Paint and Coatings

Applications and Corrosion Resistance

Philip A. Schweitzer, P.E.

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Preface

Many factors must be taken into account when selecting the material of construction of a component for a particular application. Such factors include physical and mechanical properties, workability, corrosion resistance, and cost. Many alloys have been developed to resist corrosion; however, the use of these materials may not be practical from the standpoint of cost, based on the specific application. Using paints or other coating materials, less-expensive materials having the requisite physical and mechanical properties can be employed, although they do not have the corrosion resistance required.

Steel structures can be protected by the application of an appropriate paint system. It is important to select the proper paint system for the specific application. Just as metallic alloys differ in their resistance to corrosion from different corrodents, so do paint systems as well as other coating systems.

This book is designed to assist the designer, engineer, maintenance personnel, and any other person charged with the protection from corrosion of equipment, structures, and various components. This is true whether it be for the construction of a bridge, household appliance, concrete structure, a piece of chemical processing equipment, or the decorative facing of a building.

The first few chapters of this book (Chapters 1 through 4) provide background information on the principles of coating and the theory of adhesion, as well as the importance of surface preparation. The remaining chapters (Chapters 5 through 16) address paint systems, organic coatings for immersion applications, metallic coatings, conversion coatings, cementitious coatings, monolithic surfacings for concrete, tribiological synergistic coatings, and high-temperature coatings.

Included in each category is the method or methods of application, areas of application, and corrosion-resistance properties. Included are tables that provide comparisons of the various coating materials in the presence of selected corrodents.

This book will be helpful to those who are involved in the design, material selection, and maintenance of structures, equipment, plant facilities, and miscellaneous components.

Philip Schweitzer

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1 Introduction to Coatings

Construction metals are selected because of their mechanical properties and machineability at a low price, while at the same time they should be corrosion resistant. Very seldom can these properties be met in one and the same material. This is where coatings come into play. By applying an appropriate coating, a base metal with good mechanical properties can be utilized while the appropriate coating provides corrosion protection. At other times, a coating can be applied for decorative purposes.

Polymers (plastics) are painted because this is frequently a less-expensive process than using precolored resins or molded-in coloring. They are also painted when necessary to provide UV (ultraviolet) protection. However, they are difficult to paint, and proper consideration must be given to:

1. *Heat distortion point and heat resistance.* This determines whether a bake-type paint can be used and, if so, the maximum baking temperature the polymer can tolerate.
2. *Solvent resistance.* Because different polymers are subject to attack by different solvents, this will dictate the choice of paint system. Some softening of the surface is desirable to improve adhesion, but a solvent that attacks the surface aggressively and results in cracking or crazing should be avoided.
3. *Residual stress.* Molded parts may have localized areas of stress. A coating applied in these areas can swell the polymer and cause crazing. Annealing the part prior to coating it will minimize or eliminate the stress problem.
4. *Mold-release residues.* If excessive amounts of mold-release compounds remain on the part, adhesion problems are likely to occur. To prevent such a problem, the polymer must be thoroughly rinsed or otherwise cleaned.
5. *Plasticizers and other additives.* Most polymers are formulated with plasticizers and additives. These materials have a tendency to migrate to the surface and may even soften the coating and destroy the adhesion. The specific polymer formulation should be checked to determine whether the coating will cause short- or long-term softening or adhesion problems.
6. *Other factors.* The long-term adhesion of the coating is affected by properties of the polymer such as stiffness, rigidity, dimensional stability, and coefficient of expansion. The physical properties of the paint film must accommodate those of the polymer.

TABLE 1.1
Classes of Coatings

Organic	Inorganic	Conversion	Metallic[a]
Coal tars	Silicates	Anodizing	Galvanizing
Phenolics	Ceramics	Phosphating	Vacuum vapor
Vinyls	Glass	Chromate	deposition
Acrylics		Molybdate	Electroplating
Epoxy			Diffusion
Alkyds			
Urethanes			

[a] These are processes rather than individual coatings as many metals can be applied by each process. The process and item to be coated will determine which metal will be used.

The majority of coatings are applied on external surfaces to protect the metal from natural atmospheric corrosion and atmospheric pollution. On occasion, it may also be necessary to provide protection from accidental spills and splashes. In some instances, coatings are applied internally in vessels for corrosion resistance. Under these circumstances, the applied material is usually referred to as a lining.

Basically, there are four different classes of coatings (Table 1.1).

PRINCIPLES OF CORROSION PROTECTION

Most metals used for construction purposes are unsuitable when exposed to the atmosphere. These unsuitable metals are produced by reducing ores artificially; therefore, they will return to their original ores or to similar metallic compounds when exposed to the atmosphere. For example, metallic iron is oxidized to ferric oxhydride in a thermodynamically stable state (iron in the higher level of free energy is changed to lepidocrocite, √ FeOOH, in the lower level):

$$4Fe + 3O_2 + 2H_2O \rightarrow 4FeOOH$$

This reaction of a metal in a natural environment is called corrosion. By means of a coating, a longer period of time is required for rust to form on the substrate, as shown in Figure 1.1. Therefore, it is important that the proper coating material be selected for application in a specific environment.

For a coating to be effective, it must isolate the base material from the environment. The service life of the coating depends on the thickness and the chemical properties of the coating layer. The latter determines the durability of a coating material in a specific environment, which is the corrosion resistance of a metal coating or the stability of the organic or inorganic compounds in an organic or

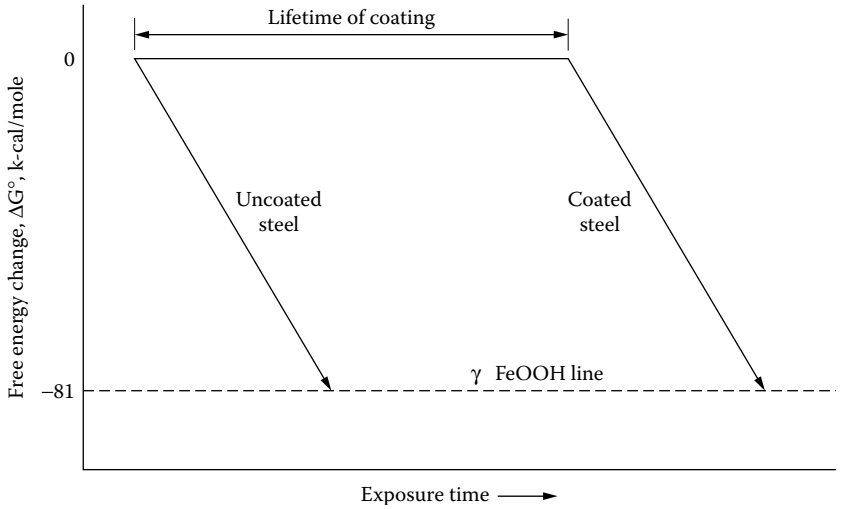


FIGURE 1.1 Role of corrosion-resistant coating.

inorganic coating material. To be effective, the coating's durability must be greater than that of the base metal or it must be maintained by some other means. In addition, a coating is often required to protect the base metal with its original pore and crack, or with a defect that may have resulted from mechanical damage or pitting corrosion.

Organic Coatings

Organic coatings provide protection either by a barrier action from the layer or from active corrosion inhibition provided by pigments in the coating. In actual practice, the barrier properties are limited because all organic coatings are permeable to water and oxygen to some extent. The average transmission rate of water through a coating is about 10 to 100 times larger than the water consumption rate of a freely flowing surface; and in normal outdoor conditions, an organic coating is saturated with water at least half of its service life. For the remainder of the time, it contains a quantity of water comparable in behavior to an atmosphere of high humidity. Table 1.2 shows the diffusion data for water through organic films.

It has been determined that, in most cases, the diffusion of oxygen through the coating is large enough to allow unlimited corrosion. Taking these factors into account indicates that the physical barriers alone do not account for the protective action of coatings. Table 1.3 shows the flux of oxygen through representative free films of paint 100 μm thick.

Additional protection may be supplied by resistance inhibition, which is also part of the barrier mechanism. Retardation of the corrosion action is accomplished by inhibiting the charge transport between cathodic and anodic sites. The reaction

TABLE 1.2
Diffusion Data for Water through Organic Films

Polymer	Temp. (°C)	$p \times 10^9$ (cm^3[STP]cm)	$D \times 10^9$ (cm^2/sec)
Epoxy	25	10–44	2–8
	40	—	5
Phenolic	25	166	0.2–10
Polyethylene (low density)	25	9	230
Polymethyl methacrylate	50	250	130
Polyisobutylene	30	7–22	—
Polystyrene	25	97	—
Polyvinyl acetate	40	600	150
Polyvinyl chloride	30	13	16
Vinylidene chloride/acrylonitrile copolymer	25	1.7	0.32

Source: From Leidheiser, Jr., H., Coatings, in *Corrosion Mechanisms,* F. Mansfield, Ed., Marcel Dekker, New York, 1987, pp. 165–209.

rate can be reduced via an increase in the electrical resistance or the ionic resistance in the corrosion cycle. Applying an organic coating to a metallic surface increases the ionic resistance. The electrical resistance may be increased by the formation of an oxide film on the metal; this is the case for aluminum substrates.

Corrosion of a substrate beneath an organic coating is an electrochemical process that follows the same principle of an uncoated substrate. It differs from

TABLE 1.3
Flux of Oxygen through Representative Free Films of Paint, 100 μm Thick

Paint	J (mg/cm^2 day)
Alkyd (15% PVC Fe_2O_3)	0.0069
Alkyd (35% PVC Fe_2O_3)	0.0081
Alkyl-melamine	0.001
Chlorinated rubber (35% PVC Fe_2O_3)	0.017
Cellulose acetate	0.026 (95% RH)
Cellulose nitrate	0.115 (95% RH)
Epoxy melamine	0.008
Epoxy coal tar	0.0041
Epoxy polyamide (35% PVC Fe_2O_3)	0.0064
Vinyl chloride/vinyl acetate copolymer	0.004 (95% RH)

Source: From Leidheiser, Jr., H., Coatings, in *Corrosion Mechanisms,* F. Mansfield, Ed., Marcel Dekker, New York, 1987, pp. 165–209.

crevice corrosion in that the reactants often reach the substrate through a solid. In addition, during the early stages of corrosion, small volumes of liquid are present, resulting in extreme values of pH and ion concentrations. The total corrosion process takes place as follows:

1. Migration through the coating of water, oxygen, and ions
2. Development of an aqueous phase at the coating/substrate interface
3. Activation of the substrate surface for the anodic and cathodic reactions
4. Deterioration of the coating/substrate interfacial bond

Metallic Coatings

Metallic coatings are classified according to the electrochemical principle upon which they operate to provide protection. These categories are:

1. EMF control
2. Cathodic control protection
3. Anodic control protection
4. Mixed control protection
5. Resistance control protection

The mechanism of the corrosion cell can explain the theories upon which these five categories operate.

Corrosion Cell

A corrosion cell is formed on a metal surface when oxygen and water are present (refer to Figure 1.2). The electrochemical reactions taking place in the corrosion cell include:

Anodic reaction (M = metal):

$$M \rightarrow M^{n+} + ne \tag{1.1}$$

Cathodic reaction in acidic solution:

$$2H^+ + 2e \rightarrow H_2 \tag{1.2}$$

Cathodic reaction in neutral and alkaline solutions:

$$O_2 + 2H_2O + 4e \rightarrow 4OH^- \tag{1.3}$$

The Evans diagram in Figure 1.3 represents the mechanism of the corrosion cell. The cathodic current is expressed in the same direction as the anodic current.

