbonate with added flexural strength.

9.2.8 Polyester Resins. A large group of synthetic resins produced by condensation of acids such as maleic, phthalic, or itaconic with an alcohol or glycol, such as allyl alcohol or ethylene glycol to form an unsaturated polyester. When polymerized the resins will give a cross-linked, three-dimensional molecular structure, which in turn will copolymerize with an unsaturated hydrocarbon such as styrene or cyclopentadiene to form a copolymer of complex structure of several monomers linked and cross-linked. At least one of the acids or alcohols of the first reaction must be unsaturated. The polyesters made with saturated acids and saturated hydroxy compounds are called alkyd resins, and these are largely limited to the production of protective coatings and are not copolymerized.

The resins undergo polymerization during cure without releasing water, and do not require high pressure for curing. Through the second modification stage with hydrocarbons, a wide range of characteristics can be obtained. The most important use of the polyesters is as laminating and molding materials, especially glass-fiber-reinforced plastic products. The resins have high strength, good chemical resistance, high adhesion, and capacity to take bright colors. They are also used, without fillers, as casting resins, for filling and strengthening porous materials, such as ceramics and plaster of Paris, and for sealing the pores in metal castings. Some of the resins are tough and are used to produce textile fibers and thin plastic sheets and film. Other resins are used with fillers to produce molding powders that cure at low pressures of 500 to 900 lb/in.^{2} (3 to 6 MPa) with fast operating cycles.

Product	Manufacturer	Remarks
Mylar Film	Du Pont	Polyester made by condensing terephthalic acid and ethylene glycol. The extremely thin film, 0.00025 to 0.0005 in. (0.00063 to 0.0013 cm) is used for capacitors and for insulating motors and transformers. The film has: a high dielectric strength, up to 6,000 volts per mil (236 x 10^6 volts per meter); a tensile strength of 20,000 lb/in^2 (137 MPa) with elongation of 70%; is highly resistant to chemicals and has low water absorption; is thermoplastic, with a melting point at about 490°F (254°C).

Polyester fibers are widely used in clothing fabrics. The textile fiber produced from dimethyl terephthalate is known as Dacron. The English textile fibers called Teron and Terylen are similar materials. Melinex is the English name for the film.

Product	Manufacturer	Remarks
Mylar 50T	Du Pont	Used for magnetic sound-recording tape. The 0.005-in. (0.013-cm) tape has breaking strength of 120 oz (3.4 kg) per 1/4 in. (0.64 cm) of width.
Urylon		Japanese fiber that has a low specific gravity, 1.07, and a high melting point, 482°F (250°C). The fiber is produced from azelaic acid.

Product	Manufacturer	Remarks
Terefilm	Acme Backing Corp.	Polyester film that is a cyclohexylene dimethylene terephthalate. Film has a dielectric strength of the 0.0005-in. (0.0013-cm), is 8,000 volts per mil (315 x 10^6 volts per meter), with tensile strength of 20,000 lb/in^2 (137 MPa), and heat distortion temperature of 340°F (171°C). Is used for insulation and magnetic tape.

Electronic tape can also have a magnetic-powder coating on the polyester. But where high temperature may be encountered, as in a spacecraft, the magnetic coating is applied to metal tapes.

Product	Manufacturer	Remarks
Densimag	Whittaker Corp.	Magnetic coating on a nonmagnetic stainless-steel tape. Has a combined thickness of 0.00105 in. (0.00267 cm). Tape will operate at temperatures to 600°F (316°C).
Koplac Resins	Koppers Co., Inc.	Polyesters based on styrene.
Vibrin 135	Naugatuck Chemical Co.	Polyester resin made with triallyl cyanurate and modified with maleic anhydride. Moldings reinforced with glass fiber have a tensile strength of 38,000 lb/in^2 (261 MPa), and retain a strength of 23,000 $lb/in.^2$ at 500°F (260°C).
Vibrin 136A	Naugatuck Chemical Co.	Another polyester resin made with triallyl cyanurate and modified with maleic anhydride with a higher strength and very high radar transparency. Its used for radomes and nose cones.

Transparent thermoplastic polyester resins are made by copolymerizing esters of itaconic acid with vinyl chloride, methacrylate, or acrylonitrile. Itaconic acid, $CH_2{:}CCH_2(COOH)_2$, is made from anhydrous glucose. Pimelic acid, $HO_2C(CH_2)CO_2H$, is made from petroleum as a white crystalline solid, and is used for making polyester and polyamide resins. Another acid used for these resins is glutaric acid, $HO_2C)CH_2)_3CO_2H$, produced from acrylein. Glutaric anhydride, $O{:}HC(CH_2)_3HC{:}O$, is also used, and its cross-linking ability is used for insolublizing starches and proteins to give water resistance to paints and paper coatings.

Het acid, made by Hooker Chemical, is a complex chlorinated phthalic acid produced by hydrolyzing the product of the condensation of maleic anhydride hexachlorocyclopentadiene made from pentane. This acid reacts with glycols and maleic anhydride that forms a hard polyester resin that is cross-linked with styrene to give the liquid hetron resin, which will cure with heat and a catalyst to an insoluble solid. The resin contains 30% chlorine. It is used for making laminated or reinforced plastics.

Another chlorinated polyester resin is RF resin made by Interchemical Co. This resin is flame resistant, cures at normal temperatures, and is used in lay-up lamination work, such as boat building and tank construction.

Some of the polyester type resins have rubber-like properties, with higher tensile strengths than the rubbers and superior resistance to oxidation.

Product	**Manufacturer**	**Remarks**
Vulcollan	Goodyear Tire & Rubber Co.	Resin with higher wear resistance and chemical resistance than GRS rubber. It is made by reacting adipic acid with ethylene glycol and propylene glycol and then adding diisocyanate to control the solidifying action. Can be processed like rubber, but solidifies more rapidly.
Chemigum SL	Goodyear Tire & Rubber Co.	Polyester rubber.

Polyesters also offer a great variety of possibilities in textile fibers.

Product	**Manufacturer**	**Remarks**
Kodel	Eastman Chemical Products, Inc.	A white polyester fiber that is easy to dye. Is resistant to piling, which is the tendency of surface fibers to form balls, has high dimensional stability, and is heat resistant.
Trevira 271	Hoechst Fibers Industries	A flame resistant polyester fiber made from polyethylene terephthalate polymers that have been modified by including a flame retardant in the polymer structure. If subjected directly to a flame, the fabrics made of this fiber melt and shrink away. When the flame is removed, the fabrics self-extinguish.

9.2.9 **<u>Polyethylene Resins.</u>** A group of polyolefin polymers derived from ethylene by polymerization by heat and pressure. Polyethylene plastics are one of the lowest cost and most widely used plastics. As a group, they are noted for their toughness, excellent dielectric strength, and chemical resistance. Another outstanding characteristic is their low water absorption and permeability. This is the reason for their wide use in sheet form as moisture barriers. The resins are white in thick sections, but otherwise the range varies from translucent to opaque. They feel waxy. There are many available types, ranging from flexible to rigid materials, are classified by density (specific gravity) into three major groups: Low density = 0.910 to 0.925, medium density = 0.926 to 0.940, and high density = 0.941 to 0.959.

The variations in properties among these three groups are directly related to density. As density increases, polymer cross-bonding or branching and crystallinity increase. Thus stiffness, tensile strength, hardness, and heat and chemical resistance increase with density in polyethylenes. Low density polyethylenes are flexible, tough, and less translucent than high density grades. High density grades, often called linear polyethylene grades, are stronger, more rigid, and have high creep resistance under load, but they have lower impact resistance. Low density polyethylenes are used in blow-molded bottles and containers, gaskets, paintbrush handles, and flexible film packaging. High density grades are used in wire insulation, beverage cases, dishpans, toys and the film is used in boil-in-bag packaging. In general, polyethylenes are not used in load bearing applications because of their tendency to creep. However, a special type, high molecular weight polyethylene is used for machine parts, bearings, bushings, and gears.

Polyethylenes can be blended or combined with other monomers -- propylene, ethyl acrylate, and vinyl acetate -- to produce copolymers to improve such properties as stress-crack resistance and clarity and to increase flexibility. They can also be modified by exposure to high energy radiation, which produces cross-linking and, thereby, increases heat resistance and stiffness.

Product	**Manufacturer**	**Remarks**
Zetafax Resin	Dow Chemical Corp.	An ethyleneacrylic resin that has good adhesion to metals and a high chemical resistance. Zetabon is a Zetafax-coated metal tape for cable shielding.
Ultrathene UE630-81A	U.S. Industrial Chemicals Co.	An ethylene vinyl acetate copolymer for for rubber-like packaging film.
Aircoflex Resins	Air Reduction Co.	Similar copolymers for use as pigment binders, paper and textile coatings, and adhesives. Have higher molecular weight and better stability than polyethylene.

Product	Manufacturer	Remarks
Polythene and Alathon	Du Pont	Names for polyethylene. Used in the forms of molding powder, rod, sheet, tubes, and foil for packaging and paper coatings.
Agilene	American Agile Corp.	Is a polyethylene. The plastic can be cross-linked by irradiation. Irradiated polyethylene parts become thermoset and have increased strength, toughness, and higher heat resistance.
Irrathane	General Electric Co.	Irradiated polyethylene. The plastic can be cross-linked chemically by heating with carbon black and a diperoxide. When used as piping this method increases strength, improves weather resistance, and eliminates stress cracking.
Irrathene Tape SPT	General Electric Co.	A flexible irradiated polyethylene self-sealing insulating tape for corona-resistant electric cables. This tape can withstand temperatures to 260°F (127°C).
Fortiflex A	Celanese Corp.	A polyethylene with a specific gravity of 0.96 and a linear crystalline structure. Has a tensile strength of 4,500 lb/in^2 (30 MPa), flexural strength of 5,500 lb/in^2 (37 MPa), Rockwell hardness of R40, and will withstand operating temperatures above 400°F (204°C). Is used for rigid chemical piping. If used for piping and wire covering, small amounts of carbon black can be added to increase its resistance to the weather.
Fortiflex F-087	Celanese Corp.	Has a specific gravity of 0.938 and transfer elongation of 600%. Is used for packaging film and takes printing ink well.

Product	Manufacturer	Remarks
Microthene	U.S. Industrial Chemical Co.	A high density powder of 350 mesh for rotational molding of thin-walled parts.
Dylan	Koppers Co.	A low pressure linear polyethylene used for polyethylene fibers. Has a density of 0.95, a tensile strength of 3,500 lb/in.^{2} (23 MPa), elongation of 225%, and a softening point at 255°F (123°C).

The fibers and fabrics are marketed under trade names. One such trade name is Reevon, by Reeves Brothers, Inc. The fibers and fabrics are used as upholstery fabric woven of polyethylene monofilament.

Polyethylene foam is light weight, has negligible water absorption, and is used in sheet and film for thermal insulation, and for wire insulation.

Product	Manufacturer	Remarks
Orthofoam and Metafoam	Ludlow Papers	Polyethylene foam. Comes in sheets from 0.016 to 0.035 in. (0.041 to 0.089 cm) thick. The low density material has a tensile strength to 1,500 lb/in.^{2} (9 MPa). The high density material has a tensile strength to 12,000 lb/in.^{2} (82 MPa) with elongation of 2.5 to 5%.
Polyethylene DGDA-2580	Union Carbide Corp.	Foam is used for extruded insulation coatings on electric cables. Gives uniformly dispersed closed cells so that the material has about 30% gas by volume. Extruded coatings have a smooth surface, a tensile strength of 2,800 lb/in.^{2} (18 MPa), and a dielectric constant of 15 to 1.7.

Polyethylene film is resistant to oils, greases, and fatty acids; also has good tear strength and fold endurance, and the light weight gives a large area per pound. It is widely used for packaging.

Product	Manufacturer	Remarks
Tenite 161M	Eastman Chemical Products, Inc.	An extruding grade film that has a density of 0.923, tensile strength of 2,200 lb/in.^{2} (14 MPa), and elongation of 600%. When film is irradiated and stretched biaxially, it can be shrunk as much as 20% in all directions by applying a blast of hot air or dipping into water (180°F (82°C)). Films are used for packaging meats and poultry where a tight, close fit is desired.
Cryovac L	W.R. Grace & Co.	Is similar to Tenite 161M film. Is a high density polyethylene that has a high concentration of hydrogen atoms that are capable of slowing down or stopping fast neutrons. Sheets made with a small amount of boron to stop the low energy neutrons are used for atomic shielding where light weight is necessary.
Panelyte Sheet	St. Regis Paper Co.	Is a sheet film made for this purpose. Made of Petrothene 100, U.S. International Chemicals Co., a polyethylene containing 2% boron.

Polyethylene rubbers are rubber-like materials made by cross-linking with chlorine and sulfur, or they are ethylene copolymers. Chlorosulfonated polyethylene is a white spongy material. It has chlorine atoms and sulfonyl chloride groups spaced along the molecule. It is blended with rubber to add stiffness, abrasion resistance, and resistance to ozone, and also for wire covering.

Product	Manufacturer	Remarks
Hypalon S-2	Du Pont	Is a chlorinated polyethylene.
Plaskon CPF200	Allied Chemical Corp.	A chlorinated polyethylene containing containing about 73% chlorine. Is used for coatings and has a high resistance to acids and alkalies.

Product	Manufacturer	Remarks
Ethylene-propylene rubber	Various companies	A chemically resistant rubber of high tear strength.
Ethylene butadiene resin	Phillips Petroleum Co.	Can be vulcanized with sulfur to increase hardness and widen temperature range. For greater elongation a terpolymer with butene can be made.

Polyethylene of low molecular weight is used for extending and modifying waxes. Is also used in coating compounds to increase toughness, gloss, and heat-sealing properties.

Product	Manufacturer	Remarks
Epolene N-11	Eastman Chemical Products, Inc.	For blending with waxes. Has a molecular weight of 1,500, a density of 0.925, and a softening point at 103°C.
Epolene N	Eastman Chemical Products, Inc.	Used in paste polishes. Has a molecular weight of 2,500 to 3,000.
Epolene LVE	Eastman Chemical Products, Inc.	Used in paper and textile coatings. Is a low density polyethylene with a molecular weight of 1,500.
Epolene HDE	Eastman Chemical Products, Inc.	Used for self-polishing floor waxes to add hardness to the film. Has a molecular weight of 1,500, but a high density of 0956.

Such materials are called polyethylene wax, but they are not chemical waxes. They can be emulsified by oxidation, and they can be given additional properties by copolymerization with other plastics.

Product	**Manufacturer**	**Remarks**
Elvax	Du Pont	Is a copolymer of ethylene with vinyl acetate. Is compatible with vegetable and paraffin waxes. When added to these waxes it increases adhesiveness, gloss, toughness, and heat sealing.
Ladcote	LA. Dreyfus Co.	Is a copolymer of ethylene with vinyl acetate.
Chemetron 100	Chemetron Corp.	Is a modified ethylene wax. Is an ethylene stearamide and comes in powder or beads. Improves luster, pigment dispersion, and mar resistance in lacquers.

Polymethylene waxes are microcrystalline and have sharper melting points than the ethylene waxes. They are more expensive, but have high luster and durability.

Polybutylene plastics are rubber-like polyolefins with superior resistance to creep and stress cracking. Films of this resin have high tear resistance, toughness, and flexibility, and are used widely for industrial refuse bags. Chemical and electrical properties are similar to those of the polyethylene and polypropylene plastics.

Polymethyl pentene is a moderately crystalline polyolefin plastic resin that is transparent even in thick sections. Almost optically clear, it has a light transmission value of 90%. Parts molded of this plastic are hard and shiny with good impact strength down to -20°F (-29°C). Specific gravity (0.83) is the lowest of any commercial solid plastic. A major use is for molded food containers for quick frozen foods that are later heated by the consumer.

9.2.10 **Polypropylene Resins.** An important group of synthetic plastics used for molding resins, film, and texture fibers. Developed in 1957 in Italy and Germany, they are produced as polypropylene by catalytic polymerization of propylene, or may be copolymers with ethylene or other material. Propylene is a methyl ethylene ($CH_3CH:CH_2$) produced in the cracking of petroleum, and also used for making isopropyl alcohol and other chemicals. The boiling point is 48.2°C. It belongs to the class of unsaturated hydrocarbons known as olefins, which are designated by the word ending **ene.** These unsaturated hydrocarbons tend to polymerize and form gums, and thus are not used in fuels although they have anti-knock properties.

In polyproplyene plastics the carbon atoms linked in the molecular chain between the CH_2 units each have a CH_3 and an H attached as side links, with the bulky side groups spiraled regularly around the closely packed chain. The resulting plastic has a crystalline structure with increased hardness and toughness and a higher melting point. This type of stereosymmetric plastic has been called isotactic plastic. It can also be produced with butylene or styrene, and the general term for the plastics is polyolefins. Copolymers of propylene are termed polyallomers.

Polyproplyene is low in weight. The molded plastic has a density of 0.910, a tensile strength of 5,000 lb/in.^{2} (34 MPa), with elongation of 150%, and Rockwell hardness of R95. The dielectric strength is 1,500 volts per mil (59 x 10^6 volts per meter), dielectric constant 2.3, and a softening point at 150°C. Blown bottles of polypropylene have good clarity and are nontoxic. The melt flow is superior to that of ethylene. A unique property is that thin sections of polypropylene can withstand prolonged flexing. This characteristic has made polypropylenes popular for "living hinge" applications. In tests, they have been flexed over 70 million times without a failure.

The many different grades of polypropylenes fall into three basic groups: (1) homopolymers, (2) copolymers, and (3) reinforced and polymer blends. Properties of the homopolymers vary with molecular weight distribution and the degree of crystallinity. Commonly, copolymers are produced by adding other types of olefin monomers to the propylene monomers to improve properties, such as low temperature toughness. Copolymers are also made by radiation grafting. Polypropylenes are reinforced with glass or asbestos fibers to improve mechanical properties and increase resistance to deformation at elevated temperatures.

Product	**Manufacturer**	**Remarks**
Tenite	Eastman Chemical Products, Inc.	A polypropylene used for molded parts, film, fiber, pipe, and wire covering.
Olefane	Avisun Corp.	A polypropylene film used for packaging, has a specific gravity of 0.89. Is resistant to moisture, oils, and solvents. Is crystal clear and flexible. Can withstand temperatures to 250°F (121°C). The 0.001-in. (0.003-cm) film has 31,000 ft/lb (20,830 m/kg).
Dynafilm 200	U.S. Industrial Chemicals Co.	A polypropylene laminated with polyethylene for easy heat sealing for packaging. The 0.001-in. (0.003-cm) film has a strength of 3,000 lb/in.^{2} (20 MPa) and 400% elongation.

Product	Manufacturer	Remarks
Dynafilm 300	U.S. Industrial Chemicals Co.	Has the appearance, feel, and machine handling properties of a Cellophane film. Consists of oriented polypropylene coated on both sides with vinyl acetate. The film ranges in thicknesses of 0.0008 to 0.0012 in. (0.0020 to 0.0030 cm) and heat seals at 100°F (38°C).

Polypropylene fiber was originally produced in Italy under the name of Merkalon. Unless modified, it is more brittle at low temperatures and has less light stability than polyethylene, but it has about twice the strength of high density linear polyethylene. Monofilament fibers are used for filter fabrics. They have a high abrasion resistance and a melting point at 310°F (154°C).

Multifilament yarns are used for textiles and rope. Polypropylene rope is used for marine hawsers, will float on water, and does not absorb water like Manila rope. It has a permanent elongation, or set, of 20%, compared to 19% for nylon rope and 11% for Manila rope. The working elasticity is 16% compared to 25% for nylon and 8% for Manila. The tensile strength of the rope is 59,000 lb/in.^{2} (406 MPa). Fine denier multi-filament polypropylene yarn used for weaving and knitting dyes easily and comes in many colors.

Chlorinated polypropylene is used in coatings, paper sizing, and adhesives. It has good heat and light stability, and high abrasion and chemical resistance.