In Figure 1.3, the E value is the single potential for H_2/H^+ or for O_2/OH^- at the cathode, and the E_a value is the single potential for metal/metal in equilibria at the anode. The single potential is given by the Nernst equation:

$$E = E^O + \frac{RT}{nF} In\ a \tag{1.4}$$

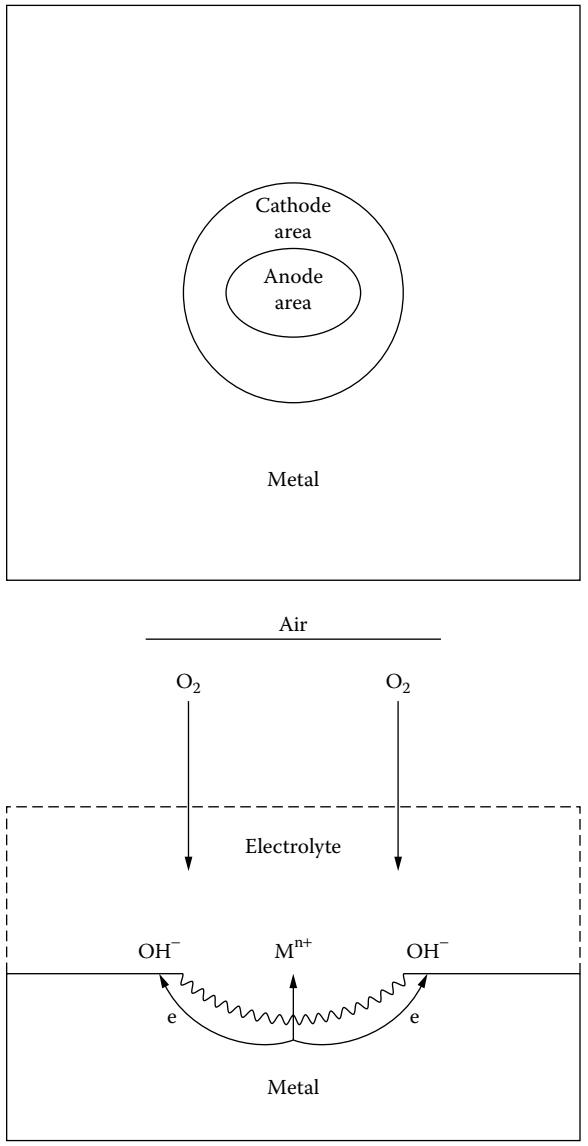


FIGURE 1.2 Structure of a corrosion cell.

where:

E = single potential
E^O = standard single potential
R = absolute temperature
n = charge on an ion

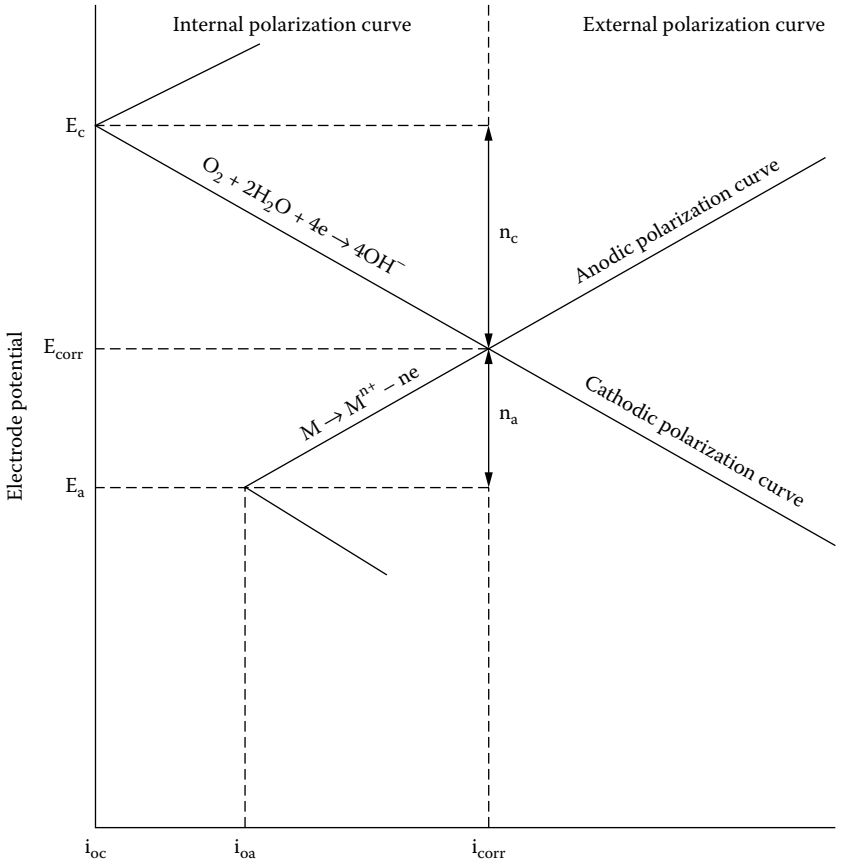


FIGURE 1.3 Mechanism of a corrosion cell.

F = Faraday constant
a = activity of an ion

When $a = 1$, $EI = E$. The standard single potential E^0 shows the degree of activity of the metal and gas.

The electrochemical series consists of the arrangement of the metals in order of electrode potential. The more negative the single potential, the more active the metal. Table 1.4 provides the single potentials of the various metals and nonmetallic reactants.

When the electromotive force $(E_c - E_a)$ is supplied, the corrosion cell is formed with a current flowing between the anode and the cathode. The cathodic electrode potential is shifted toward the less noble direction. The shifting of potentials is called cathodic and anodic polarization. The reaction rate curves

TABLE 1.4
Standard Single Potentials (E°)

Active		Inert	
Electrode	E° (V, SHE, 25°C)	Electrode	E° (V, SHE, 25°C)
Li/Li^{+}	−3.01	Mo/Mo^{3+}	−0.2
Rb/Rb^{+}	−2.98	Sn/Sn^{2+}	−0.140
Cs/Cs^{+}	−2.92	Pb/Pb^{2+}	−0.126
K/K^{+}	−2.92	H_2/H^{+}	±0
Ba/Ba^{2+}	−2.92	Bi/BiO	+0.32
Sr/Sr^{2+}	−2.89	Cu/Cu^{2+}	+0.34
Ca/Ca^{2+}	−2.84	Rh/Rh^{2+}	+0.6
Na/Na^{+}	−2.71	Hg/Hg^{+}	+0.798
Mg/Mg^{2+}	−2.38	Ag/Ag^{+}	+0.799
Th/Th^{4+}	−2.10	Pd/Pd^{2+}	+0.83
Ti/Ti^{2+}	−1.75	Ir/Ir^{3+}	+1.0
Be/Be^{2+}	−1.70	Pt/Pt^{2+}	+1.2
Al/Al^{3+}	−1.66	Au/Au^{3+}	+1.42
V/V^{2+}	−1.5	Au/Au^{+}	+1.7
Mn/Mn^{2+}	−1.05		
Zn/Zn^{2+}	−0.763	O_2/OH^{-}	+0.401
Cr/Cr^{3+}	−0.71	I_2/I^{-}	+0.536
Fe/Fe^{2+}	−0.44	Br_2/Br^{-}	+1.066
Cd/Cd	−0.402	Cl_2/Cl^{-}	+1.356
In/In^{3+}	−0.34	F_2/F^{-}	+2.85
Ti/Ti^{+}	−0.335	S/S^{2-}	−0.51
Co/Co^{2+}	−0.27	Se/Se^{2+}	−0.78
Ni/Ni^{2+}	−0.23	Te/Te^{2+}	−0.92

$(E - i)$ are known as cathodic or anodic polarization curves. The corrosion potential E^{o}_{corr} and the corrosion current i_{corr} are given by the intersection of the cathodic and anodic polarization curves — an indication that both electrodes react at the same rate in the corrosion process.

The polarization curves in the current density range greater than i_{corr} are called external polarization curves, and those in the current density range less than i_{corr} are called internal polarization curves. By sweeping the electrode potential from the corrosion potential to the cathodic or anodic direction, the external polarization curve can be determined. The internal polarization curve cannot be measured directly by the electrochemical technique because it is impossible to pick up the current separately from the anode and cathode, which exist in the electrode. By analyzing the metallic ions dissolved and the oxidizer reaction, the internal polarization curve can be determined.

Anodic or cathodic overpotential is represented by the difference in potential between E_{corr} and E_a or E_{corr} and E_c and is expressed as n_a or n_c, where:

$$n_a = E_{corr} - E_a \qquad n_a > 0 \tag{1.5}$$

$$n_c = E_{corr} - E_c \qquad n_c < 0 \tag{1.6}$$

The anodic and cathodic resistance is given by n_a/i_{corr}.

As soon as the cell circuit is formed, the corrosion reaction begins:

$$E - E_a = [n_c] - i_{corr}R \tag{1.7}$$

where R is the resistance of the electrolyte between the anode and cathode. As the current passes through the process (the anodic process, the cathodic process, and the transit process in the electrolytes), the electromotive force of a corrosion cell is dissipated.

When the electrode is polarized, the overpotential n is composed of the activation overpotential n^a and the concentration overpotential n^c:

$$n = n^a + n^c \tag{1.8}$$

The activation overpotential n^a results from the potential energy barrier to be overcome for a charge to cross the double layer interface ($M = M^{n+} + ne$) and is given as follows.

In the anodic reaction:

$$n_a^a = \beta_a \log \frac{i_a}{i_{oa}} \text{ (Tafel equation)} \tag{1.9}$$

$$\beta_a = 2.3\frac{RT}{\propto nF} \tag{1.10}$$

In the cathodic reaction:

$$n_c^a = \beta_c \log \frac{i_c}{i_{oc}} \text{ (Tafel equation)} \tag{1.11}$$

$$\beta_c = \frac{2.3\,RT}{(1-\propto)nF} \tag{1.12}$$

where:

n_a^a = activation overpotential in the anodic region
n_c^a = activation overpotential in the cathodic region
β_a = anodic Tafel coefficient
β_c = cathodic Tafel coefficient

$\propto$ = transfer coefficient
i_a = anodic current density
i_c = cathodic current density
i_{oa} = exchange current density of anode
i_{oc} = exchange current density of cathode

The degree of contribution of electrical energy for the activation energy in the electrode reaction ($0 < \propto < 1$) is indicated by the energy transfer factor $\propto$, which in most cases is in the range of 0.3 to 0.7. The exchange current density i_a or i_c is the flux of charge that passes through the electrical double layer at the single equilibrium potential E_a or E_c. A linear relationship exists between n^a and log i_a or log i_c. The Tafel coefficient β_a or β_c is the slope dn^a/d (log i_a or log i_d) of the polarization curve. Therefore, β is one of the important factors controlling the corrosion rate.

The electrical reaction at the low reaction rate is controlled by the activation overpotential. One of the processes controlled by the activation overpotential is the cathodic reaction in the acid solution:

$$2H^+ + 2e = H_2 \tag{1.13}$$

Table 1.5 shows the hydrogen overpotential of various metals. The activation overpotential varies with the kind of metal and the electrolyte condition. Metal dissolution and metal ion deposition are usually controlled by the activation overpotential.

TABLE 1.5
Hydrogen Overpotentials of Various Metals

Metal	Temp. (°C)	Solutions	Hydrogen Overpotential, $\lvert n^\circ \rvert$ (V/mA/cm²)	Tafel Coefficient, $\lvert \beta_c \rvert$ (V)	Exchange Current Density, $\lvert i_{oc} \rvert$ (A/cm²)
Pt smooth	20	1 *N* HCl	0.00	0.03	10^{-3}
Mo	20	1 *N* HCl	0.12	0.04	10^{-6}
Au	20	1 *N* HCl	0.15	0.05	10^{-6}
Ag	20	0.1 *N* HCl	0.30	0.09	5×10^{-7}
Ni	20	0.1 *N* HCl	0.31	0.10	8×10^{-7}
Bi	20	1 *N* HCl	0.40	0.10	10^{-7}
Fe	16	1 *N* HCl	0.45	0.15	10^{-6}
Cu	20	0.1 *N* HCl	0.44	0.12	2×10^{-7}
Al	20	2 *N* H_2SO_4	0.70	0.10	10^{-10}
Sn	20	1 *N* HCl	0.75	0.15	10^{-8}
Cd	16	1 *N* HCl	0.80	0.20	10^{-7}
Zn	20	1 *N* H_2SO_4	0.94	0.12	1.6×10^{-11}
Pb	20	0.01–8 *N* HCl	1.16	0.12	2×10^{13}

The anodic overpotential is given by:

$$n_a = \beta_a \log \frac{i_a}{i_{oa}} \tag{1.14}$$

At high reaction rates, the concentration overpotential n^c becomes the controlling factor in the electrode reaction. In this case, the electrode reaction is controlled by a mass transfer process, which is the diffusion rate of the reactive species. The diffusion current is given as:

$$i = \frac{nFD\,(C - C_O)}{\delta} \tag{1.15}$$

where:

i = current density
D = diffusion coefficient
C = concentration of reactive species in the bulk solution
C_o = concentration of reactive species at the interface
δ = thickness of the diffusion layer

When the concentration of the reactive species at the interface is zero, $C = 0$, and the current density reaches a critical value, i_L, called the limiting current density:

$$i_L = \frac{nFDC}{\delta} \tag{1.16}$$

From Equations 1.15 and 1.16,

$$\frac{C_o}{C} = 1 = \frac{i}{i_L} \tag{1.17}$$

The concentration overpotential is given as:

$$n^c = \left[2.3\frac{\mathrm{RT}}{nF}\right]\log\left[\frac{C_O}{C}\right] \tag{1.18}$$

From Equations 1.17 and 1.18,

$$n^c = \left[\frac{2.3\,\mathrm{RT}}{nF}\right]\log\left[1 - \frac{i}{i_L}\right] \tag{1.19}$$

As seen in Equation 1.19, the concentration overpotential increases rapidly as i approaches i_L.

The cathodic reaction is controlled by the activation overpotential n_c^a and the concentration overpotential n_{CO}^C.
The cathodic overpotential is:

$$n_c = n_C^a + n_{CO}^C \tag{1.20}$$

The cathodic overpotential can be written in the form:

$$n_c = \beta_c \log\left[\frac{i_c}{i_{oc}} + \frac{2.3\,\mathrm{RT}}{nF}\right]\log\left[1 - \frac{i_c}{i_{cL}}\right] \tag{1.21}$$

See Equations 1.12, 1.19, and 1.20. In most cases, the corrosion rate can be determined from the anodic and cathodic overpotentials because the rate determination process is determined by the slopes of the polarization curves.

As mentioned previously, the role of the coating is to isolate the substrate from the environment. The coating accomplishes this based on two characteristics of the coating material: (1) the corrosion resistance of the coating material when the coating is formed by the defect-free continuous layer and (2) the electrochemical action of the coating material when the coating layer has some defect, such as a pore or crack. The mechanism of the corrosion cell can explain the action required of the coating layer. For better understanding, Equation 1.7 is rewritten as follows:

$$i_{\mathrm{corr}} = \frac{(E_c - E_a) - |n_c| n_a|}{R} \tag{1.22}$$

A corrosion-resistant coating is achieved by one of five different methods to decrease i_{corr} based on Equation 1.22:

1. EMF control protection: decrease in electromotive force $(E_c - E_a)$
2. Cathodic control protection: increase in cathodic overpotential $|n_c|$
3. Anodic control protection. increase in anodic overpotential $|n_a|$
4. Mixed control protection: increase in both anodic overpotential $|n_a|$ and cathodic overpotential $|n_c|$
5. Resistance control protection: increase in resistance of corrosion cell R

EMF CONTROL PROTECTION

The difference in potential between the anode and the cathode $(E_c - E_a)$ is the EMF of the corrosion cell. It is also the degree of thermodynamic instability of the surface metal for the environment. That is, the less the EMF, the lower the

corrosion rate. By covering the surface of the active metal with a continuous layer of a more stable metal, the active metal surface becomes more thermodynamically stable. Dissolved oxygen and hydrogen ions, which are the reactants in the cathodic reaction, are normal oxidizers found in natural environments. In the natural atmosphere, the single potential of dissolved oxygen is nearly constant. Because of this, metals with more noble electrode potentials are used as coating materials. These include copper, silver, platinum, gold, and their alloys. A copper coating system provides excellent corrosion resistance under the condition that the defect-free continuous layer covers the surface of the iron substrate. In so doing, the EMF of the iron surface is decreased by the copper coating. The corrosion potential is changed from E_{corr} of uncoated iron to E_{corr} of copper by coating with copper. Under this condition, the iron corrodes at the low rate of the i_{corr} of copper; however, if the iron substrate is exposed to the environment, as the result of mechanical damage, the substrate is corroded predominately at the rate of the i_{corr} of exposed copper by coupling iron and copper (galvanic corrosion).

Organic coatings and paints are also able to provide EMF control protection. Surface conditions are converted to more stable states by coating with organic compounds. These coatings delay the generation of electromotive force, causing the corrosion of the substrate.

How long an organic coating will be serviceable depends on the durability of the coating itself and its adhesive ability on the base metal. The former is the stability of the coating layer exposed to various environmental factors, and the latter is determined by the condition of the interface between the organic film and the substrate.

The EMF can also be decreased by the use of a glass lining, porcelain enameling, and temporary coating with grease and oils.

CATHODIC CONTROL PROTECTION

Cathodic control protection protects the substrate by coating with a less noble metal, for which the slopes of the polarization curves are steep. The cathodic overpotential of the surface is increased by the coating; therefore, the corrosion potential becomes more negative than that of the substrate. Coating materials used for this purpose include zinc, aluminum, manganese, cadmium, and their alloys. The electrode potentials of these metals are more negative than those of iron or steel. When exposed to the environment, these coatings act as sacrificial anodes for the iron and steel substrates.

The protective ability of these coatings includes:

1. Original barrier action of the coating layer
2. Secondary barrier action of the corrosion product layer
3. Galvanic action of the coating layer as sacrificial anode

Barrier coatings 1 and 2 predominate as the protective ability although a sacrificial metal coating is characterized by galvanic action.

Initially, the substrate is protected against corrosion by the barrier action of the coating, followed by the barrier action of the corrosion product layer.

Upon exposure to air, aluminum forms a chemically inert Al_2O_3 oxide film a rapidly forming self-healing film. Therefore, the passive film on aluminum, as well as the corrosion product layer, is a main barrier and leads to a resistant material in natural environments.

On the other hand, the surface oxide film that forms on zinc is not as an effective barrier as the oxide film of aluminum.

Upon exposure to the natural atmosphere, many corrosion cells are formed on the surface of a sacrificial metal coating, thereby accelerating the corrosion rate. During this period, corrosion products are gradually formed and converted to a stable layer. This period may last for several months, after which the corrosion rate becomes constant. These corrosion products from the second barrier are amorphous Al_2O_3 on aluminum and $Zn(OH)_2$ and basic zinc salts on zinc. ZnO, being electrically conductive, loosens the corrosion product layer and therefore does not contribute to formation of the barrier. When materials such as CO_2, NaCl, and SO_x are present, basic zinc salts are formed, for example, $2ZnCO_3 \cdot 3Zn(OH)_2$ in mild atmospheres, $ZnCl_2 \cdot 6Zn(OH)_2$ in chloride atmospheres, and $ZnSO_4 \cdot 4Zn(OH)_2$ in SO_x atmospheres. How stable each basic zinc salt will be depends on the pH and anion concentration of the electrolyte on the zinc. Zinc carbonate forms an effective barrier on steel in mild atmospheres, while basic zinc sulfate and chloride dissolve with decreasing pH of the electrolyte. The basic zinc sulfate is restricted under atmospheric conditions in its effort to act as a barrier because the pH value of rain in an SO_x atmosphere is usually low, in the area of less than 5. In a chloride environment, the pH in the electrolyte is not as low as in the SO_x atmosphere; therefore, a secondary barrier will form. However, in a severe chloride environment, the zinc coating layer will corrode despite the existence of basic zinc chloride on the surface.

Galvanic Action of Coating Layer

Sacrificial metal coatings protect the substrate metal by means of galvanic action.

When the base metal is exposed to the atmosphere as a result of mechanical damage or the like, the exposed portion of the base metal is polarized cathodically to the corrosion potential of the coating layer. As a result, little corrosion takes place on the exposed metal. A galvanic couple is formed between the exposed part of the base metal and the surrounding coating metal. Sacrificial metals are more negative in electrochemical potential than other metals, such as iron or steel. Therefore, the sacrificial metal acts as a cathode. This type of reaction of sacrificial metal coatings is known as galvanic or cathodic protection. In addition, the defects are protected by a second barrier of corrosion products

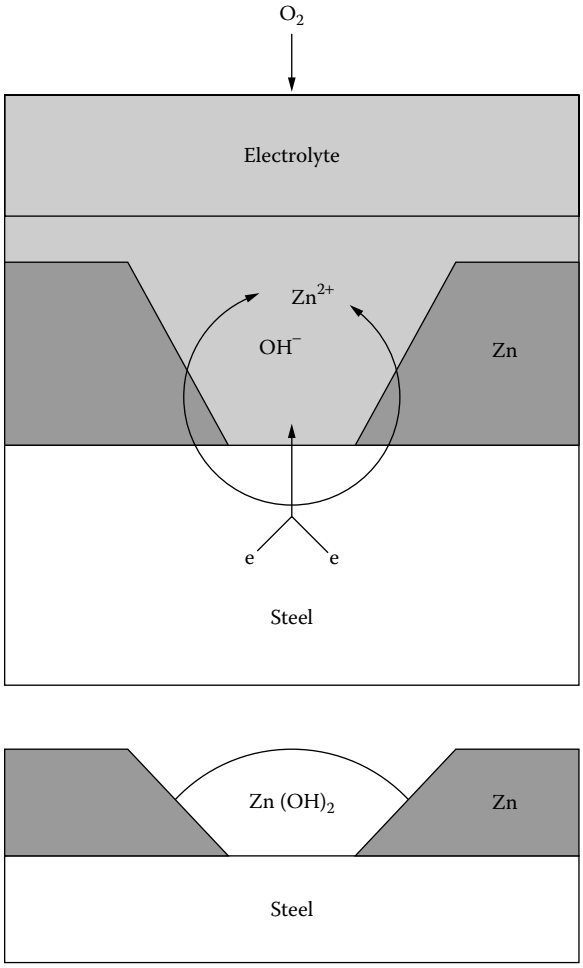


FIGURE 1.4 Schematic illustration of a sacrificial coating.

of the coating layer. Figure 1.4 schematically illustrates the galvanic action of a sacrificial metal coating.

ANODIC CONTROL PROTECTION

Noble metal coatings provide anodic control protection. They are usually used where corrosion protection and decorative appearance are required. Nickel, chromium, tin, lead, and their alloys are the coating metals that provide anodic protection.