9.2.11 Polystyrene. Often referred to as styrene resin, it is used for molding, in lacquers, and for coatings formed by the polymerization of monomeric styrene, which is a colorless liquid of the composition $C_6H_5CH{:}CH_2$, specific gravity 0.906, and boiling point at 145°C. It is made from ethylene, and is ethylene with one of the hydrogen atoms replaced by a phenyl group. It is also called phenyl ethylene and vinyl benzene. As it can be made by heating cinnamic acid, $C_6H_5CH{:}CHCO_2H$, an acid found in natural balsams and resins, it is also called cinnamene. In the form of vinyl toluene, which consists of mixed isomers of methyl styrene, the material reacts with drying oils to form alkyd resins for paints and coatings.

The polymerized resin is a transparent solid, very light in weight with a specific gravity of 1.054 to 1.070. The tensile strength is 4,000 to 10,000 lb/in^2 (27 to 68 MPa), a compressive strength of 12,000 to 17,000 lb/in.^{2} (82 to 117 MPa), and a dielectric strength of 450 to 600 volts per mil (18 to 24 x 10^6 volts per meter). It is also tougher and stronger at low temperatures than most other plastics. It is valued as an electrical insulating material, and the films are used for wrapping cable.

When produced from methyl stryene, parts have a hardness to Rockwell M83, with tensile strengths to 8,900 lb/in^2 (61 MPa), and a stiffness that makes them suitable for such products as cabinets and housings. Dielectric strength is also high, above 800 volts per mil (32 x 10^6 volts per meter). The resin is also used for electronic parts. The heat distortion temperature is 215°F (101°C).

Styrenes are subject to creep. Therefore, the long term bearing strength (over 2 weeks) is only about one-third the short time tensile strength. Since their maximum useful service temperature is about 160°F (71°C), their use is restricted to room-temperature applications. Because of their low cost and ease of processing, polystyrenes are widely used for consumer products. The impact gradesand glass-filled types are used for engineering parts and semi-structural applications. Also, polystyrene foams are used more than all of the foam plastics. Because of good processing characteristics, polystyrenes are produced in a wide range of forms. They can be extruded, injection-, compression-, and blow-molded, and thermo formed. They are also available as film sheets and foam.

Polystyrenes can be divided into the following major types: general purpose grades, the lowest in cost, are characterized by clarity; colorability; and rigidity. They are applicable where appearance and rigidity, but not toughness, are required. Common uses are: wall tiles, compact cases, knobs, brush backs, and container lids. Impact grades of polystyrenes are produced by physically blending styrene and rubber. Grades are generally specified as medium, high, and extra high. As impact strength increases, rigidity decreases.

<u>Medium impact grades</u> are used where a combination of moderate toughness and translucency is desired. For example, products such as containers, closures, and small radio cabinets.

<u>High impact grades</u> have improved heat resistance and surface gloss. They are used for refrigerator door liners and crisper trays, containers, toys, and heater ducts in automobiles.

<u>Extra high impact grades</u> are quite low in stiffness. Their use is limited to parts subject to high speed loading.

Styrene can be polymerized with butadiene, acrylonitrile, and other resins. The terpolymer, acrylonitrile-butadiene-styrene (ABS) is one of the common combinations. Styrene-acrylonitrile (SAN) has excellent resistance to acids, bases, salts, and some solvents. It also is among the stiffest of the thermoplastics, with a tensile modulus of 400,000 to 550,000 lb/in^2 (2,757 to 3,791 MPa). Styrene resins for molding are now marketed under a wide variety of trade names, with or without fillers and reinforcing agents. Many of these are copolymer resins, or are modified with plasticizers or cross-linking agents.

Product	Manufacturer	Remarks
Victron	U.S. Rubber Ro.	A clear transparent polystyrene.
Lustron	Monsanto	A polystyrene in various grades.
Stymer	---	A polystyrene resin for sizing textiles.
Piccotex	Pennsylvania Industrial Chemical Corp.	A styrene copolymer in solid form soluble in mineral spirits for use in paints, coatings, and adhesives.
Styron and Styraloy	Dow Chemical Co.	Polystyrene molding resins.
Tyril	Dow Chemical Co.	Originally called Styrex, is a styrene-acrylonitrile copolymer.
Loalin	Catalin Corp.	A polystyrene with a specific gravity of 1.05 to 1.07. Is crystal clear and will take light pastel colors. In the clear form it transmits 90% light. Is water-resistant and has a dielectric strength of 500 to 700 volts per mil (1,970 to 2,758 volts per meter). It is not affected by alcohol, acids, or alkalies, but is soluble in aromatic hydrocarbons. It is preferably injection molded.
Exon 860	Firestone Plastics Co.	A soft grade polystyrene that molds easily into products of high flexibility. The molded material has a tensile strength of 6,000 lb/in.^{2} (41 MPa) with elongation of 50%, Rockwell hardness of R100, and a dielectric strength of 510 volts per mil (20 x 10^6 volts per meter).

Product	**Manufacturer**	**Remarks**
Fibertuff	Koppers Co.	Marketed in pellets for injection molding. Is 60% polystyrene and 40% glass fiber. Molded parts have a specific gravity of 1.33, a tensile strength of 11,000 lb/in.^{2} (75 MPa), heat distortion point of 220°F (104°C), and high impact resistance.

Styrene-butylene resins are copolymers that mold easily and produce thermoplastic products of low water absorption and good electrical properties. They have strength equal to the vinyls with greater elongation. Foamed polystyrene is available in blocks and heavy sheets for thermal insulation. It weighs about 1 lb/ft^3 (16 kg/m^3) and is rigid. Flexible styrene foam is also made into very thin sheets for wrapping frozen foods. It is grease resistant and a good insulator, and is low in cost. Styrene is now best known for its use in synthetic rubbers, but the difference between resins and rubbers is flexibility.

9.2.12 Urethanes (also known as polyurethanes). A group of plastic materials based on polyether or polyester resin. The chemistry involved is the reaction of a diisocyanate with a hydroxyl-terminated polyester or polyether to form a higher molecular weight prepolymer, which in turn is chain-extended by adding difunctional compounds containing active hydrogens, such as water, glycols, diamines, or amino alcohols. The urethanes are block-polymers capable of being formed by a literally indeterminate number of combinations of these components. The urethanes have excellent tensile strength and elongation, good ozone resistance, and good abrasion resistance. Combinations of hardness and elasticity not available with other systems are possible in urethanes, ranging from Shore hardness of 15 to 30 on the “A” scale for most industrial or mechanical goods applications, to the 70 to 85 Shore “D” scale. Urethanes are fairly resistant to many chemicals, such as aliphatic solvents, alcohols, ether, certain fuels, and oils. They are attacked by hot water, polar solvents, and concentrated acids and bases.

Urethane elastomers are made with various isocyanates, the principal ones being tolylene diisocyanate (TDI) and 4,4’-diphenylmethane diisocyanate (MDI) reacting with linear polyols of the polyester and polyether families. Various chain extenders, such as glycols, water, diamines, or aminoalcohols, are used in either a prepolymer or a one-shot of system to form the long-chain polymer.

Urethane textile fibers were first made in Germany under the name of Igamide. The Fiber K, or Lycra, of Du Pont, and the Vyrene, of the U.S. Rubber Co., are flexible urethane fibers used for flexible garments. They are more durable than ordinary rubber fibers or filaments, and are 30% lighter in weight. They are resistant to oils and to washing chemicals, and also have the advantage that they are white in color. Spandex fibers are stretchable fibers produced from a fiber forming substance in which a long chain of synthetic molecules are composed of a segmented polyurethane. Stretch before break of these fibers is from 520 to 610%, compared to 760% for rubber. Recovery is not as good as rubber. Spandex is white and dyeable. Resistance to chemicals is good but is degraded by hypochlorides.

9.2.13 Polyvinyl Resins. A group of products varying from liquids to hard solids, made by the polymerization of ethylene derivatives, used in finishes, coatings, and molding resins, or it can be made directly by reacting acetic acid with ethylene and oxygen. In general, the term vinyl designates plastics made by polymerizing vinyl chloride; vinyl acetate, or vinylidene chloride, but may include plastics made from styrene and other chemicals.

The term is generic for compounds of the basic formula RCH:CR’CR". The simplest are the polyesters of vinyl alcohol, such as vinyl acetate. This resin is lightweight, with a specific gravity of 1.18, and is transparent, but it has poor molding qualities and its strength is no more than 5,000 lb/in.^{2} (34 MPa). The vinyl resins are brittle at low temperatures. Elvacet, of Du Pont, and Lemac, of the American Monomer Corp., are vinyl acetate molding resins. But the vinyl halides, CH_2:CHX also polymerize readily to form vinylite resins, which mold well, have tensile strengths to 9,000 lb/in^2 (62 MPa), high dielectric strength, and high chemical resistance, and a wide range of useful resins is produced by copolymers of vinyl acetate and vinyl chloride. Various grades of Bakelite, Geon, Tygon, and other resins are these chloride acetate copolymers.

Vinyl alcohol, CH_2:CHOH, is a liquid boiling at 96°F (35.5°C). Polyvinyl alcohol is a white, odorless, tasteless powder, which when dry forms a colorless and tough film. The material is used as a thickener for latex, in chewing gum, and for sixes and adhesives. It can be compounded with plasticizers and molded or extruded into tough and elastic products. Hydrolized polyvinyl alcohol has greater water resistance, higher adhesion, and its lower residual acetate gives lower foaming. Soluble film, for packaging detergents and other water-dispersible materials to eliminate the need of opening the package, is a clear polyvinyl alcohol film. Textile fibers are also made from polyvinyl alcohol, either water-soluble or insolubilized with formaldehyde or another agent. Vinal, manufactured by the Air Reduction Chemical Co., is a polyvinyl alcohol textile fiber that is hot-drawn by a semi-melt process and insolubilized after drawing. The fiber has a high degree of orientation and crystallinity, which gives good strength and is resistant to water. Polyvinyl alcohol fibers are called Vinylon in Europe and Kuravilon in Japan.

Vinyl alcohol reacted with an aldehyde and an acid catalyst produces a group of polymers known as vinyl acetal resins, and separately designated by type names, as polyvinyl butyral and polyvinyl formal. The polyvinyl alcohols are called Solvars, and the polyvinyl acetates are called Gelvas. The vinyl ethers range from vinyl methyl ether, CH_2:$CHOCH_3$, to vinyl ethylhexyl ether, from soft compounds to hard resins. Vinyl ether is a liquid which polymerizes, or can react with hydroxyl groups to form acetal resins. Gantrez M, of General Aniline & Film Corp., is a water-soluble polyvinyl methyl ether for use in paints, inks, and adhesives. Alkyd vinyl ethers are made by reacting acetylene with an alcohol under pressure, producing methyl vinyl ether, ethyl vinyl ether, or butyl vinyl ether. They have reactive double bonds that can be used to copolymerize with other vinyls to give a variety of physical properties.

Polyvinyl formals, Formvars, are used in molding compounds, wire coatings, and impregnating compounds. It is one of the toughest of the thermoplastics. Formvar, of the Shawinigan Products Corp., has a specific gravity of about 1.3, a tensile strength up to 12,000 lb/in^2 (82 MPa), elongation from 5 to 20%, Rockwell hardness of M85, and dielectric strength of 450 volts per mil (17 x 10^6 volts per meter). This type of plastic is resistant to alkalies but is attacked by acids.

A plastisol is a vinyl resin dissolved in a plasticizer to make a pourable liquid without a volatile solvent for casting. The poured liquid is solidified to increase viscosity. The polyvinyl acetals, Alvars, are used in lacquers, adhesives, and phonograph records. The transparent polyvinyl butyrals, Butvars, are used as interlayers in laminated glass. They are made by reacting polyvinyl alcohol with butyraldehyde, C_3H_7CHO. Vinal is a general name for vinyl butayl resin used for laminated glass.

Vinyl acetate is a water-white mobile liquid with a boiling point of 70°C, usually shipped with a copper salt to prevent polymerization in transit. The composition is CH_3:COO:CH:CH_2. It may be polymerized in benzene and marketed in solution, or in water solution for use as an extender for rubber, and for adhesives and coatings. The higher the polymerization of the resin, the higher the softening point of the resin. The formula for polyvinyl acetate resin is given as $(CH_2\text{:CHOOCCH}_3)_x$. It is a colorless, odorless thermoplastic with a density of 1.189, unaffected by water, gasoline, or oils, but soluble in the lower alcohols, benzene, and chlorinated hydrocarbons.

Polyvinyl acetate resins are stable to light, transparent to ultraviolet light, and are valued for lacquers and coatings because of ther high adhesion, durability, and ease of compounding with gums and resins. Resins of low molecular weight are used for coatings, and those of high molecular weight for molding.

Product	**Manufacturer**	**Remarks**
Darex and Everflex	W.R. Grace &	Paint and coating resins.
Vinylite and Vinyloid	Union Carbide	Vinyl acetate resins for molding.

Product	**Manufacturer**	**Remarks**
Wood Glu	Paisley Products, Inc.	A milky water dispersion of polyvinyl acetate used as an adhesive for wood and paper. Vinyl acetate will copolymerize with maleic acrylonitrile, or acrylic esters. With ethylene it produces a copolymer latex of superior toughness and abrasion resistance for coatings.
Aircoflex 500	Air Reduction Co.	A vinyl acetate ethylene copolymer latex.

Vinyl chloride, CH_2CHCl, also called ethenyl chloride and chloroethylene, produced by reacting ethylene with oxygen from the air and ethylene dichloride, is the basic material for the polyvinyl chloride resins. It is a gas. The plastic was produced originally in Germany under the name of Igelite for cable insulation and as Vinnol for tire tubes. The tensile strength of the plastic may vary from the flexible resins with about 3,000 lb/in.^{2} (20 MPa) and Shore hardness of 90. The dielectric strength is high, up to 1,300 volts per mil (52 x 10^6 volts per meter). It is resistant to acids and alkalies. Polyvinyl chloride usually comes as a white powder for molding or extruding, but PVC pearls, of the Escambia Chemical Corp., is the material made by a water-suspension process in the form of white porous particles capable of easily absorbing a high proportion of plasticizer.

Product	**Manufacturer**	**Remarks**
Polvin and Opalon	Monsanto	Polyvinyl chloride resins.
Ultron	Monsanto	Polyvinyl chloride film.

Unplasticized polyvinyl chloride is used for rigid chemical-resistant pipe.

Kraloy D-500	Kraloy Plastic Pipe Co.	Polyvinyl chloride in rigid pipe.
Carlon V	Carlon Products	Polyvinyl chloride in rigid pipe.
Vyflex Sheet	Kaykor Industries, Inc.	Rigid unplasticized polyvinyl chloride in sheets of making acid tanks, ducts, and flumes.

Polyvinyl chloride sheet, unmodified, may have a tensile strength of 8,200 lb/in.^{2} (57 MPa), flexural strength of 12,600 lb/in^2 (86 MPa), and a light transmission of 78%. But in bends or comers of moldings, or in folds of a sheet, the resin shows opaque whitening. This can be eliminated by modifying the resin with an acrylic. The resins have improved processing qualities and flexibility, especially for blown bottles and extruded parts, but the light transmission is reduced.

Product	**Manufacturer**	**Remarks**
Acryloid KM-607	Rohm & Haas	A white acrylic powder. When used in polyvinyl sheet to a content of 20%, it gives a tensile strength of 6,700 lb/in^2 (46 MPa) and a light transmission of 72%.

Vinylidene chloride plastics are derived from ethylene and chlorine polymerized to produce a thermoplastic with softening point of 240 to 280°F (116 to 138°C). The resins are noted for their toughness and resistance to water and chemicals. The molded resins have a specific gravity of 1.68 to 1.75, tensile strength of 4,000 to 7,000 lb/in.^{2} (27 to 48 MPa), and flexural strength of 15,000 to 17,000 lb/in.^{2} (103 to 117 MPa).

Product	**Manufacturer**	**Remarks**
Saran	Dow Chemical Co.	A vinylidene chloride plastic extruded into tubes for handling chemicals, brines, and solvents to temperatures as high as 275°F (135°C). Is also extruded into strands and woven into a box-weave material as a substitute for rattan.
Saran Latex	Dow Chemical Co.	Water dispersion of the plastic, used for coating and impregnating fabrics. For coating food-packaging papers, it is waterproof and greaseproof, is odorless and tasteless, and gives the papers a high gloss. Saran is also produced as a strong transparent film for packaging.
Saranex	Dow Chemical Co.	A Saran film laminated with polyethylene sheet to give it heat-sealing qualities.

Product	**Manufacturer**	**Remarks**
Saran Bristles	Dow Chemical Co.	Bristles on brushes that are made in diameters from 0.10 to 0.20 in. (0.025 to 0.051 cm).
Velon	Firestone Tire & Rubber Co.	Material used for screens and fabrics.
Zetex	B.F. Goodrich Co.	A polyvinylidene cyanide.

Vinyl benzoate is an oily liquid of the composition CH_2:$CHOOCC_6H_5$, which can be polymerized to form resins with higher softening points than polyvinyl acetate, but are more brittle at low temperatures. These resins, copolymerized with vinyl acetate, are used for water-repellent coatings.

Vinyl crotonate, $CH_2CHOOCCH$:$CHCH_3$, is a liquid with a specific gravity of 0.9434. Its copolymers are brittle resins, but it is used as a cross-linking agent for other resins to raise the softening point and to increase abrasion resistance.

Vinyl formate, CH_2:$CHOOCCH$, is a colorless liquid which polymerizes to form clear polyvinyl formate resins that are harder and more resistant to solvents than polyvinyl acetate. The monomer is also copolymerized with ethylene monomers to form resins for mixing in specialty rubbers.

Methyl vinyl pyridine, $(CH_3)(CHCH_2)C_5H_3N$, is produced by the Phillips Chemical Co. for making resins, fibers, and oil-resistant rubbers. It is a colorless liquid with a boiling point of 64.4°C. The active methyl groups give condensation reactions, and will copolymerize with butadiene, styrene, or acrylonitrile.

Polyvinyl carbazole, under the name of Luvican, was used in Germany as a mica substitute for high frequency insulation. It is a brown resin that softens at 150°C.

An adhesive to replace rubber cement was made in Germany by combining Oppanol C, a high molecular weight polyvinyl isobutylene ether, with Igovin, a low molecular weight polyvinyl isobutyl ether, and compounding with zinc oxide and wool grease.

Product	Manufacturer	Remarks
Marvinol VR-10	Glenn L. Martin Co.	Coatings and impregnations produced by the reaction of acetylene and hydrogen chloride with a catalyst. It is also used for casting into films.
Marvinol Resins	U.S. Rubber Co.	Are polyvinyl chloride. The vinyl plastics are used for wall tile and sheet wall coverings. They are adaptable to bright colors, are nonstaining, and easily cleaned.
Kalitex	U.S. Plywood Corp.	A vinyl sheet wall covering with an embossed burlap-weave pattern with colors on the reverse side.
Vinyon	Union Carbide	A vinyl chloride-acetate fiber in various grades. Since it is resistant to strong acids and alkalies, Vinyon fiber is made into filter cloth for temperatures not above 160°C. It is also used in wool mixtures. It is produced by the copolymerization of vinyl chloride and vinyl acetate.
Vinyon N	Union Carbide	A vinyl chloride-acrylonitrile copolymer marketed as a fine, silk like textile fiber. The fiber has high strength, an elongation of 30%, and is nonflammable. It has a light yellow color and is easily dyed.
Carilan	---	A Japanese vinyl acetate fiber.

The possibility of variation in vinyl resins by changing the monomer, copolymerization, and difference in compounding is so great that the term vinyl resin is almost meaningless when used alone. The resins are marketed under a continuously increasing number of trade names. In general, each resin is designed for specific uses, but not limited to those uses.

Product	**Manufacturer**	**Remarks**
Advagum	Advance Solvents & Chemical Corp.	A highly plasticized vinyl copolymer used as an extender for rubbers.
Pliovac	Goodyear Tire & Rubber Co.	A high molecular-weight vinyl chloride for coatings, tiling, and extrusions.
Victron	Naugatuck Chemical Co.	Vinyl acetal resins.
Saflex	Monsanto Co.	Vinyl acetal resins.
Butacite	Du Pont	A clear polyvinyl butyral for laminated glass.
Formex	General Electric Co.	A vinyl formal resin for insulating wire.
Boltaron 6200	Bolta Products, Inc.	A rigid unplasticized polyvinyl chloride in sheets, rods, and pipes. Can resist thermal distortion below 175°F (80°C).
Ingerin	---	A German polyvinyl ether.
Cosal	---	Made from vinyl isobutyl ether.
Mipolam	---	A German vinyl polymer for floor coverings.
Kynar	Pennwalt	A polymer of vinylidene fluoride, $CH_2:CF_2$, with a high molecular weight, about 500,000. It is a hard, white thermoplastic resin with a slippery surface, and has a high resistance to chemicals. It resists temperatures to 650°F (343°C), and does not become brittle at low temperatures. It extrudes easily, and has been used for wire insulation, gaskets, seals, molded parts, and piping.