Single-Layer Coatings

Single-layer metal coatings provide corrosion protection as a result of the original barrier action of the noble metal. With the exception of lead, a second barrier of corrosion products is formed. Noble metals do not provide cathodic protection to steel substrates in natural atmospheres because the corrosion potential of the noble metal is more noble than that of steel. Refer to Table 1.4.

The service life of a single-layer coating is affected by any discontinuity in the coating, such as that caused by pores and cracks. For metals to form a protective barrier, the coating thickness must be greater than 30 μm to ensure the absence of defects. The surface of a bright nickel coating will remain bright in a clean atmosphere but will change to a dull color when exposed to an SO_x atmosphere.

Chromium coatings are applied as a thin layer to maintain a bright, tarnish-free surface. Cracking of chromium coatings begins at a thickness of 0.5 μm, after which a network of fine cracks forms.

For the protection of steel in an SO_x atmosphere, lead and its alloys (5 to 10% tin) coatings are employed. Pitting will occur in the lead coating at the time of initial exposure, but the pits are self-healing and then the lead surface is protected by the formation of insoluble lead sulfate.

Multilayer Coatings

There are three types of nickel coatings: bright nickel, semibright, and dull. The difference between them is the quantity of sulfur contained in them, as shown below:

Bright nickel deposits	0.04% sulfur
Semibright nickel deposits	0.005% sulfur
Dull nickel deposits	0.001% sulfur

The corrosion potentials of the nickel deposits depend on the sulfur content. Figure 1.5 shows the effect of sulfur content on the corrosion potential of a nickel deposit. As the sulfur content increases, the corrosion potential of a nickel deposit becomes more negative. A bright nickel coating is less protective than a semibright or dull nickel coating. The difference in potential between bright nickel and semibright deposits is more than 50 mV.

The differences in the potential are used in the application of multilayer coatings. The more negative bright nickel deposits are used as sacrificial intermediate layers. When bright nickel is used as an intermediate layer, the corrosion behavior is characterized by a sideways diversion. Pitting corrosion is driven laterally when it reaches the more noble semibright deposit. Thus, the behavior of bright nickel prolongs the time for pitting penetration to reach the base metal.

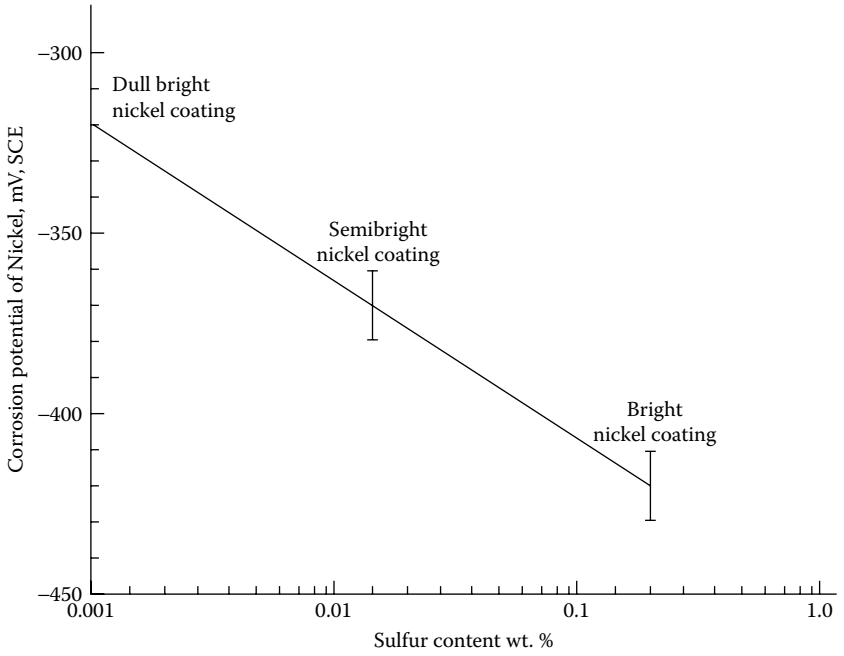


FIGURE 1.5 Effect of sulfur on the corrosion potential of nickel deposit.

The most negative of all nickel deposits is trinickel. In the triplex layer coating system, a coating of trinickel approximately 1 μm thick, containing 0.01 to 0.25% sulfur, is applied between bright nickel and semibright nickel deposits. The high-sulfur nickel layer dissolves preferentially, even when pitting corrosion reaches the surface of the semibright deposit. Because the high-sulfur layer reacts with the bright nickel layer, pitting corrosion does not penetrate the high-sulfur nickel in the tunneling form. The application of a high-sulfur nickel strike definitely improves the protective ability of a multistage nickel coating.

RESISTANCE CONTROL PROTECTION

Resistance control protection is achieved using organic compounds, such as some paints, as coating materials. The coating layer delays the transit of ions to the substrate, thereby inhibiting the formation of corrosion cells. Figure 1.6 illustrates the principles of resistance control by an organic coating. The corrosion rate of iron is inhibited by the coating from the i_{corr} of uncoated iron to i_{corr} of coated iron.

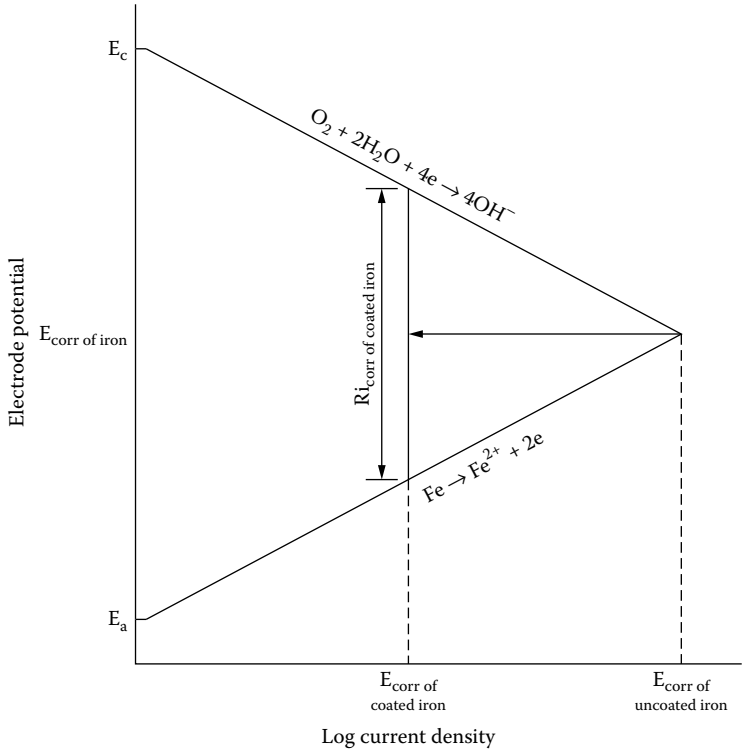


FIGURE 1.6 Resistance control protection.

REFERENCES

1. Leidheiser, Jr., H., Coatings, in *Corrosion Mechanisms,* F. Mansfield, Ed., Marcel Dekker, New York, 1987, pp. 165–209.
2. Suzuki, I., *Corrosion Resistant Coatings Technology,* Marcel Dekker, New York, 1989.

2 Principles of Coating

An understanding of the basic principles that describe and predict liquid flow and interfacial interactions is necessary for the effective formulation and the efficient application of coatings. The two primary sciences of liquid flow and solid–liquid interaction are rheology and surface chemistry. Rheology deals with the science of flow and deformation while surface chemistry deals with the science of wetting and dewetting. The key rheological property of coatings is viscosity, which is simply the resistance of a coating to flow, the ratio of shear stress to shear rate.

During the application of a coating, various types of mechanical forces are exerted. The amount of shear force directly affects the viscosity value for non-Newtonian fluids. Most coatings are subject to some degree of "shear thinning" when worked by mixing. As the shear rate increases, the viscosity drops, and in some cases dramatically.

This appears to be simple enough except for two other effects. The first is referred to as the *yield point*, the shear rate required to cause flow. Ketchup illustrates this effect. Ketchup often refuses to flow until a little extra shear force is applied. Then it often flows too freely. Once the yield point has been exceeded, the solid-like behavior vanishes — the loose network structure is broken up.

Yield value, which is an important property of liquids, will also be discussed. Rheology must be studied as a dynamic variable and understood how it changes during the coating process. A key concept of coating technology is the mutual interaction in which the coating process alters viscosity and how rheology affects this process.

The second factor is time dependency. Viscosity can depend on the amount of mechanical force applied and on the length of time it is applied.

Rheology involves much more than merely examining viscosity at a single shear rate. It concerns the changes in viscosity as different levels of force are applied, as temperature is varied, and as solvents and additives come into play. Brookfield viscometric readings, although valuable, do not show the complete picture for non-Newtonian fluids.

Surface chemistry, for our purpose, involves the attractive forces liquid molecules have for each other and for the substrate. The primary concern is the wetting phenomenon, how it relates to the coating process, and the problems encountered. An understanding of wetting and dewetting will help explain many of the anomalies experienced in coating.

The two sciences of rheology and surface tension, when considered together, provide the necessary tools to handle the complex technology of coating.

RHEOLOGY

Rheology, the science of flow and deformation, is necessary to the understanding of coating use, application, and quality control. The most important rheological characteristic of liquids — and therefore of coatings — is that of viscosity, the resistance to flow. Even more important is the way that viscosity changes during coating. Newtonian fluids, like solvents, exhibit an absolute viscosity that does not change by the application of mechanical shear. However, practically all coatings show an appreciable change in viscosity as different forces are applied.

As indicated, viscosity, the resistance to flow, is the key property describing the behavior of liquids subjected to forces such as mixing. Viscosity is simply the ratio of the shear stress to the shear rate:

$$\eta = \frac{\text{Shear stress}}{\text{Shear rate}} = \frac{r}{D} \text{ (dynes-sec/cm}^2\text{)}$$

The viscosity unit (i.e., dynes-seconds per square centimeter, or Poise) is a rather small unit for low viscosity fluids such as water (approximately 0.01P). Therefore, the more common centipoise unit (cP) is used. Because 100 cP = 1P, water has a viscosity of approximately 1 cP. Table 2.1 lists the viscosities of some common industrial liquids. A high viscosity liquid requires considerable force (work) to produce a change in shape. For example, high-viscosity coatings are more difficult

TABLE 2.1
Viscosities of Common Industrial Liquids

Liquid	Viscosity (cP)[a]
Acetone	0.32
Chloroform	0.58
Toluene	0.59
Water (20.20°C)	1.000
Cyclohexane	1.1
Ethyl alcohol	1.2
Turpentine	1.5
Mercury, metal	1.6
Creosote	12.0
Sulfuric acid	25.4
Linseed oil	33.1
Olive oil	84.0
Castor oil	986.0
Glycerine	1490.0

[a] Values are for approximately 20°C.

to pump than low-viscosity coatings. High-viscosity coatings also take longer to flow out when applied.

Thin or low-viscosity liquids flow easily while high-viscosity liquids move with considerable resistance. In the ideal, or Newtonian, case viscosity is constant over any region of shear. However, very few liquids are truly Newtonian. Most liquids drop in viscosity as shear work is applied. This phenomenon is known as shear thinning. A liquid can be affected by the amount of time that force is applied. A shear-thinned liquid will tend to return to its initial viscosity over time. Therefore, if viscosity is to be reported accurately, the time under shearing action and the time at rest must also be noted.

Viscosity Behavior

The effect on the viscosity of a fluid varies from fluid to fluid as force is applied. These different effects are described below.