9.3 THERMOSETTING APPLICATIONS.

9.3.1 Acrylonitrile-Butadiene-Styrene (ABS). Common trade names for these materials are Cycolac, Kralastic, and Lustran. They are opaque and distinguished by a good balance of properties, including high impact strength, rigidity, and hardness over a temperature range of -40 to 230°F (-40 to 110°C). Compared to other structural or engineering plastics, they are considered to fall at the lower end of the scale. Medium impact grades are hard, rigid, and tough, and are used for appearance parts that require high strength, good fatigue resistance, and surface hardness and gloss. High impact grades are formulated for similar products where additional impact strength is gained at some sacrifice in rigidity and hardness. Low impact grades have high impact strength down to -40°F (-40°C). Again, some sacrifice is made in strength, rigidity, and heat resistance. Heat resistant, high strength grades provide the best heat resistance -- continuous use up to about 200°F (93°C), and a 264 lb/in.^{2} (2 MPa) heat distortion temperature of around 215°F (102°C). Impact strength is about comparable to that of medium impact grades, but strength, modulus of elasticity, and hardness are higher. At stresses above their tensile strength, ABS plastics usually yield plastically instead of rupturing, and impact failures are ductile. Because of relatively low creep, they have good, long term load-carrying ability. This low creep plus low water absorption and relatively high heat resistance provide ABS plastics with good dimensional stability. ABS plastics are readily processed by extrusion, injection molding, blow molding, calendering, and vacuum forming. Resins have been developed especially for cold forming or stamping from extruded sheets. ABS plastics are used in helmets, refrigerator liners, luggage tote trays, housings, grills for hot air systems, and pump impellers. Extruded shapes include tubing and pipe. ABS plated parts are now in wide use, replacing metal parts in the automotive and appliance field.

9.3.2 Alkyd Resins. A group of thermosetting synthetic resins known chemically as hydroxycarboxylic resins, of which the one produced from phthalic anhydride and glycerol is representative. They are made by the esterification of a polybasic acid with a polyhydric alcohol, and have the characteristics of homogeneity and solubility that make them especially suitable for coatings and finishes, plastic molding compounds, caulking compounds, adhesives, and plasticizers for other resins. The resins have high adhesion to metals; are transparent, color easy, tough, flexible, heat- and chemical-resistant; and have good dielectric strength. They vary greatly with the raw materials used and with varying percentage compositions, from soft rubbery gums to hard brittle solids. Phthalic anhydride imparts hardness and stability. Maleic acid makes a higher melting point resin. Azelaic acid gives a softer and less brittle resin. The long chain dibasic acids, such as adipic acid, give resins of great toughness and flexibility. In place of glycerol the blycols yield soft resins, and sometimes the glycerol is modified with a proportion of glycol. The resins are reacted with oils, fatty acids, or other resins, such as urea or melamine, to make them compatible with drying oils and to impart special characteristics.

Since alkyd resins are basically esterification products of innumerable polybasic acids and polyhydric alcohols, and can be modified with many types of oils and resins, the actual number of different alkyd resins is unlimited, and the users' specification is normally by service requirements rather than composition. Short-oil alkyds, with 30 to 45% nonoxidizing oils, are used in baking enamels, while the long-oil alkyds, with 56 to 75% oxidizing oils, are soluble in mineral spirits and are used for brushing enamels.

Alkyd coatings are used for such diverse applications as air-drying water emulsion wall paints and baked enamels for automobiles and applicances.

The properties of oil-modified alkyd coatings depend on the specific oil used as well as the percentage of oil in the composition. In general, they are comparatively low in cost and have excellent color retention, durability, and flexibility, but only fair drying speed, chemical resistance, heat resistance, and salt spray resistance. The oil-modified alkyds can be further modified with other resins to produce resin-modified alkyds. The resin is sometimes added during manufacture of the alkyd and becomes an integral part of the alkyd, or the modifying resin is blended with the alkyd when the paint is formulated. When mixed with urea formaldehyde or melamine resin, harder and more resistant baked enamels are produced. Alkyds blended with ehtyl cellulose are used as tough flexible coatings for electric cable. Other resins blended with alkyds to produce special or improved properties include phenolic, rosin, vinyl, and silicone.

Alkyd plastics molding compounds are composed of a polyester resin and usually a diallyl phthalate monomer plus various inorganic fillers, depending on the desired properties. The raw material is produced in three forms: granular, putty, and glass-reinforced. As a class, the alkyds have excellent heat resistance up to about 300°F (150°C), high stiffness, and moderate tensile and impact strength. Their low moisture absorption combined with good dielectric strength makes them particularly suitable for electronic and electrical hardware such as switchgear, insulators and parts for motor controllers, and automotive ignition systems. They are easily molded at low pressures and cure rapidly. Amberlac and Duraplex, manufactured by Rohm & Haas Co., are alkyd resins that come in a wide range of formulations.

Paraplex resins are oil-modified soft resins used for coatings for textiles and paper, and for blending with cellulose plastics for better adhesion on lacquers. Paraplex, P-43HV, however, is a polyester-styene copolymer supplied as a clear liquid for laminating, molding, or casting at low pressure.

Product	Manufacturer	Remarks
Aquaplex	Rohm & Haas Co.	A group of oil-modified resins for use in water paints.
Teglac	American Cyanamid Co.	Resins used for indoor finishes and clear-coat varnishes, are hard alkyd resins made with natural resin acids as blending agents.
Cycopol	American Cyanamid Co.	An alkyd-styrene copolymer resing for fast drying enamels. Gives high gloss and durability.
Beckosol 1341	Reichhold Chemicals, Inc.	A phenol-modified alkyd resing for fast drying enamels.
Petrex Resin	Hercules, Inc.	A series of alkyd resins used in lacquers, varnishes, adhesives, and inks.
Arpolaz 1248-M	U.S. Industrial Chemicals, Inc.	A high gloss phthalic alkyd resin, soluble in mineral spirits, for industrial finishes.
Iso Burnok 32-0	T.F. Washburn Co.	A soybean oil isothalic alkyd used as a vehicle for thixotropic paints. Has high clarity and is odorless.
Dyal	Sherwin-Williams Co.	An alkyd resin for finishes.
Amalite and Amavar	American Alkyd	Alkyd resins for finishes.
Palaskon Alkyd	Allied Chemical Corp.	A mineral filled alkyd molding powder used for electrical parts having good arc resistance and heat resistance to 350°F (176°C).
Neolyn Resins	Hercules, Inc.	Alkyd resins produced from rosin. They are used as modifiers for nitro-cellulose and for vinyl resins in lacquers and adhesives to add toughness to the film.

Product	Manufacturer	Remarks
Cellolyn 501	Hercules, Inc.	A lauric acid-penta-erythritol alkyd used in durable, color stable nitrocellulose lacquers.

A series of alkyd resins is produced when maleic anhydride or fumaric acid is reacted with rosin and then esterified with glycerol or other polyhydric alcohol. Isocyanate resins are linear alkyds lengthened by isocyanates and then treated with a glycol or a diamine to cross-link the molecular chain. Plastics made from these resins are noted for good abrasion resistance.

9.3.3 **Epoxy Resins.** A class of synthetic resins characterized by having in the molecule a highly reactive oxirane ring of triangular configuration consisting of an oxygen atom bonded to two adjoining and bonded carbon atoms. They are usually made by the reaction of epichlorohydrin with phenol compounds, but epoxidation is also done by the oxidation of a carbon-to-carbon double bond with an organic peracid such as peracetic. Epichlorohydrin is produced from ally1 chloride, and is a colorless liquid with a chlorine atom and an epoxide ring. The dipoxy resins made by the oxidation of olefins with peracetic acid have higher heat resistance than those made with bisphenol. Epoxidation is not limited to making plastic resins, and epoxidized oils, usually epoxidized with peracetic acid, are used as paint oils and as plasticizers for vinyl resins.

Epoxy resins are more costly than many other resins, but, because of their unusual combinations of high mechanical and electrical properties, they are important, especially for such uses as adhesives, resistant coatings, and for encapsulation of electron units. For encapsulation, they cast easily with little shrinkage. They have very high adhesion to metals and nonmetals, heat resistance from 350 to 700°F (177 to 260°C), dielectric strength to 550 volts per mil (22 volts per meter), and Rockwell hardness of M110. The tensile strength may be up to 12,000 lb/in^2 (82 MPa), with elongation to 2 to 5%, but some resilient encapsulating resins are made with elongation to 150% with lower tensile strengths. The resins have high resistance to common solvents, oils, and chemicals.

An unlimited variety of epoxy resins is possible by varying the basic reactions with different chemicals or different catalysts, or both, by combining with other resins, or by cross-linking with organic acids, amines, and other agents. To reduce cost when used as laminating adhesives they may be blended with furfural resins, giving adhesives with high strength and high chemical resistance. Blends with polyamides have high dielectric strength, mold well, and are used for encapsulating electrical components.

Product	Manufacturer	Remarks
Epon Resins	Shell Chemical Corp.	Epoxy resins made with epichlorohydrin and bisphenols.
Kern-Krete	Sherwin-Williams Co.	Coating for ceramic blocks.
Erkopon	Earl Paint Corp.	Coating for tanks based on ethoxyline resins or polyarly ethylene oxide condensates. Made from epichlorohydrin and bisphenol with an ethylenediamine catalyst.

By using a polyamide curing agent, an epoxy can be made water-emulsifiable for use in water-based paints. The water-soluble epoxy of General Mills, Inc., is a reaction product of Genepoxy M195, a bisphenol epichlorohydrin epoxy resin, and Versamid 265-WR70, an ethylene glycol ether acetate.

Product	Manufacturer	Remarks
Resin X-3441	Dow Chemical Co.	An epoxy resin with 19% bromine in the molecule. It is flame resistant. Another grade, with 49% bromine, is a semi-solid used for heat resistant adhesives and coatings.

Oxiron resins, of FMC Corp., are epoxidized polyolefins. They have five or more reactive epoxy groups along each molecule of the chain instead of the usual two terminal epoxy groups on each molecule. With dibasic acids or anhydrides they form strong, hard resins of high heat resistance; or resins of lower viscosity are made for laminating and casting.

Product	Manufacturer	Remarks
Novolac DEN 438	Dow Chemical Co.	An epoxy resin with a high distortion point of 570°F (299°C), made by the reaction of epichlorohydrin with a phenol-formaldehyde resin with an anhydride catalyst. Has a very high strength at elevated temperatures as an adhesive for laminates.

Product	Manufacturer	Remarks
Narmco Adhesive	Whittaker Corp.	An epoxy adhesive with a sheer strength of 5,500 lb/in^2 (38 MPa).

Epoxies can be copolymerized with other resins. Epoxy-acrylate resin, used for glass-fiber laminates, combines the resistance and adhesiveness of the epoxy with the fast cure and strength of the acrylate.

Product	Manufacturer	Remarks
ERRA-0300	Union Carbide	An epoxy resin that has cyclopentyl oxide terminal groups instead of diglycidyl ether. Has a yield strength of 18,200 lb/in^2 (123 MPa) at 392°F (200°C), a heat deflection temperature of 434°F (223°C).
Aracast	Ciba-Geigy Corp.	Epoxy resins produced by a reaction of hydantoin with epichlorohydrin. Hydantoin is a nitrogen-containing heterocyclic compound. They have high mechanical properties, good dielectrical characteristics, and ultraviolet light resistance. They retain light transmission properties after thermal aging of several thousand hours at 302°F (150°C).

Novoloids are fibers that contain at least 85%, by weight, cross-linked novalac epoxies. Kynol is a novoloid noted for its resistance to exceptionally high temperatures. At 1,920°F (1,049°C) the fiber is virtually unaffected. The fiber also has high dielectric strength and excellent resistance to all organic solvents and nonoxidizing acids.

A family of one-component epoxy resins, named Arnox, are produced by General Electric Co. Suitable for compression, transfer, injection molding, filament winding, and pultrusion, they cure rapidly at temperatures of 250 to 350°F (121 to 177°C). The compression and transfer molding grade is a black, mineral-filled compound. The injection molding grade is a pelletized glass-fiber reinforced compound with a shelf life of 9 to 12 months below 80°F (27°C).

9.3.4 Melamine Resins. A synthetic resin of alkyd type made by reacting melamine with formaldehyde. The resin is thermosetting, colorless, odorless, and resistant to organic solvents. It is more resistant to alkalies and acids than urea resins, has better heat and color stability, and is harder. The melamine resins are used as molding plastics, and are also valued for dishes for hot food or acid juices. They do not soften or warp when washed in hot water. Melamine, a trimer of cyanamide, has the composition $(N:C"NH_2)_3$.

Melamine may be made by reacting urea with ammonia at elevated temperatures and pressure. It has a specific gravity of 1.56 and melting point of 354°C. Melamine alone imparts to other resins a high gloss and color retention. The melamine resins have good adhesives but are too hard for use alone in coatings and varnishes. They are combined with alcohol-modified urea-formaldehyde resins to give coating materials of good color, gloss, flexibility, and chemical resistance.

Product	**Manufacturer**	**Remarks**
Uformite MU-56	Resinous Products & Chemical Co.	A urea-modified melamine-formaldehyde resin used for coatings and varnishes.
Melmac 1077	American Cyanamid Co.	A melamine-formaldehyde molding resin with cellulose filler. Has a tensile strength of 7,500 lb/in.^{2} (52 MPa) and dielectric strength of 325 volts per mil (12.8 x 10^6 volts per meter).
Melmac 592	American Cyanamid Co.	Has a mineral filler. Has a dielectric strength of 400 volts per mil (16 x 10^6 volts per meter) and will withstand temperatures to 300°F (149°C).
Melurac 300	American Cyanamid Co.	A melamine-urea-formaldehyde resin with a lignin extender used as an adhesive for water-resistant plywood.
Melmac 483	American Cyanamid Co.	A phenol-modified melamine-formaldehyde resin solution used for laminating fibrous materials.
Melmac 404	American Cyanamid Co.	A highly translucent melamine-formaldehyde resin for molding high-gloss buttons.

Product	Manufacturer	Remarks
Lanoset	- - -	A methylol-melamine made by alkylating a melamine-formaldehyde resin with methyl alcohol. It is used for shrinkproofing woolen fabrics.
Resimene 812	Monsanto	A colorless melamine-formaldehyde resin powder that can be dissolved in water or ethyl alcohol, for impregnating paper or fabrics, or for laminating.

9.3.5 Phenol-Formaldehyde Resin. A synthetic resin, commonly known as phenolic, made by the reaction of phenol and formaldehyde, and used as a molding material for making mechanical and electrical parts. It was the earliest type of hard, thermoset synthetic resins. It is the most widely used groups of plastics for a variety of products because of its combination of strength, chemical resistance, electrical properties, glossy finish, and nonstrategic abundance of low cost raw materials. The resins are also used for laminating, coatings, and casting resins.

The reaction was known as early as 1872 but was not used commercially until much later. A condensation product of 50 parts phenol and 30 parts 40% formaldehyde made under an English patent of 1905 was called Resinite, and was originally offered as a substitute for Celluloid. Various modifications were made by other inventors. Redmanol was not of the first of the American products by the Bakelite Corp. Juvelite was made in Germany by condensing phenol and formaldehyde with the aid of mineral acids. Laccain was made under an English patent by using organic acids as catalysts. A Russian phenol resin, under the name of Karbolite, used an equal amount of naphthalenesulfonic acid, $C_{10}H_7SO_3H$, with the formaldehyde.

The hundreds of different phenolic molding compounds can be divided into six groups on the basis of major performance characteristics. General purpose phenolics are low cost compounds with fillers such as food flour and flock, and are formulated for noncritical functional requirements. They provide a balance of moderately good mechanical and electrical properties, and are suitable in temperatures up to 300°F (149°C). Impact-resistant grades are higher in cost. They are designed for use in electrical and structural components subject to impact loads. The fillers are usually either paper, chopped fabric, or glass fibers. Electrical grades, with mineral fillers, have high electrical resistivity plus good arc resistance, and they retain their resistivity under high temperature and high humidity conditions.

Heat-resistant grades are usually mineral- or glass-filled compounds that retain their mechanical properties in the 375 to 500°F (190 to 260°C) temperature range. Some of these, such as phenylsilanes, provide long term stability at temperatures up to 550°F (288°C). Special purpose grades are formulated for service applications requiring exceptional resistance to chemicals or water, or combinations of conditions such as impact loading and a chemical environment. The chemical-resistant grades, for example, are inert to most common solvents and weak acids, and their alkali resistance is good. Non-bleeding grades are compounded specially for use in container closures and for cosmetic cases.

The resins are marketed usually in granular form partly polymerized for molding under heat and pressure, which complete the polymerization, making the product infusible and relatively insoluble. They may also come as solutions, or compounded with reinforcing fillers and pigments. The tensile strength of a molded part made from a simple phenol-formaldehyde resin may be only about 6,000 lb/in.^{2} (41 MPa), with a specific gravity of 1.27 and dielectric strength of about 450 volts per mil (17.7 x 10^6 volts per meter). Reinforcement is needed for higher strength, and with a wood-flour filler the tensile strength may be as high as 10,000 lb/in^2 (68 MPa). With a fabric filler the flexural strength may be 15,000 lb/in^2 (103 MPa), or 18,000 lb/in.^{2} (124 MPa) with a mineral fiber. The specific gravity is also raised, and the mineral fillers usually increase the dielectric strength.

Proper balance of fillers is important, since too much may produce brittleness. Organic fillers absorb the resin and tend to cause brittleness and reduce the flexural strength, although organic fibers and fabrics generally give higher impact strength. Wood flour is the usual filler for general service products, but prepared compounds may have mineral powders, mica, asbestos, organic fibers of macerated fabrics, or mixtures of organic and mineral materials. The Resinox resins, of Monsanto, are in grades with fibrous and mineral fillers, and Moldarata, of the Westinghouse Electric Corp., is in various grades. Bakelite was the original name for phenol plastics, but trade names now usually cover a range of different plastics, and the types and grades are designated by numbers.

The specific gravity of filled phenol plastics may be as high as 1.70. The natural color is amber and, as the resin tends to discolor, it is usually pigmented with dark colors. Normal phenol resin cures to single-carbon methylene groups between the phenolic groups, and the molded part tends to be brittle. Thus, many of the innumerable various of phenol are now used to produce resins, and modem phenol resins may also be blended or cross-linked with other resins to give higher mechanical and electrical characteristics.

Furfural is frequently blended with formaldehyde to improve flow, lower specific gravity, and reduce the cost. The alkylated phenols give higher physical properties. Phenol-phosphor resin is a phenol resin modified with phosphonitrilic chloride. When cured the resin contains 15% phosphorous, 6% nitrogen, and less than 1% chlorine.

The tensile strength is 7,000 lb/in^2 (48 MPa) and it will withstand continuous temperatures to 500°F (260°C).

Product	Manufacturer	Remarks
Flexiphen 160	Koppers Co.	Resin that has some of the single-carbon methylene linkages replaced by hydrocarbon chains, giving 30% higher flexural strength with 5% lower specific gravity.
Resinox 3700	Monsanto Chemical Co.	A mineral-filled-phenolic resin of high arc resistance and high dimensional stability for electrical parts.
Synvar	Synvar Corp.	Resin that comes in a number of grades.
Durez	Hooker Chemical Corp.	Resin that comes in a number of grades.

Phenol resins may also be cast and then hardened by heating. The cast resins usually have a higher percentage of formaldehyde and do not have fillers. In a syrupy state they are poured into lead molds and hardened in a slow oven.