Plasticity

Plastic fluids behave more like plastic solids until a specific minimum force is applied to overcome the yield point. Gels and ketchup are extreme examples. Once the yield point is reached, the liquids begin to approach Newtonian behavior as the shear rate increases. Although plastic behavior is of no benefit to ketchup, it has some benefits in paints. Actually, it is the yield point phenomenon that is of practical value, as illustrated in no-drip paints. When the brush stroke force has been removed, the paint's viscosity builds quickly until the flow stops. Dripping is prevented because the yield point exceeds the force of gravity.

Pseudoplasticity

The viscosity of pseudoplastic fluids drops as force is applied. However, there is no yield point. The more energy applied, the more the thinning. When the shear rate is reduced, the viscosity increases at the same rate by which the force is diminished. There is no hysteresis; the stress–shear rate curve is the same in both directions, as shown in Figure 2.1. Figure 2.2 compares pseudoplastic behavior using viscosity–shear rate curves.

Many coatings exhibit this type of behavior, but with time dependency. There is a pronounced delay in the viscosity increase after the force has been reduced. This form of pseudoplasticity with a hysteresis loop is called thixotropy. Pseudoplasticity is useful in coatings, but thixotropy is more useful.

Thixotropy

Some coatings take advantage of thixotropic behavior to overcome the problem of having a sufficiently low viscosity on time. These coatings retain a low viscosity

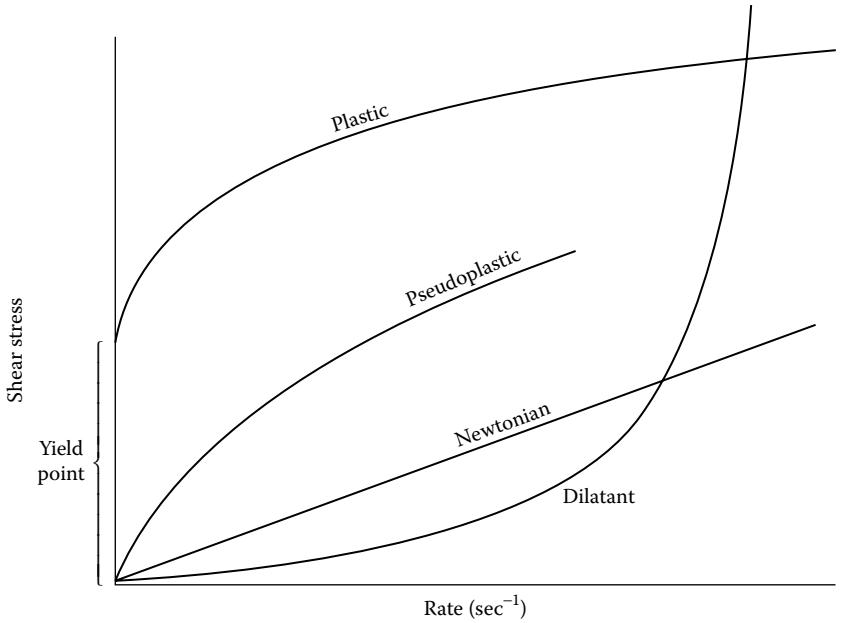


FIGURE 2.1 Shear-stress-shear-rate curves.

for a short time after shearing, thus permitting good leveling, but thicken fast enough to prevent sagging.

This thixotropic behavior of a coating is shown in Figure 2.3. The coating is initially sheared at an increasing shear rate, producing curve a in Figure 2.3. Then the coating is sheared at a constant rate until the viscosity (curve b) is reached. The shear rate is then gradually reduced, producing curve c. The degree of thixotropy is indicated by the enclosed area of the thixotropic loop. Dripless paints owe their driplessness to thixotropy. The paint begins as a moderately viscous material that stays on the brush. It quickly drops in viscosity under the stress of brushing for long smooth application. A return to higher viscosity when shearing (brushing) stops prevents dripping and sagging.

Dilatancy

Dilatants are liquids whose viscosity increases as shear is applied. Very few liquids possess this property. This property should not be confused with the increase in viscosity resulting from the loss of solvent. True dilatancy takes place without solvent loss. For example, a solvent-borne coating applied by a roll coater will show a viscosity increase as the run progresses. The rotating roller serves as a solvent evaporator, increasing the coating's solids content and, therefore, the viscosity. True dilatancy occurs independently of solvent loss.

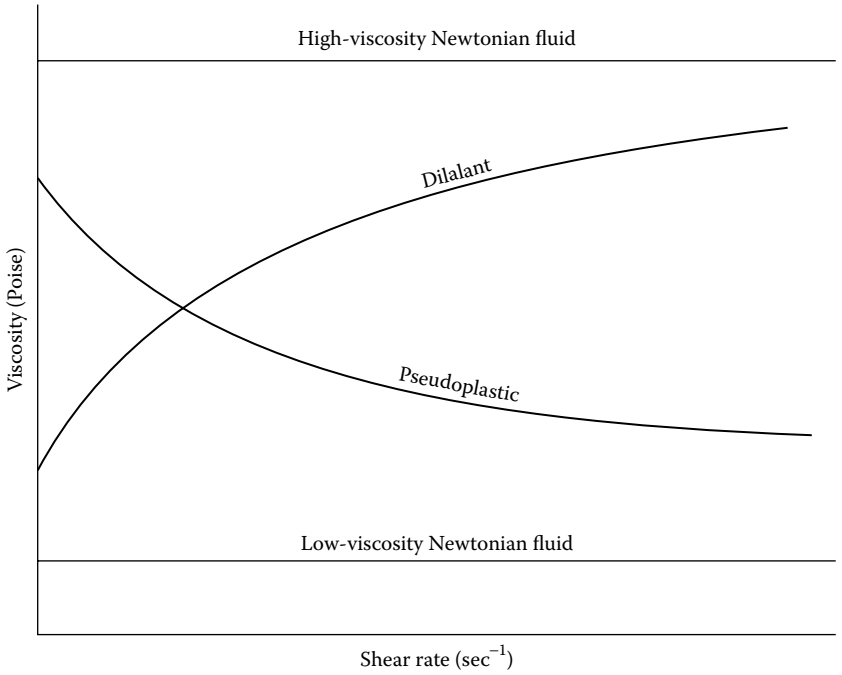


FIGURE 2.2 Viscosity shear-rate curves.

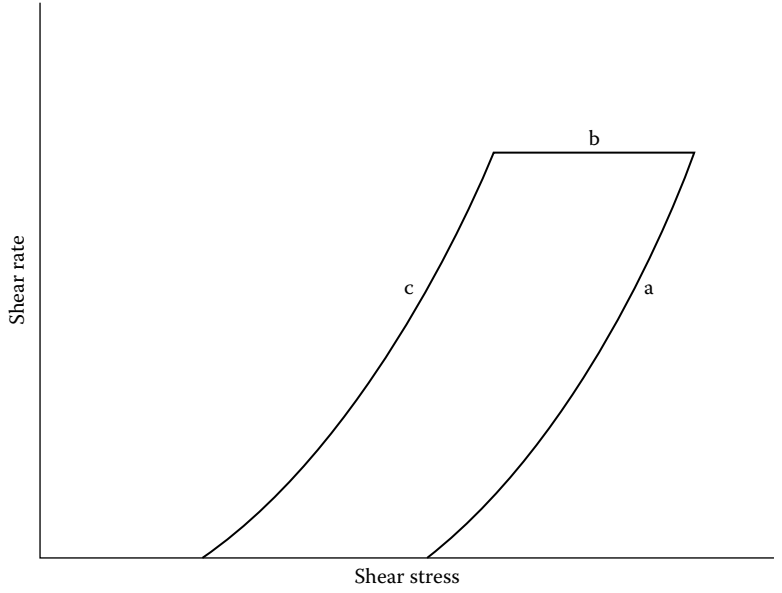


FIGURE 2.3 Thixotropic loop.

Effect of Temperature

Viscosity is extremely sensitive to temperature changes. All comparative measurements should be taken at the same temperature (usually 73.4°F/23°C). A viscosity value without a temperature notation is useless.

Each fluid is affected differently by a temperature change, but the change per degree is usually constant for a specific liquid. In general, a coating's viscosity can be reduced by an increase in temperature and increased by a reduction in temperature.

Effect of Solvents

Higher solution viscosity results from higher resin solids, whereas an increase in solvent volume reduces the viscosity. Soluble resins (polymers) produce more pronounced viscosity changes than do insoluble pigments or plastic particles. A plastisol suspension (plastic particles in a liquid plasticizer) may have a medium viscosity at 80% solids, whereas a coating may be highly viscous with a 50% solid concentration. The specific solvent will also have an effect on the viscosity, depending on whether they are true solvents, latent solvents, or non-solvents. Refer to References 1 and 2 for more detail.

Viscosity Measurement

Many instruments are available. A rheometer is capable of accurately measuring viscosities through a wide range of shear stress. Much simpler equipment is typically used in the plastic decoration industry. The most common device is the Brookfield viscometer, in which an electric motor is coupled to an immersion spindle through a tensiometer. The spindle is rotated in the liquid to be measured. The higher the viscosity (resistance to flow), the larger the tensiometer reading. Several spindle diameters are available, and a number of rotational speeds can be selected. Viscosity must be reported along with the spindle size, rotational speed, and temperature.

The Brookfield instrument is a good tool for incoming quality control. Although certainly not a replacement for the rheometer, the viscometer can be used to estimate viscosity change with shear. Viscosity readings are taken at different rpms and then compared. A highly thixotropic material will be readily identified.

An even simpler device is the flow cup, a simple container with an opening at the bottom. The Ford cup and the Zahn cup are very common in the plastic painting and coating field.

The Ford cup, the more accurate of the two, is supported on a stand. Once filled, the bottom orifice is unstoppered and the time for the liquid to flow out is recorded. Unlike the Brookfield, which yields a value in centipoise, the cup gives only a flow time. Relative flow times reflect different relative viscosities. Interconversion charts permit Ford and other cup values to be converted to centipoise (see Table 2.2).

TABLE 2.2
Viscosity Conversions

	Consistency								
	Watery			Medium			Heavy		
Poise	0.1	0.5	1.0	2.5	5.0	10	50	100	150
Centipoise	10	50	100	250	500	1000	5000	10,000	15,000
Viscosity Device									
Fisher #1	20								
Fisher #2		24	50						
Ford #4 cup	5	22	34	67					
Parlin #10	11	17	25	55					
Parlin #15				12	25	47	232	465	697
Saybolt	60	260	530	1240	2480	4600	23,500	46,500	69,500
Zahn #1	30	60							
Zahn #2	16	24	37	85					
Zahn #3			12	29	57				
Zahn #4			10	21	37				

Note: Liquids are at 25°C. Values are in seconds for liquids with a specific gravity of approximately 1.0.

The Zahn cup is dipped in a liquid sample by means of its handle and quickly withdrawn, after which the time to empty is recorded. The Zahn type of device is commonly used online, primarily as a checking device for familiar materials.

Yield Value

The yield value is the shear stress in a viscosity measurement, but one taken at a very low shear. It is the minimum shear stress applied to a liquid that produces flow. When the yield value is greater than the shear stress, flow will not take place.

A liquid undergoes deformation without flowing as force is gradually applied. The liquid, for all intents and purposes, is acting as an elastic solid. Viscosity approaches infinity below the yield value. At a critical force input (the yield value), flow starts.