Product	Manufacturer	Remarks
Crystallin	Crystallin Products Corp.	Phenol plastic.
Phenalin	Du Pont	Phenol plastic.
Catalin	American Catalin Corp.	Phenol plastic.
Ivoricast	West Cost Enterprises	A shock resistant cast phenolic plastic with wood-flour filler that cures at low heat.
Prystal	American Catalin Corp.	The name of water-clear Catalin.
Bois Glace	American Catalin	A Catalin-coated wood for desk tops.

Product	Manufacturer	Remarks
Fiberlon	Fiberloid Corp.	A cast phenol plastic.
Marblette	Marblette Corp.	A cast plastic.

9.3.6 Polyester Resins. Polyester laminates are usually made with high proportions of glass-fiber mat or glass fabric, and high strength reinforced moldings may also contain a high proportion of filler. A resin slurry may contain as high as 70% calcium carbonate or calcium sulfate, with only about 11% of glass fiber added, giving an impact strength of 24,000 lb/in^2 (165 MPa) in the cured-material.. Bars and structural shapes of glass-fiber reinforced polyester resins of high tensile and flexural strengths are made by having the glass fibers parallel in the direction of the extrusion. Glastrusions, of Hugh C. Marshall Co., in rods and tubes, are made by having the glass-fiber rovings carded under tension, then passing through an impregnating tank, an extruding die, and a heat-curing die. The rods contain 65% glass fiber and 35% resin. They have a flexural strength of 64,000 lb/in.^{2} (441 MPa), and a Rockwell M hardness of 65.

Physical properties of polyester moldings vary with the type of raw materials used and the type of reinforcing agents. A standard glass-fiber-filled molding may have a specific gravity from 1.7 to 2.0, a tensile strength of 4,000 to 10,000 lb/in^2 (27 to 68 MPa), with elongation of 16 to 20%, a flexural strength to 30,000 lb/in^2 (206 MPa), a dielectric strength to about 400 volts per mil (16 x 10^6 volts per meter), and a heat distortion temperature of 350 to 400°F (177 to 204°C). The moldings have good acid and alkali resistance. But, since an almost unlimited number of fatty acids are available from natural fatty oils or by synthesis from petroleum, and the possibilities of by combining with alcohols, glycols, and other materials are also unlimited, the polyesters form an ever-expanding group of plastics.

9.3.7 Polyurethane Resins (Urethanes). Urethane foams are made by adding a compound that produces carbon dioxide or by reaction of a diisocyanate with a compound containing active hydrogen. Foams can be classified somewhat according to modulus as flexible, semi-flexible or semi-rigid, and rigid. No sharp lines of demarcation have been set on these different classes as the gradation from the flexibles to the rigids is continuous. Densities of flexible foams range from about 1.0 lb/ft^2 (16 kg/m^3) at the lightest to 4 to 5 lb/ft^2 (64 to 80 kg/m^3) depending on the end use. Applications of flexible foams range from comfort cushioning of all types, e.g., mattresses, pillows, sofa sets, backs and arms, automobile topper pads, and run underlay, to lightweight clothing interliners for increasing warmth. Densities of rigid urethane foams range from about 1.5 to 50 lb/ft^2 (24 to 800 kg/m^3).

There are six basic types of polyurethane coatings, or urethane coatings, as defined by ASTM Specification D16. Types 1, 2, 3, and 6 have long storage life and are formulated to cure by oxidation, by reaction with atmospheric moisture, or by heat. Types 4 and 5 are catalyst-cured and are used as coatings on leather and rubber, and as fast curing industrial product finishes. Urethane coatings have good weathering characteristics as well as high resistance to stains, water, and abrasion.

9.3.8 Silicones. A group of resin like materials in which silicon takes the place of the carbon of the organic synthetic resins. Silicon is quadrivalent like carbon. But, while carbon has a valence of 2, silicon has only one valence of 4, and the angles of molecular formation are different. The two elements also differ in electronegativity, and silicon is an amphoteric element, having both acid and basic properties. The molecular formation of the silicones varies common plastics, and they are designated as inorganic plastics as distinct from the organic plastics made with carbon.

In the long chain organic synthetic resins, the carbon atoms repeat themselves, attaching on two sides to other carbon atoms, while in the silicones the silicon atom alternates with an oxygen atom so that the silicon atoms are not tied to each other. The simple silane formed by silicon and hydrogen corresponding to methane, CH_4 is also a gas, as is methane, and has the formula SiH_4 But in general, the silicones do not have the SiH radicals, but contain CH radicals as in the organic plastics. Basically, silicon is treated with methyl chloride and a catalyst to produce a gas mixture of silanes $(CH_3)_x(SiCl)_{4-x}$. After condensing, three silanes are fractioned, methyl chlorosilane, dimethyl dichlorosilane, and trimethyl trichlorosilane. These are the common building blocks of the siloxane chains, and by hydrolyzing them, cyclic linear polymer can be produced with acid or alkali catalysts to give fluids, resins, and rubbers.

Silicone resins have more heat resistance than organic resins, high dielectric strength, and are water resistant. Like organic plastics, they can be compounded with plasticizers, fillers, and pigments. They are usually cured by heat. Because of the quartz-like structure, molded parts have exceptional thermal stability. Their maximum continuous use service temperature is about 500°F (260°C). Special grades exceed this temperature and go as high as 700 to 900°F (371 to 482°C). Their heat deflection temperature for 265 $lb/in.^2$ (1.8 MPa) is 900°F (482°C). Their moisture absorption is low, and resistance to petroleum products and acids is good. Nonreinforced silicones have only moderate tensile and impact strength, but fillers and reinforcements provide substantial improvement. Because silicones are high in cost, they are premium plastics and are limited to critical or high performance products, such as high temperature components in the aircraft, aerospace, and electronic fields.

A great variety of molecular combinations are available in the silicone polymers, giving resins varying characteristics, and those having CH radicals with silicon bonds are termed organosilicon polymers. Silicon tetramethyl, $Si(CH_3)$, is a liquid boiling at (26°C). Trichlorosilane, $HSiCl_3$, also called silicochloroform, corresponds in formation to chloroform. By replacing the hydrogen atom of this compound with an alkyl group, the alkylchlorosilanes are made that have high adhesion to metals and are used in enamels. Methyl chlorosilane, $(CH_3)_2SiCl_2$, is a liquid used for waterproofing ceramic electrical insulators. The material reacts with the moisture in the ceramic, forming a water-repellent coating of methyl silicone resin and leaving a residue of hydrochloric acid that is washed off.

Product	**Manufacturer**	**Remarks**
Dry-Film 9977	General Electric Co.	A liquid mixture of dimethyl dichlorosilane and methyl trichlorosilane used for waterproofing ceramic electrical insulators.
Silicone SC-50	General Electric Co.	A sodium methyl siliconate used in concrete, in gypsum plaster, and in water paints to impart water repellency.
Velvasil	General Electric Co.	A dimethyl siloxane used in cosmetics as a water repellent and in lipsticks for smear resistance.

The dimethyl polysiloxanes are very stable fluids used widely in cosmetics, but valued also for use in shock absorbers, transformers, and in automatic control systems.

Product	**Manufacturer**	**Remarks**
Sun Filter Polish	Westley Industries	A dimethyl siloxane that is resistant to sunlight and alkaline chemicals. This material can withstand temperatures to 300°F (149°C).
Silcone cement	Charles Englehard Inc.	A polysiloxane with mineral fibers that gives strong, heat resistant bonds to metals, glass, and ceramics.

The strong cements developed by the Naval Ordnance Laboratory for making chemical bonds between glass fibers and resin in plastic laminates are made by reacting allyl trichlorosilane with phenon resorcinol, or xylenol.

Silcone insulating varnishes will withstand continuous operating temperatures at 350°F (177°C) or higher. Silicone enamels and paints are more resistant to chemicals than most organic plastics, and when pigmented with mineral pigments will withstand temperatures up to 1,000°F (538°C). For lubricants the liquid silicones are compounded with graphite or metallic soaps and will operate between -50 and 500°F (-46 and 260°C).

Product	Manufacturer	Remarks
Thermocone	Joseph Dixon Crucible Co.	A black, chemical resistant paint that can withstand temperatures to 1,000°F (538°C). Thermocone is a liquid silicone containing graphite flakes.

Silicone liquids are stable at their boiling points, between 750 and 800°F (399 and 427°C), and have low vapor pressures, so that they are also used for hydraulic fluids and heat transfer media.

Silicone oils, used for lubrication and as insulating and hydraulic fluids, are methyl silicone polymers. They retain a stable viscosity at both high and low temperatures. As hydraulic fluids they permit smaller systems to operate at higher temperatures. In general, silicone oils are poor lubricants compared with petroleum oils, but they are used for high temperatures, 150 to 200°C, at low speeds and low loads.

Silicone resins are blended with alkyd resins for use in outside paints, usually modified with a drying oil. Resin XR-807, Dow Corning, is such a silicone-alkyd containing 25% silicone resin that is used to produce paints with high weather and sunlight resistance. A catalyst is added so that the paint can be air dried. Silicone-alkyd resins are also used for baked finishes, combining the adhesiveness and flexibility of the alkyd with the heat resistance of the silicone. A phenyl ethyl silicone is used for impregnating glass-fiber cloth for electrical insulation and it has about double the insulating value of ordinary varnished cloth.

Silicone rubber is usually a long chain dimethyl silicone that will flow under heat and pressure, but can be vulcanized by cross-linking the linear chains. Basically, it consists of alternate silicon and oxygen atoms with two methyl groups attached to each silicon atom. The tensile strength is 300 lb/in^2 (2 MPa), but with fillers it is raised to 600 $lb/in.^2$ (4 MPa). It is usually compounded with silica and pigments. It is odorless and tasteless, is resistant to most chemicals but not to strong acids and alkalies, will resist heat to 500-F (260°C), and will remain flexible to -70°F (-57°C). The dielectric strength is 500 volts per mil (20 x 10^6 volts per meter).

Product	Manufacturer	Remarks
Silastic	Dow Corning	A silicone rubber. It is a white rubbery material with an elongation of 70 to 150% and had good adhesion to various materials. Used for electrical insulation, for coating fabrics, and for gaskets and other parts.
Silastic RTV 601	Dow Corning	Used to encapsulate electrical units. Has a specific gravity of 1.29, tensile strength of 300 lb/in.^{2} (2 MPa), elongation of 150%, and dielectric strength of 500 volts per mil (22 x 10^6 volts per meter). The hardness is Shore A40.

Ordinary silicone rubber has the molecular group (H"CH$_2$"Si"CH$_2$"H) in a repeating chain connected with oxygen linkages, but in the nitrile-silicone rubber, produced by General Electric, one of the end hydrogens of every fourth group in the repeating chain is replaced by a C:N radical. These polar nitrile groups have a low affinity for oils, and the rubber does not swell with oils and solvents. It retains strength and flexibility at temperatures from -100°F (-73°C) to above 500°F (260°C), and is used for such products as gaskets and chemical hose. This material, called N.S. Fluids in the form of water-white to yellow liquids having 3 to 23% nitrile content, is used for solvent-resistant lubricants and as antistatic plasticizers. As lubricants, they retain a nearly constant viscosity at varying temperatures. Fluorosilicones have fluoroalkyd groups substituted for some of the methyl groups attached to the siloxane polymer of dimethyl silicone. They are fluids, greases, and rubbers, incompatible with petroleum oils and insoluble in most solvents. The greases are the fluids thickened with lithium soap, or with a mineral filler.

9.4 ELASTOMERIC APPLICATIONS (NATURAL AND SYNTHETICS).

9.4.1 Natural Rubbers (General). A gum resin exudation of a wide variety of trees and plants, but especially of the tree Hevea brasiliensis and several other species of Hevea growing in all tropical countries and cultivated on plantations in southern Asia, Indonesia, Sri Lanka, Zaire, and Liberia, from which natural rubbers elastomers are made.

The gum resin was formerly referred to as India rubber and gum elastic. The first highly compounded rubber insulation, developed in 1867, was called Kerite. Brazilian rubber is sometimes called Para rubber. Caoutchouc was an early name for the crude rubber then cured over a fire into a dark, solid mass for shipment. Castilla rubber, or castilloa, is from the large tree Castilla elastica, and was the original rubber of the Carib and Mayan Indians, but was cultivated only in Mexico and in Panama where it was called Panama rubber. The latex and rubber are identical with hevea rubber after purification. Euphorbia rubber is from vines of the genus Euphoria, of which there are 120 species in tropical Africa. Mangabeira rubber was formerly produced in the Amazon Valley. It is the latex of the mangabeira tree, which comprises various species of the genus Hancoria and yields the edible fruit mangaba The latex is coagulated with alum or sodium chloride, but the native Indians coagulated it with the latex of the caxiguba tree, Ficus anthelmintica, giving a better rubber. The rubber is softer than hevea rubber, but ages better. The low grade Assam rubber is from a species of ficus tree, F. elastica, of India and Malaya. Ceara rubber comes from the small, rapid growing tree, Manihot glaziovii, native to the semi-desert regions of Brazil, but now grown in India and Sri Lanka. The rubber is a good grade.

Rubber latex is a colloidal emulsion of the gathered sap, containing about 35% of rubber solids, blended from various sources to give average uniformity. The latex is coagulated with acid and milled into ribbed sheets called crepe rubber, or into sheets exposed to wood smoke to kill bacteria. These rubber sheets are known as smoked sheet rubber. These sheets constitute the commercial crude rubber, although rubber latex is used directly, especially for dipped goods such as gloves; toys; and balloons; for coatings, and for making foam rubber. Rubber can be vulcanized with sulfur and heat, removing the tackiness and making it harder and more elastic in the low sulfur compounds. All natural rubber, except adhesive rubbers, is vulcanized rubber.

Ordinary soft rubber contains only 3 to 6% sulfur, but also contains softners, fillers, antioxidants, or other compounding agents, giving varying degrees of elasticity, strength, and other qualities. When as much as 30% sulfur is added, the product is called hard rubber.

Vapor-cured rubber is rubber vulcanized by sulfur chloride fumes and neutralized with magnesium carbonate. This rubber is used for thin goods only. Acid-cured rubber is rubber cured in a bath of sulfur chloride in a solvent.

The tensile strength of rubber of low vulcanization is 800 to 1,200 lb/in^2 (6 to 8 MPa) of the original cross section. A good soft rubber can be stretched as much as 1,000% without rupturing, and will return close to the original length with little permanent set. The specific gravity is about 1.05, but with fillers may be as high as 1.30. When the term vulcanized rubber is now used, it refers to hard rubber vulcanized to a rigid but resilient solid. Vulcanized rubber is used in electrical parts and tool handles. Ace hard rubber, of the American Hard Rubber Co., has a specific gravity of 1.27, a tensile strength of 8,700 lb/in^2 (60 MPa), dielectric strength of 485 volts per mil (19 x 10^6 per meter), distortion temperature 172°F (78°C), and water absorption 0.04%. Vulcanite and Ebonite are old names for hard rubber.

Reclaimed rubber is produced largely from old tires and factory scrap. It is usually lower in cost than new rubber, but is easier to process and is used in large quantities even when the price is higher. Reclaimed rubber is sold in sheets, slabs, pellets, and powder, but much of the rubber powder, or granulated rubber, used for adhesives and molding is not reclaimed rubber but is made by spray-drying latex. Vultex is a natural rubber powder in paste form for coatings and adhesives. Mealorub is a rubber powder developed by the Indonesian Rubber Research Institute for mixing with asphalt for road surfacing.

Several types of modified natural rubber are used in the production of coatings, protective films, and adhesives. These are chlorinated rubber, rubber hydrochloride, and cyclized or isomerized rubber. Chlorinated rubber, for example, modified with any one of a number of plastic resins, provides maximum protection against a wide range of chemical. These coatings are widely used in chemical plants, in gas works, and as tank-car linings.

Red rubber is rubber colored red, but was originally rubber vulcanized with antimony pentasulfide that broke down with the heat of vulcanization, yielding sulfur to the rubber and coloring it red with the residual antimony trisulfide. Many trade names accelerators, fillers, and stiffeners are marketed for rubber compounding.

Crumb rubber is any form of porous particles than can be dissolved easily without milling, cutting, or pelletizing. It is used in adhesives and plastics.

Magnetic rubbers, produced in sheets and strips of various magnetic strengths, are made of synthetic rubbers compounded with magnetic metal powders.

Chlorinated Rubber. An ivory-colored or white powder produced by the reaction of chlorine and rubber. It contains about 67% by weight of rubber, and is represented by the empirical formula $(C_{10}H_{13}Cl_7)_x$, although it is a mixture of two products, one having a CH_2 linkage instead of a CHCl. Chlorinated rubber is used in acid- and corrosion-resistant paints, in adhesives, and in plastics.

The uncompounded film is brittle, and for paints chlorinated rubber is plasticized to produce a hard, tough, adhesive coating, resistant to oils, acids, and alkalies. The specific gravity of chlorinated rubber is 1.64, and bulking value of 0.0735 gal/lb. The tensile strength of the film is 4,500 lb/in.^{2} (31.5 MPa). It is soluble in hydrocarbons, carbon tetrachloride, and esters, but insoluble in water. The unplasticized material has a high dielectric strength, up to 2,300 bolts per mil (90.6 x 10^6 volts per meter).

Product	Manufacturer	Remarks
Tornesit and Parlon	Hercules Inc.	Chlorinated rubbers.
Paratex	Truscon Laboratories	Chlorinated-rubber coating materials.
Roxaprene	Roxalin Flexible Lacquer Co., Inc.	Chlorinated-rubber coating materials.
Pliofilm	Goodyear Tire & Rubber Co.	Rubber hydrochloride made by saturating the rubber molecule with hydrochloric acid. Made into transparent sheet wrapping material, which heat-seals at 105 105 to 130°C, or is used as a coating material for fabrics and paper. Gives a tough, flexible, water-resistant film.
Pliolite	Goodyear Tire & Rubber Co.	A cyclized rubber made by highly chlorinating the rubber. Used in insulating compounds, adhesives, and protective paints. Is soluble in hydrocarbons, but is resistant to acids and alkalies. Pliowax is this material compounded with paraffin or ceresin wax. Pliolite S-1 is this material made from synthetic rubber.

Dartex and Alloprene are German chlorinated rubbers, and Rulahyde is Dutch.

Resistant fibers have also been made from chlorinated rubbers.

Product	Manufacturer	Remarks
Tensolite	Tensolite Corp.	Filter cloth made from chlorinated rubber.
Betacote 95	Essex Chemical Corp.	A maintenance paint for chemical-processing plants that is based on chlorinated rubber. Adheres to metals, cements, and wood and dries rapidly. The coating is resistant to acids, alkalies, and solvents.

Cyclized Rubber. Cyclized rubber is made by heating rubber with sulfonyl chloride or with chlorostannic acid, $H_2SnCl_6"6H_2O$. It contains about 92% rubber hydrocarbons, and has the long straight chains of natural rubber joined together with a larger ring-shaped structure. The molecule is less saturated than ordinary natural rubber, and the material is tougher. It is thermoplastic, somewhat similar to gutta percha or balata, and makes a good adhesive. The specific gravity is 1.06, softening point 80 to 100°C, and tensile strength up to 4,500 lb/in.^{2} (31.5 MPa). It has been used in adhesives for bonding rubbers to metals, and for waterproofing paper.

9.4.2 Synthetic Rubbers (General).

Elastomers. Synthetic rubbers are hydrocarbon, polymeric materials similar in structure to plastic resins. The difference between plastics and elastomers is largely one of definition based on the property of extensibility or stretching. ASTM defines an elastomer as “a polymeric material which at room temperature can be stretched to at least twice its original length and upon immediate release of the stress will return quickly to approximately its original length.” Some grades of plastics approach this rubber-like state, for example, certain polyethylenes. Also, a number of plastics have elastomer grades, such as the olefins, styrenes, fluoroplastics, and silicones. As indicated above, the major distinguishing characteristic of elastomers is their great extensibility and high energy storing capacity. Unlike many metals that cannot be strained more than a fraction of 1% without exceeding their elastic limit, elastomers have usable elongations up to several hundred percent. Also, because of their capacity for storing energy, even after they are strained several hundred percent, virtually complete recovery is achieved once the stress is removed.

Until World War II, almost all rubber was natural. During the war, synthetic rubbers began to replace the scarce natural rubber, and, since that time, production of synthetic rubber has increased until now their use far surpasses that of natural rubber. There are thousands of different elastomer compounds. Not only are there many different classes of elastomers, but individual types can be modified with a variety of additives, fillers, and reinforcements. Also, curing temperatures, pressures, and processing methods can be varied to produce elastomers tailored to the needs of specific applications.

In the raw material or crude stage, elastomers are thermoplastic. Thus crude rubber has little resiliency and practically no strength. By a vulcanization process in which sulfur and/or other additives are added to the heated crude rubber, the polymers are cross-linked by means of covalent bonds to one another, producing a thermoset-like material. The amount of cross-linking that occurs between the sulfur (or other additive) and the carbon atoms determines many of the elastomer’s properties. As cross-linking increases, resistance to slippage of the polymers over one another increases, resilience and extensibility decreases, and the elastomer approaches the nature of a thermosetting plastic. For example, hard rubbers, which have the highest cross-linking of the elastomers, in many respects are similar to phenolics. In the unstretched state, elastomers are essentially amorphous because the polymers are randomly entangled and there is no special preferred geometrical pattern present. However, when stretched, the polymer chains tend to straighten and become aligned, thus increasing in crystallinity. This tendency to crystallize when stretched is related to an elastomer's strength. Thus, as crystallinity increases, strength also tends to increase.

There are roughly 15 major classes of elastomers that have been identified. The major characteristics of each group are highlighted. Two basic specifications that provide a standard nomenclature and classification system for these classes are: ASTM Standard D1418, which categorizes elastomers into compositional classes, and joint ASTM D2000/SAE J200 provides a classification system based on material properties. The first letter indicates specific resistance to heat aging, and the second letter denotes resistance to swelling in oil.

Chlorinated polyethylene elastomers are produced by substituting chlorine for hydrogen on a high density polyethylene chain resulting in a fully saturated structure with no double or triple bonds. The elastomer requires the catalytic reaction of a peroxide for curing. Thus, most molded parts are black Five grades of CPE polymers are produced, differing principally in chlorine content. The higher chlorine content grades have best oil and fuel resistance, tear resistance, gas impermeability, and hardness. The lower chlorine content grades have lower viscosities, better low temperature properties, and improved resistance to heat and compression set.

Chlorosulfonated polyethylene elastomer, commonly known as Hypalon, contains about one-third chlorine and 1 to 2% sulfur. It can be used by itself or blended with other elastomers. Hypalon is noted for its excellent resistance to oxidation, sunlight, weathering, ozone, and many chemicals. Some grades are satisfactory for continuous service at temperatures up to 350°F (177°C). It has moderate oil resistance. It also has unlimited colorability. Its mechanical properties are good but not outstanding, although abrasion resistance is excellent. Hypalon is often used in blends to improve oxidation and ozone resistance. Hypalon is used as tank linings, high temperature conveyor belts, shoe soles and heels, seals, gaskets, and spark plug boots.

Epichlorohydrin elastomers are noted for their resistance to oils, and excellent resistance to ozone, weathering, and intermediate heat. The homopolymer has extremely low permeability to gases. The copolymer has excellent resilience at low temperatures. Both have low heat buildup, making them attractive for parts subjected to repeated shocks and vibrations.

Ethylene-propylene elastomers, or EPR rubber, are available as copolymers and terpolymers. They offer good resilience, flexing characteristics, compression set resistance, and hysteresis resistance, along with excellent resistance to weathering, oxidation, and sunlight. Although fair to poor in oil resistance, their resistance to chemicals is good. Their maximum continuous service temperature is around 350°F (177°C). They are used in electrical insulation, footwear, and auto hoses and belts.

Fluorocarbon elastomers, fluorine-containing elastomers, like their plastic counterparts, are highest of all the elastomers in resisting oxidation, chemicals, oils, solvents, and heat. They are also the most expensive. They can be used continuously at temperatures over 500°F (127°C) and do not support combustion. Their brittle temperature is only -10°F (-23°C). Their mechanical and electrical properties are only moderate. Unreinforced types have tensile strengths of less than 2,000 lb/in.^{2} (13 MPa), and only fair resilience. They are used to make brake seals, O-rings, diaphragms, and hoses.

The phosphonitrile plastics and elastomers have high elasticity and high temperature resistance. They are derived from chlorophosphonitrile, or phosphonitrilic chloride, $P_3N_3Cl_3$, which has a hexagonal ring of alternating atoms of phosphorus and nitrogen with the chlorine atoms attached. In the plastic monomers the chlorine atoms are replaced by other groups. The PN polymers, of Horizons, Inc., contain OCH and C_3F_7 groups and are synthetic rubbers of high oxidation and chemical resistance. The tensile strength is up to 700 lb/in.^{2} (4.9 MPa) with elongation up to 600%. The material is used for as gaskets and cratings for severe service.

A phosphonitrilic fluorocarbon elastomer, of the Firestone Tire and Rubber Co., is a semi-organic phosphazene polymer. It remains flexible and serviceable at temperatures from -70 to 350°F (-57 to 177°C), and is highly resistant to oils and solvents over that temperature range.

Viton is a vinylidene fluoride hexafluoropropylene tetrafluorethylene copolymer, made by Du Pont, with extra high resistance to solvents, hydrocargons, steam, and water. Elastomers of the same type produced by 3M have the trade name Fluorel.

Perfluoroelastomer is a specialty, costly, fully chlorinated elastomer, by Du Pont, that resists commercial solvents, bases, and jet fuels. Kalrez can be used at continuous service temperatures of up 550°F (228°C) and at temperatures up to 650°F (343°C) for short time periods. Firestone’s phosphonitrilic fluoroelastomer (PNF200) has improved low temperature flexibility and resistance to heat aging and fuels. Its maximum continuous service temperature is 350°F (176°C).

Butyl rubbers, also referred to as isobutylene-isoprene elastomers, are copolymers of isobutylene and about 1 to 3% isoprene. They are similar in many ways to natural rubber, and are one of the lowest priced synthetics. They have excellent resistance to abrasion, tearing, and flexing. They are noted for low gas and air permeability (about 10 times better than natural rubber). For this reason, butyl rubbers make a good material for tire inner tubes, hose, tubing, and diaphragms. Although butyls are non-oil resistant, they have excellent resistance to sunlight and weathering; and generally have good chemical resistance. They also have good low temperature flexibility and heat resistance up to 300°F (149°C); however, they are not flame resistance. They have lower mechanical properties such as tensile strength, resilience, abrasion resistance, and compression set, than the other elastomers. Because of their excellent dielectric strength, they are widely used for cable insulation, encapsulating compounds, and a variety of electrical applications. Other uses include weather stripping, coated fabrics, curtain wall gaskets, high pressure steam hoses, machinery mounts, and seals for food jars and medicine bottles.

Isoprene is synthetic natural rubber. It is processed like natural rubber, and its properties are quite similar although isoprene has somewhat higher extensibility. Like natural rubber, its notable characteristics are very low hysteresis, low heat build up, and high tear resistance. It also has excellent flow characteristics, and is easily injection molded. Its uses complement those of natural rubber. Its good electrical properties plus low moisture absorption make it suitable for electrical insulation.

Neoprene, also known as chloroprene, was developed in the 1930s. Neoprene was the first commercial synthetic rubber. It is chemically and structurally similar to natural rubber, and its mechanical properties are also similar. Its resistance to oils, chemicals, sunlight, weathering, aging, and ozone is outstanding. Also, it retains its properties at temperatures up to 250°F (121°C), and is one of the few elastomers that does not support combustion, although it is consumed by fire. In addition, neoprene has excellent resistance to permeability by gases, having about one-fourth to one-tenth the permeability of natural rubber, depending on the gas. Although it is slightly inferior to natural rubber in most mechanical properties, neoprene has superior resistance to compression set, particularly at elevated temperatures. It can be used for low voltage insulation, but is relatively low in dielectric strength. Products made of chloroprene elastomers are heavy duty conveyor belts, V-belts, hose covers, footwear, brake diaphragms, motor mounts, rolls, and gaskets.

Nitrile elastomers, or NBR rubbers, originally known as Buna N, are copolymers of acrylonitrile and butadiene. They are known for their outstanding resistance to oil and fuels at both normal and elevated temperatures. Their properties can be altered by varying the ratio of the two monomers. In general, as the acrylonitrile content increases, oil resistance, tensile strength, and processability improve while resistance, compression set, low temperature flexibility, and hysteresis characteristics deteriorate. Most commercial grades range from 20 to 50% acrylonitrile. Those at the high end of the range are used where maximum resistance to fuels and oils is required, such as in oil-well parts and fuel hoses. Low acrylonitrile grades are used when good flexibility at low temperatures is important. Medium-range types, which are the most widely used, are used in flexible couplings, printing blankets, rubber rollers, and washing machine parts. Nitriles as a group are low in most mechanical properties. Because they do not crystallize appreciably when stretched, their tensile strength is low, and resilience is roughly one-third to one-half that of natural rubber. Depending on acrylonitrile content, low temperature brittleness occurs at from -15 to -75°F (-26 to -60°C). Their electrical insulation quality varies from fair to poor.

Polyacrylate elastomers are based on polymers of butyl or ethyl acrylate. They are low volume use, specifically elastomers, used in parts involving oils (especially sulfur-bearing) at elevated temperatures up to 300°F (149°C) and even as high as 400°F (204°C). A major use is for automobile transmission seals. Other oil resistance uses are gaskets and O-rings. Mechanical properties such as tensile strength and resilience are low. And, except for new formulations, they lose much of their flexibility below -10°F (-23°C). The new grades extend low temperature service to -40°F (-40°C). Polyacrylates have only fair dielectric strength, which improves, however, at elevated temperatures.

Polybutadiene elastomers are notable for their low temperature performance. With the exception of silicone, they have the lowest brittle or glass transition temperature, -100°F (-73°C), of all of the elastomers. They are also one of the most resilient, and have excellent abrasion resistance. However, resistance to chemicals, sunlight, weathering, and permeability by gases is poor. Some uses are: shoe heels, soles, gaskets, and belting. They are also often used in blends with other rubbers to provide improved resilience, abrasion resistance, and low temperature flexibility.

Polysulfide elastomer, also known as Thiokol, is rated highest in resistance to oil and gasoline. It also has excellent solvent resistance, extremely low gas permeability, and good aging characteristics. Thus, it is used for such products as oil and gasoline hoses, gaskets, washers, and diaphragms. Its major use is for equipment and parts in the coating production and application field. It is also widely applied in liquid form in sealants for the aircraft and marine industries. Thiokol's mechanical properties, including strength, compression set, and resilience, are poor. Although Thiokol is poor in flame resistance, it can be used in temperatures up to 250°F (121°C).

Silicone elastomers are polymers composed basically of silicon and oxygen atoms. There are four major elastomer composition groups. In terms of application, silicone elastomers can be divided into the following types: general purpose, low temperature, high temperature, low compression set, high tensile high tear, fluid resistant, and room temperature vulcanizing. All silicone elastomers are high performance, high price materials.

The general purpose grades, however, are competitive with some of the other specialty rubbers, and are less costly than the fluorocarbon elastomers. They have outstanding resistance to high and low temperatures, oils, and chemicals. High temperature grades have maximum continuous service temperatures up to 600°F (316°C); low temperature grades have glass transition temperatures of -180°F (-118°C).

Electrical properties, which are comparable to the best of the other elastomers, are maintained over a temperature range from -100°F (-73°C) to over 500°F (260°C). However, most grades have relatively poor mechanical properties. Tensile strength runs only around 1,200 lb/in^2 (8 MPa). However, grades have been developed with improved strength, tear resistance, and compression set.

Fluorosilicone elastomers have been developed that combine the outstanding characteristics of the fluorocarbons and silicones. However, they are expensive and require special precautions during processing. A unique characteristic of one of these elastomers is its relatively uniform modulus of elasticity over a wide temperature range and under a variety of conditions. Silicone elastomers are used extensively in products and components where high performance is required, such as, seals, gaskets, O-rings, insulation for wire and cable, and encapsulation of electronic components.

Styrene-butadiene elastomers, also called Buna S, SBR, and GR-S, are copolymers of butadiene and styrene. They are similar in many ways to the natural rubbers, and were the first widely used synthetics. They top all elastomers in volume of use, because of their low cost and use in automobile tires. A wide range of property grades are produced by varying the amounts of sytrene and butadiene. For example, styrene content varies from as low as 9% in low temperature resistant rubbers to 44% in rubbers with excellent flow characteristics. Those grades with 50% styrene are, by definition, considered plastics. Carbon black is sometimes added also as it substantially improves processing and abrasion resistance. SBR elastomers are similar in properties to natural rubber. They are non-oil resistant and are generally poor in chemical resistance. Although they have excellent impact and abrasion resistance, they are somewhat below natural rubber tensile strength, resilience, hysteresis, and some other mechanical properties. The largest single use is in tires. Other applications are similar to those of natural rubber.

Urethane elastomers are copolymers of diisocyanate with their polyester or polyether. Both are produced in solid gum form and viscous liquid. With tensile strengths above 5,000 lb/in^2 (34 MPa) and some grades approaching 7,000 lb/in^2 (49 MPa), urethanes are the strongest elastomers available. They are also the hardest, and have extremely good abrasion resistance.

Other notable properties are low compression set, good aging characteristics, and good resistance to oil and fuel. The maximum temperature for continuous use is under 200°F

(93°C), and their brittle point ranges from -60 to -90°F (-51 to -68°C). Their largest field of application is for parts requiring high wear resistance and/or strength, for example, forklift truck wheels, airplane tail wheels, shoe heels, bumpers on earthmoving machinery, and typewriter damping pads.

9.4.3 Thermoplastic Elastomeric Applications.

Thermoplastic Elastomers. A group of polymeric materials having characteristics of both plastics and elastomers (also called elastoplastics). They can be processed on standard plastics processing equipment without vulcanizing or curing. They are lightweight, resilient materials that perform well over-a wide temperature range; There are a half-dozen different types of elastomplastics. The olefinics, as thermoplastic olefinics (TPOs), are produced in durometer hardnesses from 54A to 96A Specialty flame-retardant and semi-conductive grades are also available. The TPOs are used in automobiles for paintable body filler panels and air deflectors, and as sound-deadening materials in diesel-powered vehicles. Producers of olefinics include:

Company	**Product**
Uniroyal	TPF
Du Pont	Somel
Exxon Chemical	TPV
	Vistaflex
Hercules	Pro-fax
B. F. Goodrich	Telcar

The styrenics are block copolymers, composed of polystyrene segments in a matrix of polybutadiene or polyisoprene. Lowest in cost of the elastoplastics, they are available in crumb grades and molding grades, and are produced in durometer hardnesses from 35A to 95A Manufactured by Shell Chemical (Kraton) and Philips Petroleum (Solprene), they are used for shoe soles, sealants, tubing, and sheeting.

Copolyether-ester thermoplastic elastomers of Du Pont are high performance, high cost materials, and known in the market as Hytrel. The five basic grades by durometer hardness are 40D, 47D, 55D, 63D, and 72D. Their applications include tubing and hose, V belts, couplings, oil-field parts, and jacketing for wire and cable. Their chief characteristic is toughness and impact resistance over a broad temperature range. A thermoplastic elastomer of polyvinyl chloride and nitrile, produced by Uniroyal and known as TPR 3700, provides excellent oil resistance. Trans-Pip is a trans-1, 4 polyisoprene thermoplastic elastomer of Polystar Co., developed as a replacement for refined balata rubber in golf-ball covers.

Polyester Resins. Thermoplastic polyester is a crystalline plastic molding compound. One type is made by polycondensation of 1, 4-butaneodiol and dimethyl-terephthalate (DMT) to produce polyteremethylene terephthalate (PTMT); commonly referred to as polybutylene terephthalate (PBT). The many different grades that are produced by a number of different grades that are produced can be divided into four major types:

Unmodified. Unmodified types have the greatest elongation and usually the shortest molding cycles.

Flame retardant. Flame retardant grades can maintain their flame retardance in very thin sections -- at 1/32 inch (0.8 mm), for example.

Glass-fiber reinforced. Thermoplastic polyesters reinforced with glass fibers are among the toughest plastics materials. Along with good heat resistance, they provide excellent impact strength and mechanical properties. Glass loadings range from 10 to 50%.

Mineral filled. To counter warpage associated with glass-fiber reinforced grades, mineral fillers can be added. Although some strength is sacrificed, these grades have shrinkage of 0.5% or less.

A notable disadvantage of thermoplastic polyesters is notch sensitivity and unsuitably for long time hot-water immersion. However, water resistance at room temperature is excellent. Some producers of PBT materials are:

Company	**Product**
Celanese Plastics	Celanex
Eastman Chemical	Tenitre polyterephthalate
General Electric	Valox

A recently developed thermoplastic polyester is a modified polyethylene terephthalate (PET) with the trade name Rynite. Produced by Du Pont, the material (reinforced with glass fibers) provides unusually high temperature resistance, high tensile strength, good stiffness, and high impact strength. Rynite is used in automobile parts, hardware, and consumer goods.

An extensive group of polyesters and alkyd resins with good heat stability can be made from pyromellitic dianhydride, $C_{10}H_2O_6$, a benzene tetracarboxylic dianhydride. It is marketed by Princeton Chemical Research, Inc., as PMDA, a white powder with a melting point of 287°C. It reacts with alcohols, benzene, and other hydrocarbons. It is produced from mellitic acid, $C_{16}(COOH)_6$, which has a melting point of 288°C. It is found brown coal, peat, and the mineral mellite, or honeystone, which is hydrous aluminum mellate. Tetrahydrophthalic anhydride is easier to combine with styrene than phthalic or maleic anhydride, and gives coating resins that are flexible and have quicker cure with high gloss.

Urethanes. There are three types of thermoplastic urethanes, a high priced specialty material: polyester-urethane, polyether-urethane, and caproester-urethane. All three are linear polymeric materials, and, therefore, do not have the heat resistance and compression set of the cross-linked urethanes. They are produced in three durometer hardness grades -- 55A, 80A, and 90A. The soft 80A grade is used where high flexibility is required, and the hard grade, 70D, is used for low deflection load bearing applications. Producers of these elastoplatics are:

Company	**Product**
B. F. Goodrich	Estane
American Cyanamid	Cyanaprene
Mobay Chemical	Texin
Uniroyal	Pellethane
K. J. Quinn	Q-thene
Upjohn	
Hooker Chemical	

9.4.4 **Superpolymers.** Several plastics developed in recent years that maintain mechanical and chemical integrity above 500°F (260°C) for extended periods are: polyimide, polysulfone, polyphenylene sulfide, polyarylsulfone, novaloc epoxy, and aromatic polyester. In addition to high temperature resistance, they have in common high strength and modulus of elasticity, and excellent resistance to solvents, oils, and corrosive environments. They are also high in cost. A major disadvantage with superpolymers is that they are difficult to process. Molding temperatures and pressures are extremely high compared to conventional plastics. Some of them, including polyimide and aromatic polyester, are not molded conventionally. Because they do not melt, the molding process is more of a sintering operation. These plastics are used mostly in aerospace and nuclear energy fields because of their high cost. One indication of the high temperature resistance of the superpolymers is their glass transition temperature of well over 500°F (260°C), as compared to less than 350°F (177°C) for most conventional plastics.

In the case of polyimides, the glass transition temperature is greater than 800°F (427°C), and the material decomposes rather than softens when heated excessively.

Polysulfone has the highest service temperature of any melt-processable thermoplastic. Its flexural modulus stays above 300,000 lb/in^2 (2,068 MPa) at up to 320°F (160°C). Even at such temperatures it does not discolor or degrade.

Armomatic polyester, a homopolymer also know as polyoxybenzoate, does not melt, but at 800°F (427°C) can be made to flow in a nonviscous manner similar to metals. Thus, filled and unfilled forms and parts can be made by hot sintering, high velocity forging, and plasma spraying. Notable properties are high thermal stability, good strength at 600°F (316°C), high thermal conductivity, good wear resistance, and extra high compressive strength. Aromatic polyesters have also been developed for injection and compression molding. They have long term thermal stability and a strength of 3,000 lb/in.^{2} (20 MPa) at 550°F (288°C).