When the yield value is greater than the shear stress, the liquid behaves as if it were a solid. If a coating is applied at this time, what you deposit is what you get. Leveling will not occur. Coatings that cannot be leveled, although the apparent viscosity is low, probably have a high yield value.

If this is the case, the only solution may be to change the method of application.

The most direct method of measuring this stress is by creep experiments in shear. This can be accomplished in the so-called stress-controlled rheometers (refer to Table 2.3). The minimum stress that can be imposed on a sample varies with the type of instrument; by careful use of geometry, a shear stress in the

TABLE 2.3
Some Commercially Available Rheological Instruments

Name of Instrument	Geometrics Available	Shear Rate Range	Modes Available
Weisenberg Rheogoniometer	Couette, cone and plate, parallel plate	Broad	Steady shear, oscillatory
Rheometrics mechanical spectrometer	Couette, cone and plate, parallel plate	Broad	Steady shear, oscillatroy
Carri-Med controlled stress rheometer (CSR)	Couette, parallel plate	Fixed stress	Creep and recovery, oscillatory
Rheo-Tech viscoelastic rheometer (WER)	Cone and plate	Fixed stress	Creep and recovery, oscillatory
Contraves Rheomat 115	Cone and plate, couette	Broad	Steady shear
Rheometrics stress rheometer	Cone and plate	Fixed stress	Creep and recovery, oscillatory
Haake Rotovisco	Couette, cone and plate	Broad	Steady state
Shirley-Ferrani	Cone and plate	Broad	Steady shear
ICI Rotothinner	Couette	Single high rate	Steady shear
Brookfield cone and plate	Cone and plate	Medium to high	Steady
Brookfield spindle	Undefined	Undefined	Steady shear
Gardner-Holdt	Rising bubble	Undefined	—
Cannon-Ubbelohde	Poiseuille	Limited range, high end	Shear
Brushometer	Couette	High end only, single	Steady shear

range of 1 to 5 dynes/cm^2 can be applied. Most paints with a low level of solids exhibit yield stresses in this range. However, the detection of flow is not straightforward. The measured strain in the sample must attain linearity in time, and then permanent flow takes place. Consequently, it may be necessary to take measurements over a long period of time.

An estimate of the yield stress can be obtained from constant rate-of-strain measurements of stress and viscosity. When the viscosity is plotted against stress, its magnitude appears to approach infinity at low stresses. The asymptote on the stress axis gives an estimate of the yield stress.

SURFACE CHEMISTRY

This is the science that deals with the interface of two materials. The interface can exist between any forms of matter, including a gas phase. However, for the purpose of understanding the interfacial reactions of coating materials, it is only necessary to analyze the liquid–solid interaction. The effect of surface interaction between a liquid coating and the surrounding air is small and can be ignored.

Surface Tension

Surface tension is one of the factors that determines the ability of a coating to wet and adhere to the substrate.

All liquids are composed of molecules, which when close to one another exert attractive forces. It is these mutual attractions that produce the property called surface tension. The units are dynes per centimeter (force per unit length).

When a drop of liquid is suspended in space, it assumes a spherical shape. Because surface molecules are pulled toward those directly beneath them, a minimum surface area (sphere) results. All liquids attempt to form a minimum surface sphere. When a liquid is placed on a solid, a liquid–solid interface develops. Liquid molecules are attracted not only to each other (intermolecular attraction), but also to any solid surface (intermolecular attraction) with which they come in contact. These two interactions are the only ones that must be considered in coating operations.

Wetting

The ability of a liquid to wet a surface is related to its surface tension. Using solvents with lower surface tension, one can improved the ability of a coating to wet a substrate. When placed on a flat horizontal surface, a liquid will either wet and flow out, or it will dewet to form a semispherical drop. It is also possible for an in-between state to occur in which the liquid neither recedes nor advances, but remains stationary.

The angle that the drop or edge of the liquid makes with the solid substrate is called the contact angle θ. The smaller the contact angle, the better the wetting (refer to Figure 2.4). A wetting condition takes place when the contact angle is θ°. The liquid's edge continues to advance although the rate may be slow for high-viscosity materials.

Various interfacial tensions determine the equilibrium contact angle for a liquid drop sitting in an ideally smooth, homogeneously flat, and nondeformable surface. They are related by Young's equation:

$$\gamma_{LV}\cos\theta = \gamma_{sV} - \gamma_{sL} \tag{2.1}$$

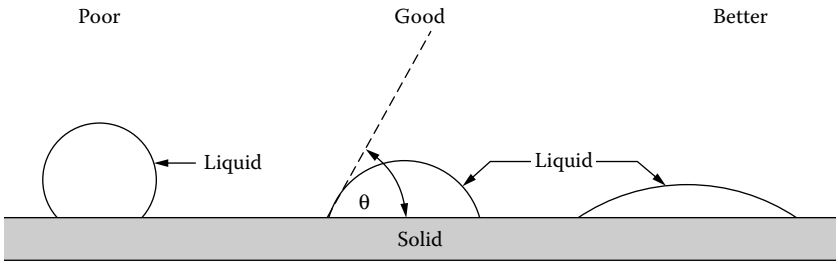


FIGURE 2.4 Schematic illustration of good and bad wetting.

where

γ_{LV} = surface tension of liquid
γ_{sV} = surface tension of solid in equilibrium with the saturated vapor of the liquid
γ_{sL} = interfacial tension between the solid and liquid

From Equation 2.1 it can be seen that for spontaneous wetting to occur, the surface tension of the liquid must be greater than the surface tension of the solid. With the application of force, it is also possible for a liquid to spread and wet a solid when θ is greater than zero.

Coalescence

Coalescence is the fusing of molten particles to form a continuous film, the first step in powder coating. Surface tension, radius of curvature, and the viscosity of the molten powder control coalescence. To have more time available for leveling, it is desirable to have small particles, low viscosity, and low surface tension.

Surfactants

Surfactants are also known as wetting agents. They are used to lower the surface tension of coatings and paints. Normally, a reduction of 1% or less is sufficient. Surfactants possess two different chemical groups, one compatible with the liquid to be modified and the other having a lower surface tension. For example, the surface tension of an epoxy can be reduced by adding a surfactant containing an alcohol group (epoxy-compatible) at one end and a fluorochemical group at the other. The alcohol group will associate with the epoxy resin presenting the incompatible fluorochemical "tail" to the surface. The epoxy coating will behave as if it were a low surface tension fluorochemical. The addition of a small amount of surfactant will permit the epoxy coating to wet difficult, low-energy surfaces, even oil-contaminated plastic.

Surfactants efficiently lower the surface tension of coatings and paints. When dewetting occurs because of intrinsically low surface energy of the substrate, the use of surfactants, also called wetting agents, is indicated. These materials are not a substitute for good housekeeping and proper parts preparation. Contamination can cause adhesion failure later.

Fluorochemicals, silicones, and hydrocarbons are common categories of surfactants. Fluorochemicals have the lowest surface tension of any material and are the most efficient wetting agents. Silicones are next in efficiency and are lower in cost. A word of caution: certain types of silicones can become airborne, causing contamination of the substrate.

While it may be desirable to lower the surface tension of a coating, the opposite is true for the substrate. The agent that helps the coating renders the substrate useless. Silicone contamination will produce the dewetting defect called "fish eyes."

Coatings and paints modified with a surfactant are usually permanently changed. This can make them difficult to wet if it is necessary to apply additional coats. The problem can be overcome in several ways. It is desirable to use the smallest amount of the least potent surfactant that will do the job. (Start with the hydrocarbon class.) Also check to see that the substrate is clean before starting.

An alternate possibility is to use a reactive surfactant. These are agents that can react with the coating or binder, rendering them less active after curing. Another approach would be to add surfactant to the second material to be applied.

SAGGING AND SLUMPING

When coatings are applied to inclined or vertical surfaces, it is possible for the coating material to flow downward (under the influence of gravity), which leads to sagging and slumping. Newtonian or shear thinning fluids tend to sag as a result of shear flow. A material with a yield stress will slump.

The velocity (V_0) of the material in flow at the fluid–air interface and the resulting sag or slump length (S) can be calculated for a fluid of index n:

$$V_0 = \left[e \frac{g}{n^\circ} \right]^{1/n} \frac{n}{n+1} h^{n+1/n} \quad \text{and} \quad S = V_0 t \tag{2.2}$$

where n^o is the zero shear viscosity and h is the film thickness. The special case of Newtonian fluids is obtained by setting $n = 1$ in Equation 2.2. The final sag or slump length S is determined by the velocity as a time factor t, which is the time interval for which the material remains fluid, or the time it takes for the material to solidify. When everything else is equal, a shear thinning fluid ($n < 1$) will exhibit lower sag/slump under its own weight until its viscosity increases to a point at which V_0 is negligible. If a material has a yield stress, no sagging will occur if the yield stress σ_y is larger than the force of gravity, pgh. However, if the coating is thick enough (large h), both sagging and slumping can occur if the film thickness is larger than h_s, which is given by:

$$h_s = \frac{\sigma_y}{Q_g} \tag{2.3}$$

Between $h = 0$ and h_s, sagging takes place. The velocity can be determined by substituting $h - h_s$ for h in Equation 2.2:

$$V_0 = \left[\frac{Q_g}{n_0} \right]^{1/n} \frac{n}{n+1} (h - h_s)^{n+1/n} \tag{2.4}$$

For $h > h_s$, plug flow occurs.

Good sag control and good sprayability of coatings can be maintained with a shear thinning fluid without a yield stress if it has an n value of 0.6.

LEVELING

Leveling depends on both surface chemistry and rheology. It is a complex phenomenon and one that is difficult to control. Coatings, regardless of the method of application, are often not smooth enough for aesthetic appeal. Splatters, runs, ridges, and other topological defects require that the liquid material level out. For this reason it is important to understand the dynamics of leveling. These imperfections must be removed before the wet coating solidifies. Leveling is the critical step to achieve a smooth uniform coating.

The factors affecting leveling include viscosity, surface tension, yield value, coating thickness, and the degree of wet coating irregularity. These factors are correlated in the leveling equation:

$$a_1 = a_0 \frac{\exp(\text{const}\ \sigma\ h^3 t)}{3\lambda^4 \eta} \tag{2.5}$$

where

a_1 = height of coating ridge
σ = surface tension of coating
η = coating viscosity
h = coating thickness or height
t = time for leveling
λ = wavelength or distance between ridges

From Equation 2.4 we see that leveling is improved by one or more of the following.

1. Longer time t
2. Higher surface tension of coating σ
3. Lower viscosity η
4. Greater coating thickness h
5. Small repeating distance between ridges λ

Because h is raised to the third power, doubling the coating thickness provides an eightfold improvement in leveling. Note that λ (wavelength between ridges) is raised to the fourth power, which indicates that ridges that are far apart create a difficult leveling situation.

Earlier it was pointed out that a high yield value could prevent leveling. The shear stress on a wet coating, must be greater than the yield value for leveling to take place. Equation 2.6 shows the relationship between various parameters and shear stress.[3]

$$T_{\max} = \frac{4\pi^3 \sigma\, ah}{\lambda^3} \quad \text{or} \quad D = \frac{t\lambda^3}{4\pi^3 \sigma h} \tag{2.6}$$

where

D = coating ridge depth
σ = surface tension
a = amplitude of coating ridge
h = coating height
λ = coating ridge wavelength

Because Equation 2.5 deals with force, the time factor and the viscosity value drop out. It is seen that increasing surface tension and coating thickness produce the maximum shear stress. Coating defect height (a) increases shear, while wavelength (λ) strongly reduces it. If coating ridges cannot be avoided, higher, more closely packed ones are preferable.