At room temperature, polyimide is the stiffest of the group with a top modulus of elasticity of 7.5 million lb/in.^{2} (51,675 MPa), followed by polyphenylene sulfide with a modulus of 4.8 million lb/in.^{2} (33,072 MPa). Polyarysulfone has the best impact resistance of the superpolymers with an impact strength of 5 ft"lb/in. (0.27 kg"m/cm) (notch).

Polyetherimide, trade name Ultem, is an amorphous thermoplastic that can be processed with conventional thermoplastic processing equipment. Its continuous use temperature is 340°F (170°C) and its deflection temperature is 400°F (200°C) at 264 lb/in.^{2} (MPa). The polymer also has inherent flame resistance without using additives. This feature, along with its resistance to food stains and cleaning agents, make it suitable for aircraft panels and seat component parts. Tensile strength ranges from 15,000 to 24,000 lb/in.^{2} (103 to 165 MPa). Flexural modulus at room temperature is 48,000 lb/in.^{2} (3,300 MPa).

Polyimide foam is a spongy, lightweight, flame resistant material that resists ignition up to 800°F (427°C) and then only chars and decomposes. Some formulations result in harder materials that can be used as lightweight wallboard or floor panels while retaining fire resistance.

9.4.5 Industrial Uses of Plastic Materials. In industry, plastics are used as a construction material above and below ground, at the waterfront both under and above the water under constant and cyclic immersion conditions, and in the air in all types of aircraft. Their use is so endemic that they cover all but the most stringent or extreme Navy requirements. They are used for: utility lines (hot and cold water, sewage) and their hangers, conduit lines, ducting for venting and air handling, valves (gate and ball), insulation (electrical and thermal), coatings, glazing, piling jackets, tanks, tank linings, doors (interior and exterior), electrical housings, bridges, walkways, steps, and hoses (air, fuel, water) just to name a few.

9.4.6 Plastics Summary. The Modem Plastics Encyclopedia provides specifications/materials data that covers the physical and chemical properties of plastics with ASTM test designation. Other references and sources covering specific physical and chemical properties and the recommended uses, applications, and designs of various plastics are given.

These tables are updated yearly and are available from the Modern Plastics Reprint Department in New York. Other tables that address other aspects such as fire retardants and machinery are also available. Subscription cost to Modern Plastics (in 1990) for a Government organization is $38.00 for 1 year and $76.00 for 3 years. The subscription includes monthly issues of Modern Plastics and the yearly Modern Plastics Encyclopedia wherein the tables are printed. The Encyclopedia is an excellent reference source for materials, machinery, and manufacturers.

CHAPTER 10. CATHODIC PROTECTION

10.1 INTRODUCTION. Cathodic protection is second only to the use of protective coatings as a means of corrosion control. It is widely used at Naval Shore Activities for protecting buried and waterfront structures and for protecting the interiors of water storage tanks. In some cases, such as underground pipelines, field experience has shown that cathodic is such an effective means of providing the required levels of safety in the operation of the systems that cathodic protection is required by regulation.

10.2 WHEN CATHODIC PROTECTION SHOULD BE CONSIDERED. Cathodic protection should be considered, possibly in conjunction with other forms of corrosion control, such as protective coatings, wherever the system requiring protection is exposed to an aggressive environment in such a manner that cathodic protection is technically feasible. Cathodic protection is technically feasible when the surfaces to be protected are buried or submerged.

10.2.1 Structures That Are Commonly Protected. External surfaces of buried metallic structures, surfaces of metal waterfront structures, such as sheet pilings or bearing piles, and the internal surfaces of tanks containing electrolytes, such as water, are applications where cathodic protection is usually technically feasible and cathodic protection is used in protecting such structures. Internal surfaces of small diameter pipelines and other areas where ion flow in the electrolyte is restricted by electrolyte resistance, cathodic protection has limited applicability.

10.2.2 Determining the Need for Protection. When construction of a new buried or submerged system is being planned, the corrosivity of the environment should be considered as one of the factors in the design of the system. If experience with similar systems in the vicinity of the construction site has shown that the site conditions are aggressive based on leak and failure records, cathodic protection should be considered as a means of controlling corrosion on the new system. Cathodic protection is one of the few methods of corrosion control that can be effectively used to control corrosion of existing buried of submerged metal surfaces. Thus, if leak records on an existing system show that corrosion is occurring, cathodic protection can be applied to stop the corrosion damage from increasing. Cathodic protection can, however, only stop further corrosion from occurring and cannot restore the material already lost due to corrosion.

10.2.3 When Protection Is Required. In some cases, cathodic protection is required by policy or regulation as discussed in Chapter 2.1 of this manual. Regulations by the Department of Transportation have established standards for transporting certain liquids and compressed gas by pipelines in order to establish minimum levels of safety. These regulations require that these pipelines be protected by cathodic protection combined with other means of corrosion control, such as protective coatings and electrical insulation. These regulations provide excellent guidelines for the application of cathodic protection to buried and submerged pipelines.

In addition to these regulations, primarily due to the safety and environmental consequences of system failure, there are an increasing number of federal, state and local governmental regulations regarding the storage and transportation of certain materials that require corrosion control. Many of these regulations either specify cathodic protection as a primary means of corrosion control or allow its use as an alternative method of controlling corrosion.

10.3 WHERE CATHODIC PROTECTION IS FEASIBLE. In order to be technically feasible, cathodic protection requires that the structure to be protected be electrically continuous and be immersed in an electrolyte of sufficient volume to allow the distribution of current onto the structure.

10.3.1 Electrical Continuity of Structure. Electrical continuity of the structure to be protected may either be through metallic continuity provided by bolting or welding of the structure. Continuity is often achieved or insured by means of electrical connections installed specifically to insure the effectiveness of cathodic protection. These connections are called “bonds.”

10.3.2 Electrolyte. The electrolyte is water or the water contained in moist earth. The conductivity of the electrolyte is an important factor in the design of cathodic protection systems.

10.3.3 Source of Current. Cathodic protection also requires the presence of a source of electrical current at the proper voltage or potential to prevent attack on the structure. These sources of current are called “anodes.” As described below, the anodes can either be fabricated from an active metal, such as magnesium or zinc, which provides a high potential source of electrons through corrosion on its surface or from a relatively inert material. This inert material has the ability to pass current from its surface without being consumed at a high rate, but requires using an external energy source to increase the potential of the electrons supplied to the structure being protected. The systems that use active anodes are called “sacrificial” systems as the anode material is sacrificed to protect the structure under protection. The inert anode systems are called “impressed current” systems as the external energy source is used to impress a current onto the structure under protection.

10.4 GUIDANCE FOR DESIGN, INSTALLATION, OPERATION, AND MAINTENANCE. Guidance for the design and installation of cathodic protection systems is available in Military Handbook 1004/10 (Ref 5). Guidance for the operation and maintenance of cathodic protection systems is available in NAVFAC Maintenance and Operation Manual MO-306 (Ref 6).

10.5 PRINCIPLES OF OPERATION. Understanding the principles of operation of cathodic protection systems is based on understanding the nature of the corrosion process. Corrosion is basically an electrochemical process. That is, it is a process where chemical reactions take place through the exchange of electrons. By preventing the exchange of electrons, cathodic protection systems prevent the corrosion reactions that would otherwise naturally occur.

10.5.1 <u>The Cathodic Protection Cell.</u> Cathodic protection prevents corrosion by making a metal, which would ordinarily behave like an anode and corrode, behave like a cathode and be free from corrosive attack. In cathodic protection this is achieved by providing electrons of a higher energy level (electric potential) than those which would be produced in the corrosion reaction at the anode. This is illustrated in Figure 10-l.

On the right side of Figure 10-1, corrosion is proceeding. Metal atoms are reacting to form metal ions and electrons. The electrons formed have a certain amount of energy as a result of the reaction. The presence of these electrons in the metal give the metal a characteristic electrochemical potential. On the left side of Figure 10-1, the application of a potential that is higher (more negative) than the potential that was produced by the corrosion reaction prevents the flow of electrons in the ordinary - to + direction and the corrosion reaction is prevented. The metal that was formerly a location from which electrons flowed (an anode) has been changed to a location to which electrons flow (a cathode) by the application of a negative charge. Corrosion has been stopped. The potential required for cathodic protection depends on the metal being protected and the environment.

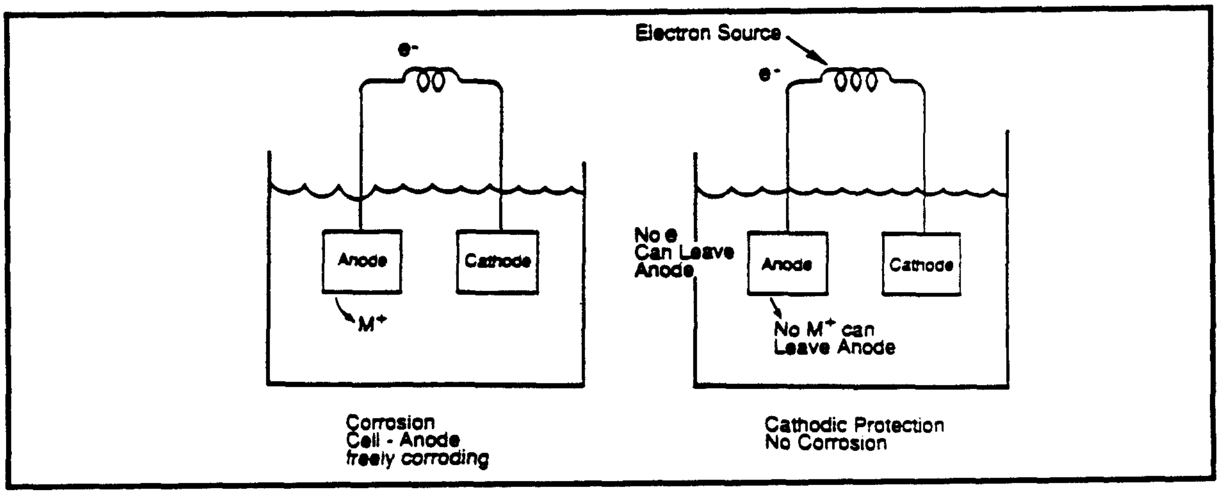

Figure 10-1
Cathodic Protection Cell

10.5.2 Current and Potential Requirements. In order to achieve these protective potentials, current must flow from the anode to the structure being protected. The amount of current required to protect a given structure is proportional to the area of the structure that is exposed to the electrolyte. Therefore, current requirements are usually given as current densities in units of amperes or milliamperes (0.001 amperes) per square foot of exposed surface. For coated structures the amount of current required is much lower than for bare structures as only those areas on the coated structure where the coating has been damaged or has deteriorated require or will receive current. Many coatings can reduce current requirements by over 90%. The current densities required for cathodic protection depend on the metal being protected and the environment. Values for the current densities required for cathodic protection of bare steel structures is shown in Table 10-1. Values of the current densities required for cathodic protection of coated steel structures is shown in Table 10-2.

Table 10-1
Current Requirements for Cathodic Protection of Bare Steel

Environment	Milliamperes per Square Foot
Soil with resistivity > 10,000 Ohm-cm	2.0 - 3.0
Soil with resistivity 1,000 - 10,000 Ohm-cm	4.0 - 6.0
Soil with resistivity < 1,000 Ohm-cm	7.0 - 25.0
Highly aggressive soil with anaerobic bacteria	15.0 - 40.0
Still Freshwater	2.0 - 4.0
Moving Freshwater	4.0 - 6.0
Turbulent Freshwater	5.0 - 15.0
Hot Freshwater	5.0 - 15.0
Still Seawater	1.0 - 3.0
Moving Seawater	3.0 - 25.0
Concrete	0.5 - 1.5

Table 10-2
Current Requirements for Cathodic Protection of Coated Steel

Structure	**Milliamperes Per Square Foot**
Pipeline, epoxy or other high performance coating	0.001 - 0.005
Pipeline, reinforced coal tar or asphalt enamel	0.005 - 0.025
Pipeline, grease coating with wrapper	0.05 - 0.150
Pipeline, asphalt mastic 1/2-inch thick	0.001 - 0.005
Pipeline, old asphalt or other deteriorated coating	0.05 - 0.35
Pipeline, old paint coating	0.10 - 0.30
Tank bottoms	0.05 - 2.0
Cold potable water tanks	0.05 - 2.0
Tanks for cold seawater	0.05 - 4.0
Hot potable water tanks	0.30 - 3.0
Steel sheet piling fresh water side	0.10 - 1.5
Steel sheet piling seawater side	0.10 - 2.0
Steel sheet piling soil side	0.05 - 1.0

10.5.3 **Sacrificial Versus Impressed Current Systems.** The method that is used to supply the required current to the structure being protected depends on the type of cathodic protection system being used: sacrificial anode or impressed current.

10.6 SACRIFICIAL ANODE CATHODIC PROTECTION SYSTEMS. In sacrificial anode systems the high energy electrons required for cathodic protection are supplied by the corrosion of an active metal. This is illustrated in Figure 10-2.

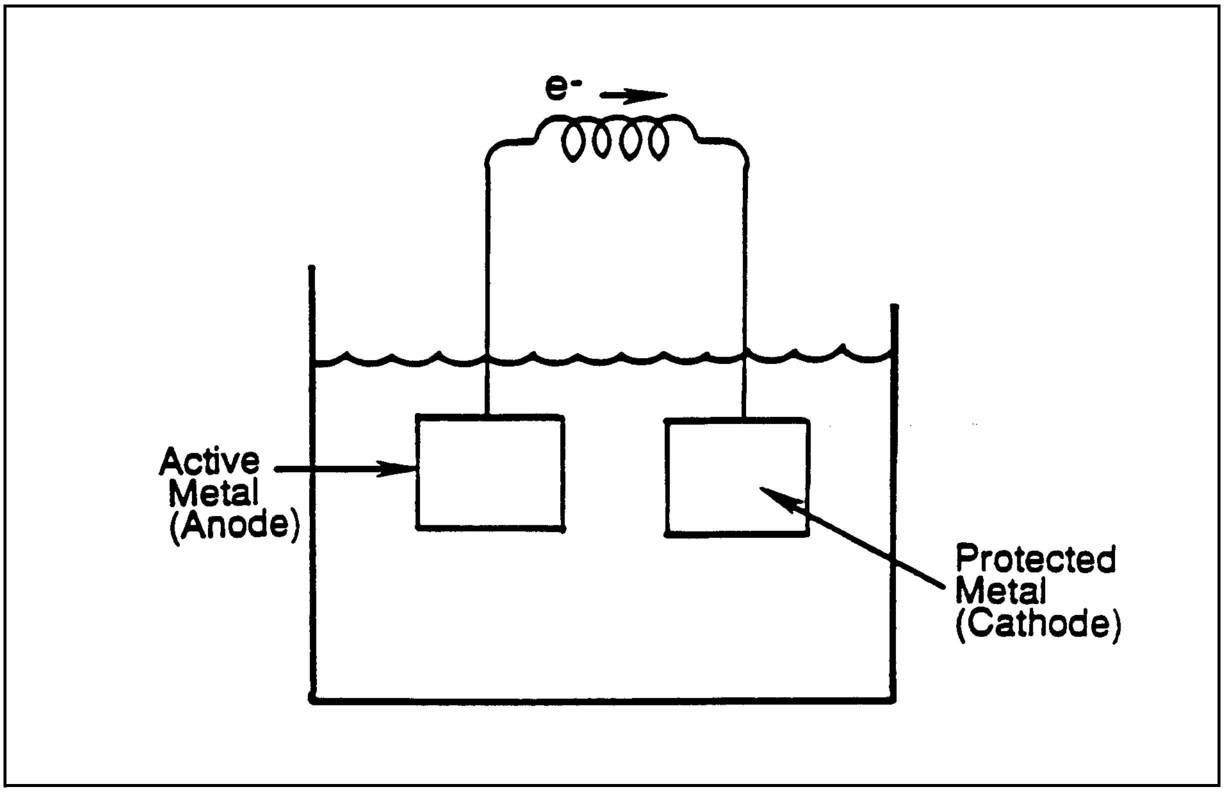

Figure 10-2
Sacrificial Anode Cathodic Protection System

Sacrificial anode systems depend on the differences in corrosion potential that are established by the corrosion reactions that occur on different metals or alloys. For example, the natural corrosion potential of iron is about -0.550 volts in seawater. The natural corrosion potential of zinc in seawater is about -1.2 volts. Thus if the two metals are electrically connected, the corrosion of the zinc becomes a source of negative charge which prevents corrosion of the iron. Sacrificial anode cathodic protection systems are illustrated in Figure 10-3.

The materials used for sacrificial anodes are either relatively pure active metals, such as zinc or magnesium, or are magnesium or aluminum alloys that have been specifically developed for use as sacrificial anodes. In applications where the anodes are buried, a special backfill material surrounds the anode in order to insure that the anode will produce the desired output.

Sacrificial anodes are normally supplied with either lead wires or cast-m straps to facilitate their connection to the structure being protected. The lead wires may be attached to the structure by welding or mechanical connections. These should have a low resistance and should be insulated to prevent increased resistance or damage due to corrosion. When anodes with cast-in straps are used, the straps can either be welded directly to the structure or the straps can be used as locations for attachment using mechanical

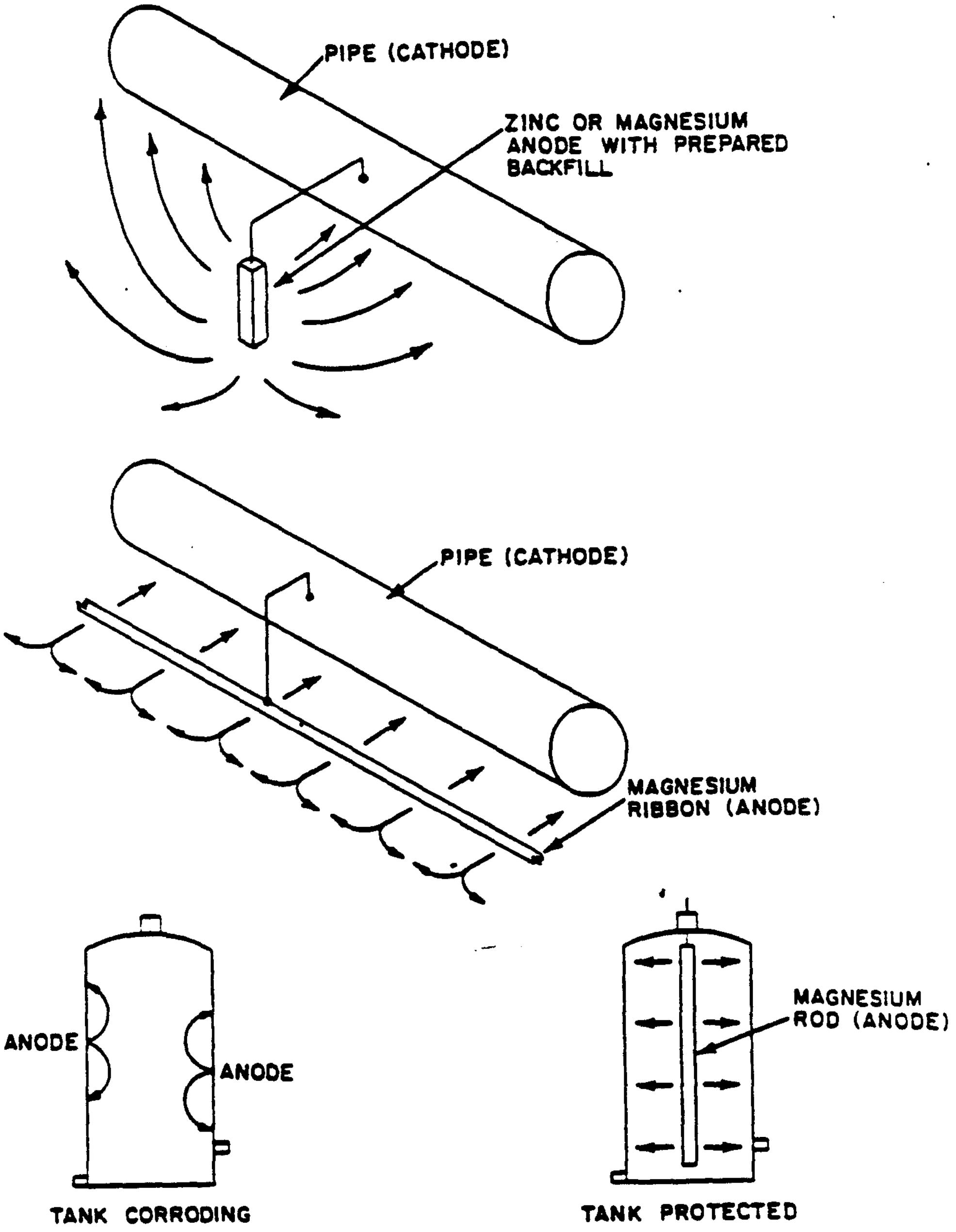

Figure 10-3
Cathodic Protection by the Galvanic Anode Method

fasteners. A low resistance mechanically adequate attachment is required for good protection and resistance to mechanical damage.

In the process of providing electrons for the cathodic protection of a less active metal the more active metal corrodes. The more active metal (anode) is sacrificed to protect the less active metal (cathode). The amount of corrosion depends on the metal being used as an anode but is directly proportional to the amount of current supplied. The anodes in sacrificial anode cathodic protection systems must be periodically inspected and replaced when consumed.

10.7 IMPRESSED CURRENT SYSTEMS. As in sacrificial anode systems, impressed current systems depend on a supply of high energy electrons to stifle anodic reactions on a metal surface. In the case of an impressed current system these high energy electrons are supplied by a rectifier. As shown in Figure 10-4 low energy electrons that are picked up at a non-reactive anode bed are given additional energy by the action of a rectifier to be more energetic than the electrons that would be produced in the corrosion reaction.

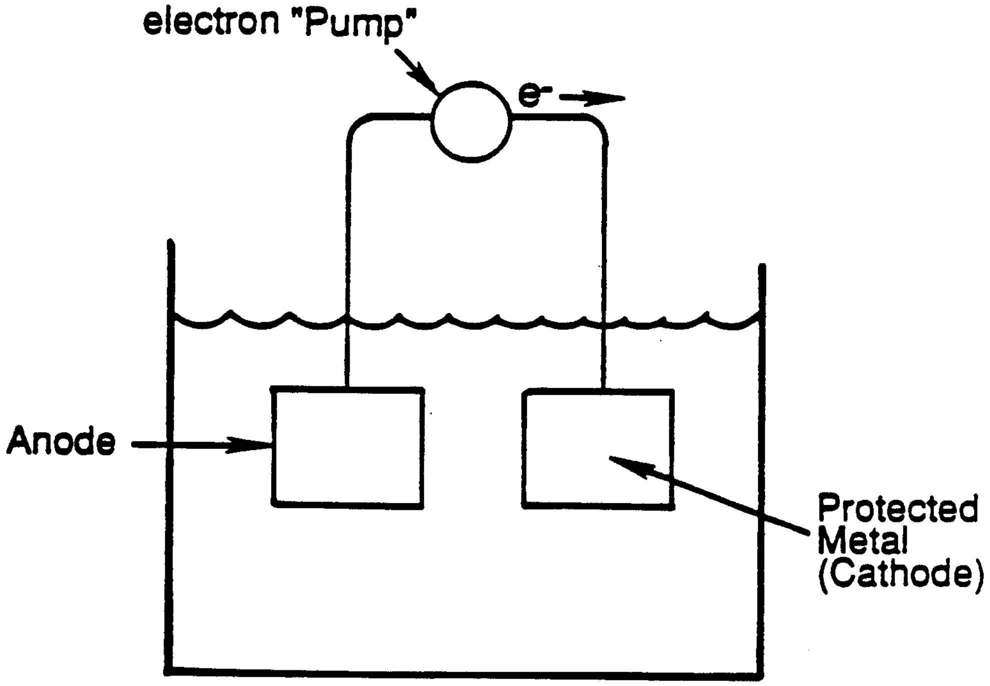

Figure 10-4
Impressed Current System

The energy for the “electron energy pump” action of the rectifier is provided by ordinary alternating current. The effect of these electrons at the structure being protected is the same as that derived from the sacrificial anode type of cathodic protection system. However, the anode material serves only as a source of electrons and need not be consumed in providing protective current. The materials used for impressed current cathodic protection can the pass a current into the environment without being consumed at a high rate. Graphite and high silicon cast iron are the most commonly used impressed current cathodic protection anode materials, however, other materials (such as magnetite, platinum, and newly developed ceramic materials) have been successfully used. For buried anodes, a backfill of carbonaceous material is used to surround the anode to decrease the electrical resistance of the anode, to provide a uniform, low resistivity environment surrounding the anode and to allow gasses produced at the anode surface to vent.

In practice, materials such as graphite are used for impressed current cathodic protection system anodes that are slowly consumed. Anodes in impressed current systems must be inspected and replaced if consumed or otherwise damaged. As is the case for any electrical equipment, rectifiers used for impressed current cathodic protection systems require preventative maintenance to insure proper operation. An impressed current cathodic protection system is shown in Figure 10-5.

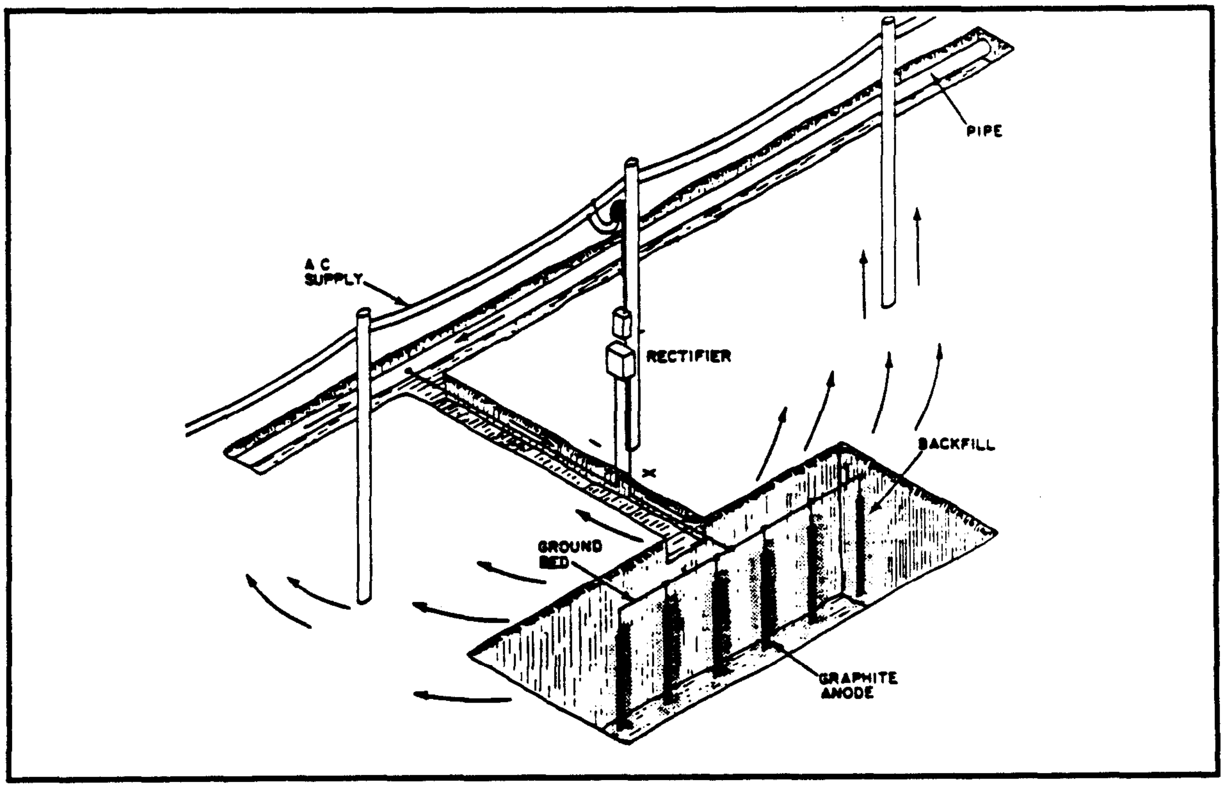

Figure 10-5
Cathodic Protection by the Impressed Current Method

10.8 DESIGN AND INSTALLATION. Methods for designing a cathodic protection system are well developed and are described in MIL-HDBK-1004/10 (Ref 5).

10.9 OPERATION AND MAINTENANCE. In order to effectively provide the increased structural lifetime and reliability intended, cathodic protection systems must be monitored and maintained. Economic considerations made at the time that the cathodic protection was selected as a means of corrosion control should have included the cost of periodic monitoring and maintenance in the analysis.

10.9.1 Why Periodic Monitoring and Maintenance Are Required. The effectiveness of cathodic protection systems usually change with time. The consumption of both sacrificial and impressed current anodes can result in decreased anode output that results in inadequate protection. Deterioration of cable insulation or connections can result in increased circuit resistance with similar effect. Rectifier output can be reduced by aging of the stacks, or can be completely interrupted by electrical failure. The corrosion environment can change if there is a change in drainage patterns or the area around an anode is paved reducing local soil moisture content. Construction of additional structures or modification to existing structure in the area can interfere with the cathodic protection system.

In order for a cathodic protection system to be effectively monitored and maintained, the parameters used in the design of the system and the “as built” configuration of the system must be known. “As built” drawings of the cathodic protection system and the structure being protected should be available as well as drawings of other structures in the area that might cause interference problems. The cathodic protection system drawings should include, as a minimum, the location and configuration of all test stations, the location and type of all anodes and rectifiers, and the location of all connections and insulating joints. These drawings should be periodically updated to show any changes made to the cathodic protection system, the structure being protected or nearby structures.

The desired potentials used in the design of the cathodic protection system should be indicated. In some cases, different criteria can be used to establish minimum protective potentials at different locations of the same structure.

The design current outputs of the rectifiers or sacrificial anodes in the system should be recorded. These data are most important in the initial system checkout but can also be used to evaluate discrepancies in structure to electrolyte potential readings.

The initial system settings and potential readings should be recorded. Changes to the system such as rectifier adjustment should be periodically recorded. Potential readings taken both at the time of initial system adjustment and during periodic monitoring should be recorded in order to detect trends in the readings. Changes in potential readings are often more important than the actual values themselves in determining the cause of improper system operation.

In order that any rectifiers in the system can be properly maintained, adjusted, and repaired, instructions for the rectifiers should be retained. An original copy should be kept in the maintenance files and a copy should be kept within the rectifier enclosure for field reference.

10.9.2 Basic Maintenance Requirements. Basic maintenance requirements are:

Monthly: Take rectifier panel meter and tap setting readings. Record readings on NAVFAC Form 11014-74B.

Quarterly: Take structure to electrolyte potential readings at selected locations (not less than four points per system). Record readings on NAVFAC Form 11014-74A.

Annually: Inspect submerged sacrificial and impressed current anodes for consumption. Inspect test stations for broken wires, loose connections, or other damage.

In addition to the basic requirements listed above, opportunities to inspect buried or otherwise inaccessible structure surfaces should be used to inspect the surfaces for evidence of corrosion or coating deterioration. Such opportunities may be presented by construction or maintenance in the vicinity of the protected structure.

CHAPTER 11. IDENTIFICATION AND CHARACTERIZATION OF CORROSION PROBLEMS

11.1 INTRODUCTION. In order to establish the need for and proper methods for the application of corrosion control to existing structures and equipment, it is necessary to locate the sites where corrosion is occurring or likely to occur and to establish the causes of corrosion. Only after the corrosion problem is located and diagnosed can it be effectively solved.

11.2 CONTROL INSPECTIONS. Maintenance control inspections are the primary means for identifying actual or potential corrosion problems. Visual observations are the primary means of performing maintenance control inspections. Inspectors must be familiar not only with the structures and equipment that they are inspecting but with the corrosion problems experienced in those structures and equipment and with the forms of corrosion that occur. It is important that the maintenance control inspector be able to properly identify and describe the type of corrosion that is detected. Through an understanding of the basics of corrosion control, the maintenance control inspector can also identify factors, such as trapped water or deteriorated protective coatings, that will eventually lead to corrosion damage.

11.3 SPECIALIZED INSPECTIONS. Specialized inspections require skills or equipment over and above that required for maintenance control inspections. Inspection of the underwater portions of waterfront structures, and some of the inspections performed on cathodic protection systems are considered specialized inspections.

11.3.1 Underwater Inspections. As divers or other means of making visual observations and other tests are required for. the effective inspection of underwater portions of waterfront structures, these inspections require specialized expertise. The Chesapeake Division, Naval Facilities Engineering Command, Fleet Project Office One has been tasked with performing these inspection both in-house and by contract.

11.3.2 Specialized Inspection of Cathodic Protection Systems. Monthly readings of rectifier settings do not require specialized expertise or equipment and are considered part of the maintenance control inspection. Other measurements such as pipe to soil potentials do require specialized equipment and expertise. The Geographical Engineering Field Division/Engineering Field Activity (EFD/EFA) provides the required training for performing these tests at the activity level or provide a standard scope of work for performing these tests by contract.

11.4 FAILURE ANALYSIS. In order to determine the cause of service failures two basic questions must be addressed: (1) What mechanisms were responsible for the corrosion? (2) What conditions lead to the attack?

11.4.1 Determination of Failure Mechanisms. In order to understand the causes of failures so that they can be avoided, the mechanisms of failures must be established. While the tests needed to identify and verify specific failure mechanisms must be selected depending on the mechanisms suspected, most metal failure analyses rely heavily on visual observation and metallurgical and chemical analyses. All of these require substantial skill and training in order to establish the causes for failure. However, field personnel often play an important part in establishing the conditions that lead to the failure, documenting the conditions of the failed components immediately after failure, selecting proper treatment and preservation of the failed components, and identifying other potential evidence, such as corrosion products.

11.4.1.1 Visual Examination. The visual appearance of failures is often one of the most important factors in evaluating the failure and in determining the need for further tests. In marine exposures, seeing the surfaces is made more difficult by possible damage to the features of interest by corrosion, mechanical damage during retrieval from remote sites, contamination of surfaces, and, as often occurs, loss of the damaged components or portions of them Assuming that the components of interest are retrieved, it is important that the information that they contain be preserved. If the components can not be inspected immediately, the surfaces should be photographed to show all details of potential interest. Close-ups color photographs with shallow angle lighting best records the features of interest.

Methods for preserving the surfaces depends on the specific materials involved, but rinsing in freshwater and drying in warm air are usually sufficient to preserve the surfaces. The components should then be stored in dry air until a more detailed examination is performed. Ultrasonic cleaning using a mild detergent solution followed by a freshwater rinse and drying in warm air is also effective. For some alloys (such as steel) that corrode freely in air, the surfaces can be rinsed in freshwater, dried, and then coated with a light oil if dry storage is not available.

The composition of corrosion products is often a clue as to the mechanisms responsible for corrosion. Corrosion product samples should be carefully removed, treated, and analyzed in accordance with the methods specified in the National Association of Corrosion Engineers Recommended Practice RP-01-73 “Collection and Identification of Corrosion Products” (Ref 7).

11.4.1.2 Service Environment. Determining the service environment is often difficult. In some cases, such as atmospheric corrosion, time of wetness, surface contamination, and temperature are important but can vary considerably with time. Exposure to a uniform non-changing environment is often rather benign in that corrosion product films that form under these conditions after an initial period of rapid attack of the clean surface can provide substantial protection from corrosion. However, when the conditions of exposure change, these films may not be stable and can quickly break down exposing the metal to a new environment in an unprotected condition. In the new condition, initial rapid corrosion of the clean surface can result on the formation of a new protective layer. If the sequence is repeated, the attack experienced can be more severe in the alternating exposure than an equivalent exposure in either of the environments.

In other cases, extreme conditions can be responsible for the breakdown of passive films or other initiation of corrosion attack which can then proceed under the more average conditions experienced. This often occurs when elevated temperatures are occasionally experienced or when salts concentrate by evaporation.

Immersion Service. Service under immersion conditions assumes that an uncorroded material is fully exposed to a liquid environment during its entire service life and that, when removed from immersion is quickly treated to arrest any corrosion that can occur.

a. Temperature. In general, corrosion rates increase with increasing temperature. In seawater, this increase is much less than the doubling of reaction rates with each 18°F rise in temperature that would be expected if the reactions were under diffusion control as are many other chemical reactions. For many materials, such as steels, where the oxygen content of the water directly affects the corrosion rate, the effect of temperature is minimal as in situations where the corrosion rate would be increased by increased temperature, the solubility of oxygen is decreased with increasing temperatures and the two effects counteract each other. Steels and copper alloys are particularly insensitive to temperature effects in normal marine immersion.

For other alloys that depend on a passive film for their corrosion resistance, the effects of temperature can be more pronounced. At elevated temperatures the solubility oxygen required for repairing protective oxide films found on many passive materials is reduced and the reactions that cause the films to break down are enhanced by the increased temperatures. Many stainless steels have what is essentially a “critical pitting temperature” in seawater that is in the range of temperatures experienced in natural seawater. In cold waters they do not pit but in warmer waters they are susceptible.

b. Chemical Composition. In some cases, the chemical composition of a given environment for immersion service is fairly stable and a complete laboratory analysis of a single sample can establish the environment responsible for corrosion. In other cases, the environment varies considerably with time or location in the system and multiple samples must be taken and analyzed.

c. Dissolved Gasses. The content of dissolved gasses, particularly oxygen is often an important factor in corrosion in immersion service. Samples for determining dissolved gasses must be taken on site using special techniques. Analysis of a liquid sample for dissolved gasses will often give very misleading results unless the sample is properly taken and handled.

d. pH. pH is a measurement of the acidic or alkaline nature of a solution. Strictly speaking it is the negative logarithm of the hydrogen ion concentration. In acidic solutions the pH is low and can be less than one in highly acidic solutions. Neutral solutions have a pH of 7.0. Alkaline solutions have a pH greater than 7 and the pH of a strongly alkaline solution can approach 14. pH solutions can be effectively measured using either a special pH meter or special papers that change color.

e. Pollutants. Pollutants can have both direct and indirect affects on the corrosion of metals. Acid or alkaline pollutants from industrial plants can have an adverse effect on the performance of many materials. Heavy metal ions can dramatically affect the performance of many metals. Aluminum alloys are particularly susceptible to increased corrosion from small amounts of dissolved metal ions such as copper. Pollution can also have an indirect affect on corrosion by affecting the biological activity that controls the oxygen content in many seawater environments. In some cases, the oxygen content can fall to zero and aggressive hydrogen sulfide can form. Polluted environments are often unique both to the environment at a specific site but over time at a particular site. Pollution effects are sometimes seasonal.