When the yield value is higher than the maximum shear (T_{max}), leveling will not take place. Extending the leveling time and reducing the viscosity will not help overcome the yield value barrier because these terms are not in the shear equation. Increasing the surface tension and the coating thickness are options but there are practical limits.

Because yield value is usually affected by shear (thixotropy), the coating application rate and premixing conditions may be important. Higher roller speed (for roll coaters) and higher spray pressure (for spray guns) can drop the yield value temporarily. It should be apparent that the best leveling is not achieved by the lowest surface tension. Higher surface tension promotes leveling, but good wetting may require a reduction in surface tension. This is another reason to use the minimum effective quantity of surfactant.

CHANGES AFTER APPLICATION

The viscosity of a fluid coating starts to increase after it has been applied to a substrate. Several factors are responsible for this increase, as illustrated in Figure 2.5. The curves shown in Figure 2.5 are typical for a coating formulation with low solid content. Coatings with a high solid content, and powder coatings, will have curves of different relative magnitudes. The principal increase in the viscosity of powder coatings will be due to freezing as the temperature approaches the melting point.

As the viscosity increases with time, various coating phenomena are abated. Leveling and sagging can only take place as long as the coating is fluid. As the viscosity increases, these phenomena can no longer take place. The measured time dependency on the viscosity is used to estimate the time taken to solidify. In general, when the viscosity is greater than 100,000 P, leveling and sagging occur to a negligible extent.

Edge and Corner Effects

Surface tension, which tends to minimize the surface area of a film, may cause a decrease or increase in the film thickness at the corners when a film is applied

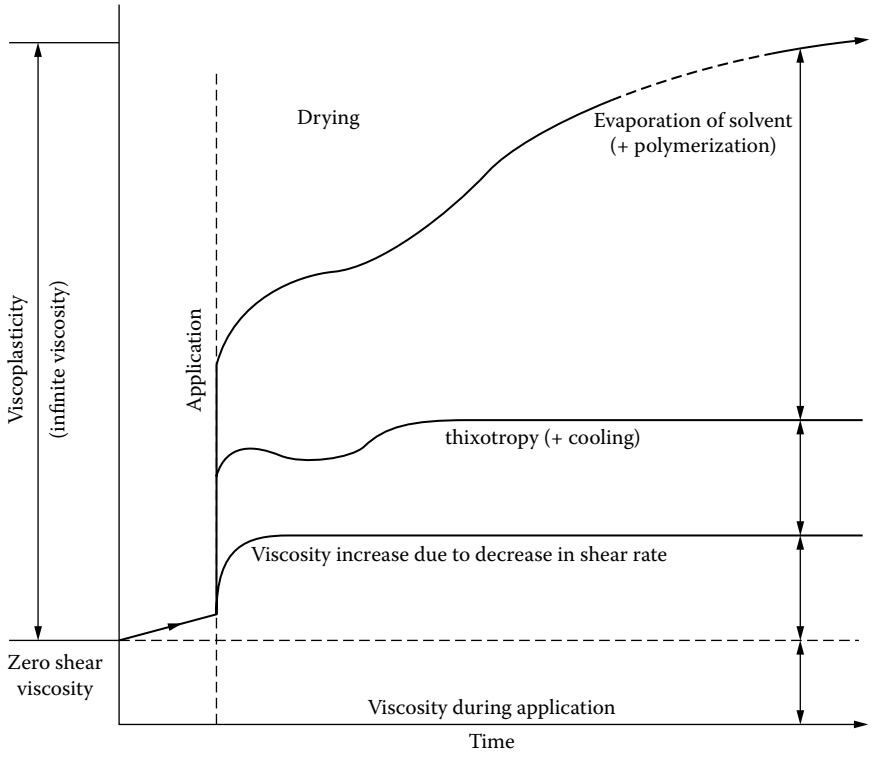


FIGURE 2.5 Change in coating viscosity during application and film formation.

around a corner. This is shown in Figures 2.6a and 2.6b, respectively. In the case of edges of coated objects, an increase in the thickness has been noticed. This phenomenon is related to surface tension variation with solvent concentration.[4] In a newly formed film, a decrease in film thickness at the edge is caused by the surface tension of the film. As a result, solvent evaporation takes place at a much greater rate at the edge of the film because there is a larger surface area per unit volume of fluid near the edge (refer to Figure 2.7a). As more solvent (which usually has a lower surface tension than the polymer) evaporates, a higher surface tension exists at the edge, hence causing a material transport toward the edge from regions 2 and 1 (Figure 2.7b). The newly formed surface in region 2 will have a lower surface tension due to the exposure of the underlying material, which has a higher solvent concentration. As a result, more materials are transported from region 2 to the surrounding areas (regions 1 and 3) because of the surface tension gradient across the regions (Figure 2.7c).

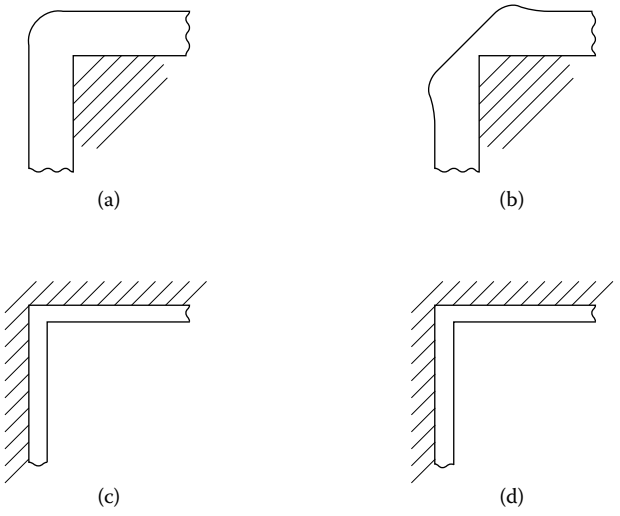


FIGURE 2.6 (a) Newly applied thick film at corner, (b) decrease in the film thickness at the corner due to surface tension, (c) newly applied film at a corner, and (d) increase in film thickness at the corner due to surface tension.

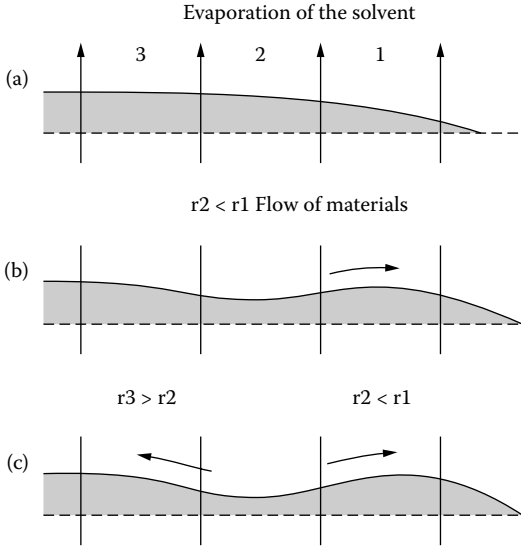


FIGURE 2.7 (a) Newly formed film near an edge, (b) flow of materials from regions 2 to 1, and (c) flow of materials from region 2 to the surroundings.

Depressions: Bernard Cells and Craters

Surface tension gradients resulting from composition variations or temperature variations can cause local distortions or depressions in a coating. This action is known as the Marangoni effect.[5] Liquid flowing from a region of lower to higher surface tension, resulting from surface tension gradients, produces depressions on the liquid surface. These depressions are of two types: Bernard cells and craters.

Bernard cells appear as hexagonal cells with raised edges and depressed centers.[6–8] The increase in the polymer concentration and the cooling resulting from solvent evaporation cause the surface density and surface tension to exceed those of the main body. As a result, an unstable configuration is created that has the tendency to move into a more stable one in which the material at the surface has a lower density and surface tension. Two characteristic numbers have been established by analysis[9]: the Raleigh number R_a and the Marangoni number M_a given by:

$$R_a = \frac{\rho g \infty t h^4}{Kn} \tag{2.7}$$

$$M_a = \frac{th^2(-d_y/dT)}{Kn} \tag{2.8}$$

where

ρ = liquid density
g = gravitational constant
∞ = thermal expansion coefficient
t = temperature gradient on the liquid surface
n = film thickness
K = thermal diffusivity
T = temperature

When the critical Marangoni number is exceeded, the cellular convective flow is formed by the surface tension gradient. As shown in Figure 2.8a, the flow is upward and downward beneath the center depression and the raised edge. However, if the Raleigh number is exceeded, the cellular convective flow, which is caused by the density gradient, is downward and upward beneath the depression and the raised edge (Figure 2.8b). In general, the surface tension gradient is the controlling force for films less than 4 mm thick, while density-gradient-driven flow predominates in liquid films greater than 4 mm.

Cratering is similar to Bernard cell formation. Circular depressions on the liquid surface are known as craters. They can be caused by the presence of a low surface tension component at the film surface. The spreading of this low surface tension component causes the bulk transfer of film materials, resulting

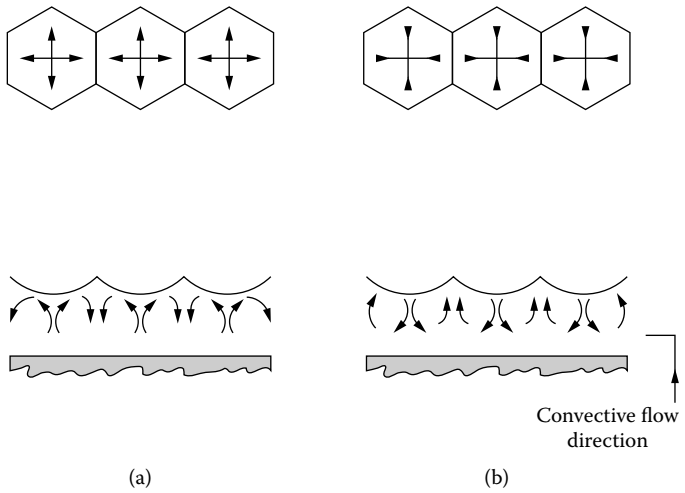


FIGURE 2.8 Schematic illustration of the formation of Bernard cells due to (a) the surface tension gradient and (b) the density gradient.

in the formation of a crater. The flow q of material during crater formation is given by[10]:

$$q = \frac{h^2 \Delta\gamma}{2n} \tag{2.9}$$

where $\Delta\gamma$ = surface tension difference between the regions of high and low surface tension.

The crater depth d_c is given by:

$$d_c = \frac{3\Delta\gamma}{\rho g n} \tag{2.10}$$

The tendency to produce craters is the result of the concentration of surfactant. Craters tend to appear when paints contain silicon oils (a surfactant) in an amount exceeding solubility limits.

From the foregoing it is seen that high surface tension and low viscosity are required for good flow out and leveling. However, high surface tension can cause cratering while excessively low viscosity results in sagging and poor edge coverage. The balance between viscosity and surface tension is essential in obtaining an optimal coating. Coating performance as a function of surface tension and melt viscosity are illustrated in Figure 2.9. Coating is a relatively complex process and requires the consideration of many factors if an optimum result is to be achieved.