Atmospheric Service. Atmospheric exposure is considered to be a continuous exposure to air without liquid immersion. Sea spray contamination and rain are considered part of atmospheric exposure.

a. Relative Humidity. Corrosion can normally occur at perceptible rates on surfaces where there is actually free moisture. Moist air where no moisture is present on the surface is usually insufficient for corrosion to occur. Materials on the surface of metals such as corrosion products and salt deposits can be hydroscopic and can absorb sufficient amounts of water from moist air to allow corrosion to proceed. The relative humidity of the environment affects the ability of such layers to provide sufficient moisture on the surface for corrosion to proceed and also affects the time required for the surfaces to dry after being wet by rain, dew, or spray. In general, corrosion is more severe in humid environments than in dry environments. In order to arrest corrosion on equipment by storing in a dry atmosphere, the relative humidity must be reduced to below 50% with 35% being necessary to completely arrest corrosion on some materials. When hydroscopic materials are on the metal surface, these must be removed before dehumidified storage will be effective unless very low humidities can be achieved. Sea salts are particularly hydroscopic and must be removed in order to prevent rapid atmospheric attack. Unless removed, the sea salts will effectively concentrate when dried and, unless very low humidities are achieved, will cause accelerated attack on many metals.

b. Temperature. The temperature of the environment can have an effect on corrosion, but the effect of temperature is usually combined with the effect of relative humidity. Warm, moist environments are most corrosive. In environments with lower relative humidity, the effect of elevated temperatures can reduce the time of wetness and the severity of corrosive attack. There is little attack on metals below the freezing point.

c. Salt. The amount of salt that accumulates on surfaces exposed to marine environments varies considerably. In general, in environments where more salt accumulates and where the salt that accumulates remains on the surface for longer periods without being washed off, corrosion will be more severe. In some cases, little salt accumulates at sites within a few feet of the sea. However, at other sites, prevalent onshore winds can carry salts several miles inland. At a site near the ocean, unless it has been shown otherwise, sufficient salt accumulation to make the site more corrosive than in uncontaminated environments must be assumed. The amount of time that salt remains on the surface is determined by the rainfall to wash the surfaces free of salt. Atmospheric corrosion is usually characterized as rural, marine, industrial and industrial marine in order of increasing corrosion.

d. Pollutants. Atmospheric pollution, particularly from heavy industry which produces acid fumes, can make an atmosphere particularly corrosive. This effect is particularly severe when the effects of pollution and salt accumulation are both present.

e. Precipitation. Not only is the amount of rain an important factor, the frequency of rain and prevailing wind are also important factors. Frequent rains followed by prolonged periods of high humidity lead to long periods where surfaces are wet with high attendant corrosion rates. In some cases when rain occurs during periods of onshore winds, and onshore winds are infrequent when rains do not follow, salt that is carried to the site is rapidly washed off and little salt accumulates. This can make a site near the sea more like a rural than a marine exposure.

Alternate Immersion. The effect of alternate immersion can often be more severe than exposure under either immersion or atmospheric conditions alone. As in the case of other variations in environment, this can cause protective films that form in one environment to break down and be exposed to conditions that can cause rapid attack of the unprotected surface. In addition, salts that accumulate during immersion can concentrate during subsequent atmospheric exposure unless completely removed. In the atmosphere, accumulations of fouling organisms usually die and this can form hydrogen sulfide and other corrosive gasses on the metal and result in accelerated attack. Tidal type immersion where portions of the surface are completely immersed and other portions alternately immersed can be particularly aggressive. The high availability of oxygen in the zone of alternate immersion can make these areas cathodic to the continuously submerged area with oxygen concentration cell attack occurring in the submerged area.

In other cases, alternate immersion can be less severe than continuous immersion. This is true for metals that depend on the availability of oxygen for the maintenance of protective films on their surface. When exposed to alternate immersion, particularly when well rinsed after immersion, many of the stainless steels that show poor performance in long-term immersion can give good service. In some cases, the time to initiation of corrosion can be very long, up to 2 or 3 years for some alloys, and cleaning and atmospheric exposure can effectively restart the time to initiation. Thus, under conditions of alternate immersion with rinsing, a given material could withstand 20 years of alternate 6-month immersion when it would show severe attack after 1 year of continuous immersion.

First Exposure. In many cases the environment to which a metal is exposed is important in its subsequent performance. This is particularly true where materials that are dependent on a protective film for their corrosion resistance are concerned. If a stainless steel is exposed to a very aggressive environment, its protective film can be damaged and reduce corrosion resistance. In some configurations where water will penetrate into crevices, it is best to first expose the equipment to freshwater. Subsequent marine immersion may eventually allow salt to penetrate the crevice area but freshwater can increase the stability of passive films in the crevice and will certainly reduce the time the surfaces in the crevice are exposed to full strength seawater.

Mechanical Factors. In addition to the chemical nature of the environment, there are many other factors that can affect both the severity of corrosion and the impact of the corrosion damage on the function of the equipment.

a. Structural Versus Dynamic Applications. Structures are often designed based on resistance to deformation rather than resistance to collapse. Localized corrosion often has a minimal effect on the stiffness of many structures and surprisingly large amounts of corrosion can be tolerated before structural failure. In other cases, the stiffness of a structure more depends on its shape to resist buckling forces. Considerable localized and general attack can be tolerated without reducing structural strength. Such structures are also often overdesigned and, if failure does occur in one member, stresses are transferred to other members and collapse is avoided. Under dynamic loadings and in many mechanical applications, small amounts of corrosion can have a large affect on function. Small amounts of corrosion in bearings or seals can have a disastrous effect. Small pits on cyclically loaded parts can serve as fatigue enhancing stress raisers. In assessing the potential effect of corrosion on function, the consequences of corrosion in specific locations must be carefully evaluated. Mechanical functions often have little redundancy and a single point of failure can result in the failure of an entire system or mission.

b. Stress. Areas of high stress are not only more likely to fail if corroded, but corrosion in more likely to occur in such an area. Situations where the effect of stress has established a type of concentration cell where the high energy of the highly stressed areas has established a corrosion cell have been suspected but not well documented. High stress, however, often cracks the protective coatings and can also rupture naturally occurring passive films. High strength materials also are commonly used in areas of high stress and are subject to both gross corrosion and environmental cracking.

c. Wear. As described in the section on fretting corrosion, the combined effect of corrosion and wear can be catastrophic. In such cases, materials that are effectively immune to attack are often used.

d. Fluid Flow. As described in the sections on erosion corrosion and cavitation, high velocity fluid flow can adversely affect many materials. Aluminum alloys are particularly susceptible to velocity attack. Steels are somewhat susceptible even at low velocities. At high velocities, copper alloys are used but most of these have a limiting flow velocity that must not be exceeded. If flow is continuous, stainless steels have a good resistance to velocity effects but if the flow is interrupted, they have poor resistance to stagnant conditions. The corrosion that began under stagnant conditions can propagate rapidly even under subsequent flow conditions. Corrosion resistant nickel base alloys and titanium alloys have excellent resistance at high velocities, but can also be affected when the velocities are extreme (in excess of 25 fps).

Velocity. High velocities should be avoided whenever possible. In hydraulic systems where high velocities cannot be avoided, the effect of velocity on corrosion must be carefully assessed. At velocities up to 10 fps 90-10 copper nickel has been widely used with success. At velocities above 10 fps, stainless steels can be used if the flow is never less than 5 fps. If both high velocity (10 fps) and low velocity (fps) flow is anticipated, recommend titanium or Inconel 625 be used. Several recently developed duplex and “super austenitic” stainless steels have been widely used in heat exchanger applications, primarily in power plants and in offshore oil production. Their performance has been good but some failures have occurred. Their performance under extended low flow conditions remains questionable.

Turbulence. Turbulence causing features in hydraulic systems should be avoided for not only corrosion considerations but from the standpoint of power or pumping requirements. Such features as those described in the sections on erosion and cavitation corrosion should be avoided in the design of seawater containing hydraulic systems.

11.4.1.3 Material Composition. Like all man made materials, the composition of metals and alloys are subject to variability. In most cases, variability within the limits established by the manufacturer will not have an effect on the properties of the materials that are critical in the application for which they are commonly used. Variations of composition within normal manufacturers limits can affect a critical performance characteristic of the material. It is vital that the material specifications used are indeed specific. Using industrial standards, such as American Society for Testing and Materials (ASTM) standards or Copper Development Association (CDA) alloy composition standards, is highly recommended. Proprietary materials procured by trade name from the original manufacturer or from authorized distributors are usually satisfactory. The specification and procurement of materials by common name such as "red brass," "mild steel," or "CRES," should be avoided. Proper quality control, certification, marking, and testing are necessary in order to insure that proper materials are used. All personnel involved must be sensitized to the fact that using improper materials can cause failures even though their intentions are to use a material that is "just as good as" or "better than" the material specified. When a material has a characteristic property, such as the non-magnetic character of stainless steel or the color of some of the copper alloys, this can often be used to identify material substitutions. In critical applications, non-destructive tests, such as chemical spot tests or X-ray spectrometry, can be used in a 100% inspection of final components to insure that the proper materials have been used.

Composition Limits. Although it is common to report alloy composition as "nominal" or "typical" or to report the actual analysis of a specific sample or heat of material, manufacturers or standardization organizations have established composition limits for most alloys. In most cases, all materials with compositions within these limits will give similar performances. In some cases, however, special composition limits have been identified for marine service and, when necessary, materials meeting these special limits must be obtained. For example, nickel aluminum bronze is used for marine castings, but in order to give a satisfactory performance, it is important that the nickel content exceeds the iron content in the material, otherwise, pitting corrosion is likely to occur. The composition limits for nickel in this alloy are 4 to 5% and the composition limits for iron are 3.5 to 4.5%, thus a casting within the normal composition limits can have the undesirable situation where the iron content exceeds the nickel content by up to 0.5%, which can be significant.

Variability. There can also be considerable variability in alloy composition from different domestic or foreign manufacturers. In very critical applications, mill certifications are required. Receipt analysis is sometimes used to verify that proper raw materials have been supplied before expensive fabrication or catastrophic failure occurs.

Material Quality. In some cases, several grades of material are available based on the level of defects that they contain. Often, rather than manufacturing the materials to more stringent specifications, a single batch of material is simply inspected and sorted according to its quality. In critical applications, special grades of material may be required and, when specified, it must be insured that materials conforming to the requirements are actually used.

Material Condition. Material properties, especially corrosion resistance, strength, and toughness are sensitive not only to material composition but other metallurgical factors. When designing equipment it is vital that these factors be considered when selecting materials and in their fabrication and use.

a. Heat Treatment. Heat treatment can dramatically affect many material properties. It is vital that the proper heat treatment be specified and used. This is true for all alloy systems. Aluminum alloys and stainless steels are particularly susceptible to variations in corrosion properties with heat treatment. Carbon and alloy steels are primarily susceptible to variations in mechanical properties in different heat treated conditions. In some cases, the material must be in a specific initial condition before subsequent heat treatment can be successfully performed. When this is required, the initial condition must be verified either by certification or by metallurgical examination. Hardness testing can confirm the heat treatment. However, in some cases, particularly in aluminum alloys and stainless steels, more than one heat treatment sequence can result in a given material hardness but with significant differences in other properties, such as toughness or corrosion resistance. It is often necessary to obtain specific heat treatment validations from the manufacturer or heat treater and to verify the heat treatment by mechanical tests, metallurgical examination, or both.

b. Cold Work. Cold work is often used to increase the strength of materials. Aluminum alloys are particularly susceptible to variations in corrosion properties with cold work. Almost any alloy will be more susceptible to damage by corrosion when it is hard worked, not because corrosion is necessarily greater, but in high stress applications, the impact of attack on the function of the highly stressed component is increased.

c. Welding. Joining by welding is highly desirable as it can produce mechanically sound and leak tight joints that exclude seawater from the interior of the joints. However, welding is a complex metallurgical process. In the weld pool, alloys are produced in few seconds from a mixture of the filler metal and base metal and are contaminated by the weld slag or shielding gas. Unlike the manufacture of the base alloy, there is not enough time for adjusting the composition of this molten metal before it solidifies and there is usually no post solidification chemical analysis. In addition, the base material adjacent to the weld is heat treated to varying degrees. Developing welding procedures that produce welded structures with appropriate strength, toughness, and corrosion properties is often one of the most difficult steps in the development of an alloy. As in the case of heat treatment, aluminum alloys and stainless steels are susceptible to variations in corrosion properties when welded and the mechanical properties of steels are sensitive to welding effects. If a welded component has been used with success or tests of welded materials are the basis for design, it is important that identical welding materials and processes be used. In addition, when manual welding is used, the welder's is critical. The welder must be qualified to perform the specific welding procedure being used and on the specific material being welded. In addition, the welder should be periodically re-certified. In many applications, non-destructive testing, such as magnetic particle inspection; radiography; and ultrasonic testing, are used in the quality control of welded components. In some critical applications, random samples of welded components are destructively tested to assure weld quality.

d. Form. Some materials are difficult to manufacture in some forms. This affects their availability. While carbon and alloy steels are manufactured in bars, plates, sheets, forgings, and rolled products; many materials are not as widely available in some forms and some may be incompatible with manufacture in certain forms. For example, many aluminum alloys are normally only produced as sheets or plates. While some of these alloys can easily be made into extrusions, limited demand for specific shapes may require that large amounts of material be ordered at one time in order to make a special manufacturing run economical.

In some cases, again particularly in the case of aluminum alloys, variations in product form can affect corrosion resistance as well as other material properties. As an example, a plate of aluminum alloy 5086 suffered pitting of up to 0.020 inch in 1 year of immersion in seawater. An extruded angle of the same material, within composition limits, was pitted only to a depth of 0.001 inch.

11.4.2 Causes of Service Failures. It is important to realize that there is a difference between the mechanism by which a failure occurs and the cause of failure.

11.4.2.1 Causes Versus Mechanisms. The cause of a failure is a description of the conditions that lead to the failure. The mechanism of failure describes the mode of failure rather than the conditions that lead to the failure. For example, a stainless steel part may fail due to crevice corrosion when the cause of failure was substituting an improper grade of stainless steel, improper assembly, or failure of a protective coating.

11.4.2.2 Design Related Failures. Causes of failures often relate more closely to features of design rather than the properties of the materials used. As described in the sections on specific forms of corrosion, design features that create such features as crevices, high stresses, and high velocity turbulent flow can be important factors leading to corrosion failures. The sensitivity of equipment to failure by corrosion attack is also primarily a function of design.

11.4.2.3 Material Related Failures. Some failures are caused by the actual material deficiencies. A material sometimes does not perform as it was expected to based on its anticipated properties.

Material Selection. In some cases, material related failure is simply an indication of selecting the wrong materials. This is often due to the lack of consideration of the effect of some important service factor in the design and selecting a material that is unsuitable under the actual service conditions. Corrosion is often one of the factors that is not properly included in the overall design process.

Faulty Material. In some cases, material defects can result in service failures. All materials contain discontinuities or defects. Only when these defects are more significant than is common in the material or are more significant than a specified defect level are they referred to as flaws. In some cases, defects are also introduced during fabrication. Improper welding and heat treatment are common ways that defects are introduced during fabrication. Surface contamination from corrosion damage is also possible and should be avoided when necessary, particularly on aluminum alloys and stainless steels. Remember, however, that no engineering material is perfect and all will contain defects. The actual cause of a given failure should not be attributed to a failure that initiates at a defect if that defect is the size and type that should be anticipated in the specified material. Only when the defects are more significant than those that are commonly present can they be considered a flaw.

Wrong Material. In too many cases, failures are caused simply caused by using the wrong material.

11.4.2.4 Manufacturing Related Failures. Some failures are caused, not by deficiencies in the materials used, but improper fabrication practices. Many manufacturing processes can, if improperly performed, affect the properties of a material as much or more than its composition. Special analytical techniques are often required to determine if failures are due to manufacturing problems.

Heat Treatment. When heat treatment is required for the development of required material properties, improper heat treatment can result in failure. In some cases, hardness testing is sufficient to confirm the heat treatment but in other cases, microscopic examination or mechanical testing is required to verify the heat treatment that the material has received.

Welding. Welding is also a critical process and improper welding techniques can lead to failure. However, many welds are susceptible to failure than the base material. Failure may occur in the welds even though the welding was properly done. In these cases, the failure occurred in the weld but the actual cause of failure is not an improper weld but is due to some other factor.

Machining. Improper machining can lead to failure in several ways. For example, improper tolerances can lead to high assembly stresses; improper surface finishes can lead to accelerated wear of bearing surfaces; and improper clearances can cause seals to leak. It is often difficult to establish machining problems as a cause of failure due to service wear, corrosion, or deformations that have occurred as a result of the failure through an analysis of the actual failed part. Analyzing similar parts either from service or from spares can sometimes be used to identify machining problems.

11.4.2.5 Protective Coatings. Coating failure can be due either to using the wrong coatings, improper application of the coating, or improper surface preparation. Chemical analysis of the coating can be used to verify that the proper coating was used. Several tests can be used to measure coating thickness, but in failure analysis, using Tooke gauge can not only identify the overall thickness of the coating but can identify the thickness of each of the individual coats that were applied. Surface preparation is often difficult to establish as a cause of coating failure but, in some cases, adhesion tests or examining surfaces from which sound coating has been chemically removed can identify improper surface preparation.

11.4.2.6 Assembly Errors. In some cases, failure is due to assembly errors: improper tightening of bolts, improper tensioning of cables, or using incorrect parts, such as improperly sized O-rings. Careful part-by-part disassembly and inspection of failed assemblies is an important part of any failure analysis.

11.4.2.7 Service Related Failures. In some cases, failures are due primarily to the environment that was encountered rather than any material or manufacturing problem.

Mechanical Overload. Overload is a common cause of service failure. This type of failure is one of the most difficult causes of failure to properly analyze as the loads that caused the failure are not often measured during service and disappear on failure. Mechanical deformations of associated equipment can sometimes be used to evaluate the loads that were encountered at the time of failure. Analysis of the operation just before and at the time of failure can also identify loading conditions. It is often the direction in which loads are applied rather than their magnitude that causes overload failures to occur.

Improper Use. Improper use is often one of the most difficult causes of failure to establish. It is usually difficult to obtain impartial descriptions of the situations leading to this type of failure.

Improper Maintenance or Repair. Maintenance and repair are often inadequate or improper. The condition of equipment at the time of failure is usually easy to establish. Reviewing maintenance requirements and records can determine whether the maintenance required was performed or whether the maintenance requirements were inadequate.

CHAPTER 12. REFERENCES AND BIBLIOGRAPHY

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Appendix A

ECONOMIC LIFE GUIDELINES*

To provide a basis for comparison between competing projects, economic lives are established for the general investment classifications listed below. These guidelines can be used in the absence of better information. However, due to the constraints of mission life and technological life, the economic life chosen should not exceed the applicable figure below.

1.	ADP Equipment	8 years
2.	Buildings	
	a. Permanent	25 years
	b. Semi-permanent, non-wood	25 years
	c. Semi-permanent, wood	20 years
	d. Temporary or rehabilitated	15 years
3.	Operating Equipment	25 years
4.	Utilities, Plants, and Utility Distribution Systems	25 years
	(This category includes investment projects for electricity, water, gas, telephone, and similar utilities.)	
5.	Energy Conserving Assets	
	a. Insulation, solar screens, heat recovery systems, and solar energy installations	25 years
	b. Energy monitoring and control systems	15 years
	c. Controls (e.g., thermostats, limit switches, automatic ignition devices, clocks, photocells, flow controls, temperature sensors, etc.)	15 years
	d. Refrigeration compressors	15 years

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*Source: Economic Analysis Handbook, NAVFAC P-442, June 1986.

Appendix B

PROJECT YEAR DISCOUNT FACTORS*

Table A

PRESENT VALUE OF $1 (Single Amount -- to be used when cash flows accrue in varying amounts each year)

Table B

PRESENT VALUE of $1 (Cumulative Uniform Series -- to be used when cash flows accrue in the same amount each year)

	Table A	Table B
Project Year	**10%**	**10%**
1	0.909	0.909
2	0.826	1.736
3	0.751	2.487
4	0.683	3.170
5	0.621	3.791
6	0.564	4.355
7	0.513	4.868
8	0.467	5.335
9	0.424	5.759
10	0.386	6.145
11	0.350	6.495
12	0.319	6.814
13	0.290	7.103
14	0.263	7.367
15	0.239	7.606
16	0.218	7.824
17	0.198	8.022
18	0.180	8.201
19	0.164	8.365
20	0.149	8.514
21	0.135	8.649
22	0.123	8.772
23	0.112	8.883
24	0.102	8.985
25	0.092	9.077

NOTE: Table A factors are based on continuous compounding at a 10% effective annual discount rate, assuming uniform cash flows throughout state 1-year periods. Table A factors are approximated by an arithmetic average of beginning and end of year single amount factors found in standard present value tables. Table B factors represent the cumulative sum of Table A factors through any given project year. Formulae for these factors are provided in Appendix C.

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*Source: Economic Analysis Handbook, NAVFAC P-442 of June 1986.

Appendix C

PRESENT VALUE FORMULAE*

Project Year 10% Discount Factors

Table A Single Amount Factor:

$$a_n = \frac{1}{(1 + R)^n}$$

Table B Cumulative Uniform Series Factor:

$$b_n = \frac{(1 + R)^n - 1}{R(1 + R)^n}$$

where: n = number of years
R = 0.10, effective annual discount rate.

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*Economic Analysis Handbook, NAVFAC, P-442, June 1986.

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