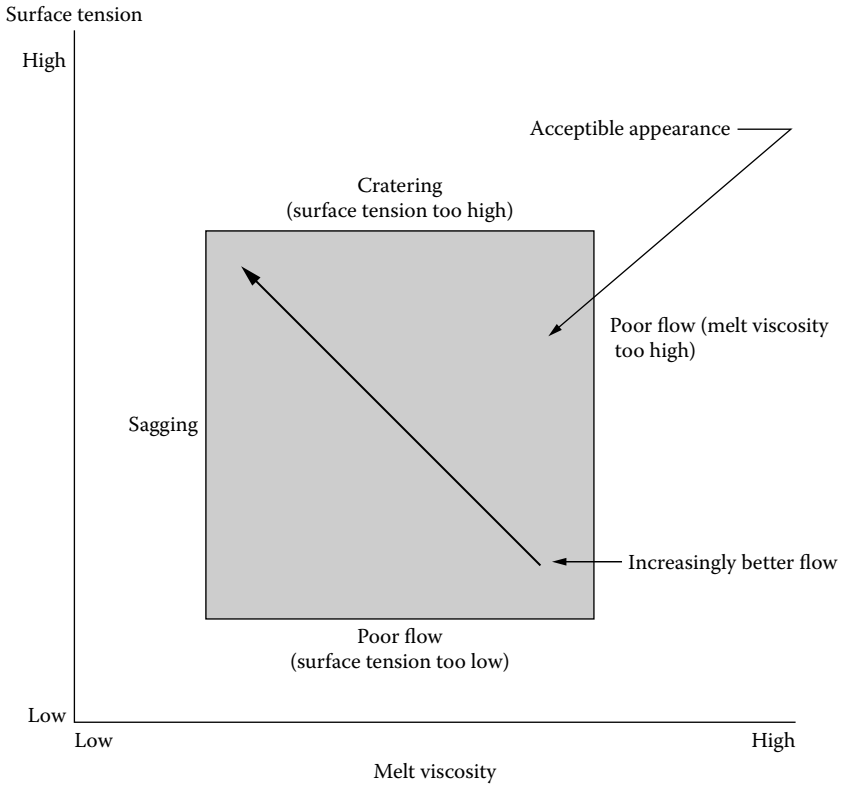


FIGURE 2.9 The effects of surface tension and melt viscosity on coating appearance.

REFERENCES

1. Patton, Temple C., *Paint Flow and Pigment Dispersion,* 2nd ed., John Wiley & Sons, New York, 1979.
2. Martens, Charles R., *Technology of Paint, Varnish, and Lacquers,* Krieger Publishing Co., New York, 1974.
3. Smith, N.D.P., Orchard, S.E., and Rhind-Tutt, A.J., The Physics of Brush Marks, *JOCCA,* 44, 618–633, Sept. 1961.
4. Weh, L., *Plastic Kautsck,* 20, 138, 1973.
5. Marangoni, C.G.M., *Nuovo Comento,* 2, 239, 1971.
6. Hansen, C.M. and Pierce, P.E., *Ind. Eng. Chem. Prod. Res. Dev.,* 12, 67, 1973.
7. Hansen C.M. and Pierce, P.E., *Ind. Eng. Chem. Prod. Res. Dev.,* 13, 218, 1974.
8. Anand, J.N. and Karma, H.J., *J Colloid Interface Sci.,* 31, 208, 1969.
9. Pearsen, J.R.A., *J Fluid Mech.,* 4, 489, 1958.
10. Fink-Jensen, P., *Farbe Lack,* 68, 155, 1962.

3 Theory of Adhesion

INTRODUCTION

Regardless of what excellent properties a coating might possess, it is useless unless it also has good adhesion. The coating's resistance to weather, chemicals, scratches, impact, or stress is only of value while the coating remains on the substrate. Consequently, the knowledge of adhesion of polymeric coatings is of importance. Except for temporary and strippable protective coatings, all other types of coatings must adhere to the substrate to provide the desired protection or decoration.

When pressure-sensitive tape is applied to a smooth surface, it sticks immediately. The application pressure can be very light. The adhesive is said to "wet" the surface. If the tape is applied to clear glass and the attached area viewed through the glass, it will be noted that in certain areas the adhesive/glass interface appears like a liquid/glass interface. This would indicate that although the pressure-sensitive adhesive is a soft, highly compliant solid, it also has liquid-like characteristics. Based on this, it is understandable why some knowledge of the interaction between liquids and solids is beneficial to the understanding of adhesion.

Adhesion is a complex phenomenon related to the physical effects and chemical reactions at the "interface." The actual mechanism by which adhesion occurs is not fully understood. Several theories have been proposed to explain the phenomenon of adhesion, including mechanical attachment, electrostatic attraction, true chemical bonding, and true paint diffusion. Based on the coating used and the chemistry and physics of the substrate surface, one or a combination of these mechanisms may be involved.

Mechanical Bonding

When a substrate surface contains pores, holes, crevices, and voids into which the coating spreads and solidifies, a mechanical bond is formed. In so doing, the coating acts as a mechanical anchor. The removal of the coating is made more difficult if the substrate has undercut areas that are filled with cured coating. Instrumental analyses have indicated that a coating can penetrate to complex tunnel-shaped undercuts and cracks where, upon curing to a hard mass, a mechanical attachment results. Figure 3.1 illustrates this mechanical bonding.

The adhesion of a coating is improved by surface roughness. By sanding, the increase in the bonding area can be increased five times. Because of other factors, the adhesion may not increase in the same proportion. The advantage of surface roughness is realized only if the coating penetrates completely into all surface irregularities. If complete penetration is not achieved, then there is less

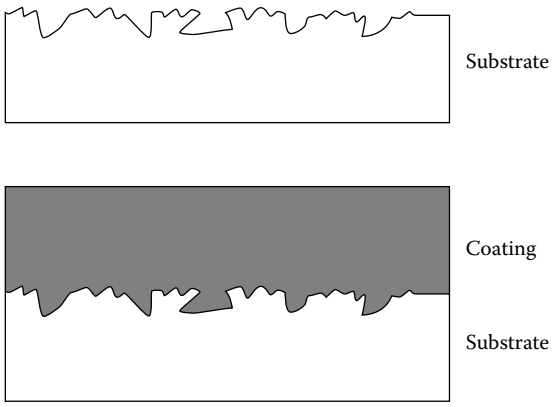


FIGURE 3.1 Schematic illustration of mechanical bonding.

coating-to-interface contact than the corresponding geometric area. This will leave voids between the coating and the substrate, resulting in trapped air bubbles. These trapped air bubbles in the voids will allow accumulation of moisture, resulting in the eventual loss of adhesion (Figure 3.2).

To adhere metal plating to ABC (Acrylonitrile-Butacliene-Styrene) and polypropylene plastics, it is necessary to pretreat the plastics to produce interlocking cavities. The plastic is sensitized with stannous chloride solution, activated by depositing Pd^{o} and Pt^{2+} solution, depositing electroless nickel, and then electroplating the desired

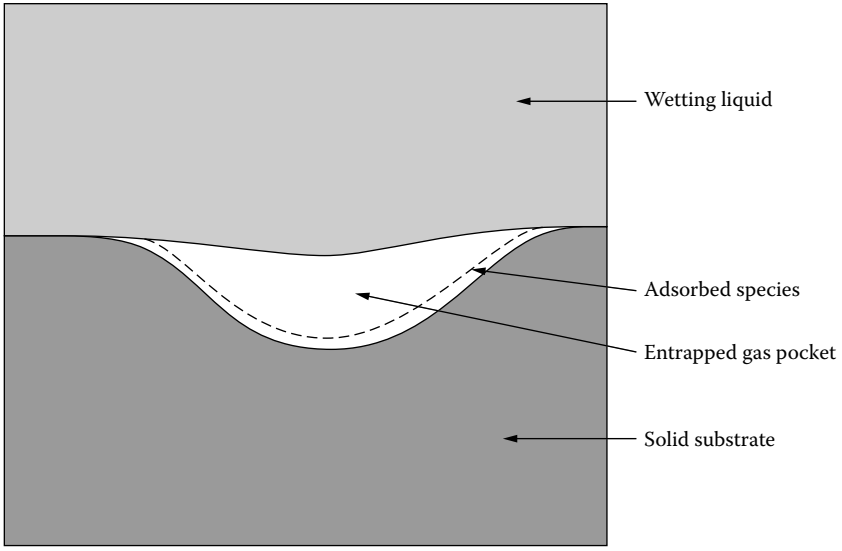


FIGURE 3.2 Marginal wetting and trapped air in a depression.

metal, such as chromium. Strong adhesion of the metal plating to the plastic is obtained only when the plastic has been pretreated to produce interlocking cavities.

Metal substrates are also subject to various pretreatments that may not only change the surface chemical composition, but also produce interlocking surface sites. One such pretreatment is the phosphating of cold-rolled steel, which produces numerous intermeshing platelets of iron phosphate crystals on the surface. The interplatelet spaces provide numerous interlocking sites.

Electrostatic Attraction

Electrostatic forces in the form of an electrical double layer can conceivably be formed at the coating/surface interface. Both coatings and surfaces contain electrical charges spread throughout the system. Interaction between these charges could be responsible for some adhesion. Much of the attraction between coating and surface is provided by these charges. Such interactions are only effective over a very short range. Because these forces are not significant beyond about 0.5 mm, the need for intimate contact between coating and surface becomes obvious.

Chemical Bonding

The formation of chemical bonds across the interface very likely takes place in thermoset coatings. Such bonding is expected to be the strongest and the most durable. For this to occur, it is necessary for mutually reactive chemical groups to be tightly bound on the substrate surface and in the coating. Figure 3.3 illustrates

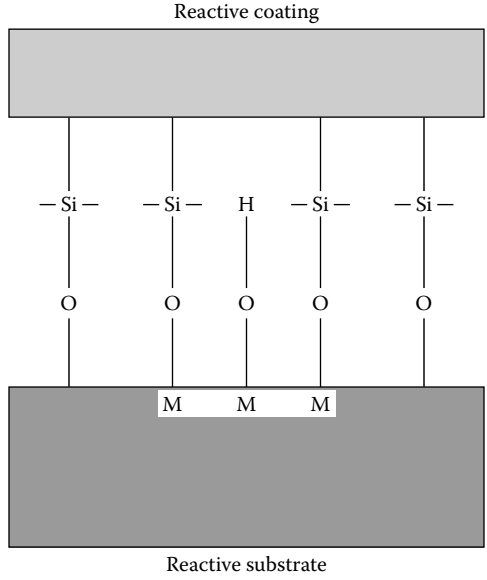


FIGURE 3.3 Structure of a silane reaction with a reactive substrate.

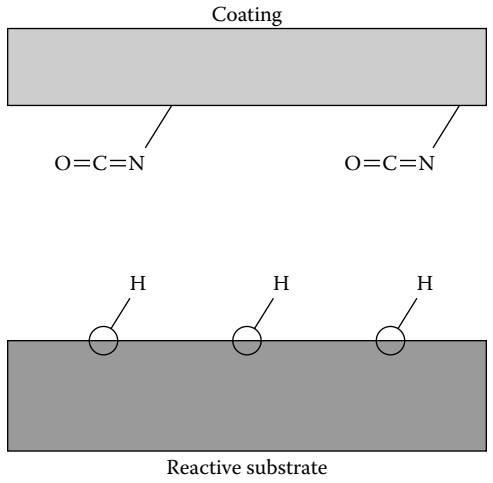


FIGURE 3.4 Reaction to two-component polyurethane with a reactive surface.

several types of chemical bonding that may take place between a coating and a particular substrate. Organo-silanes are widely used as primers on glass fibers to promote adhesion between the resin and the glass in fiberglass-reinforced plastics. They are also used as primers to promote the adhesion of resins to minerals, metals, and plastics. During application, silanol groups are produced that react with the silanol groups on the glass surface or possibly with other metal oxide groups to form strong ether linkages.

The super adhesion of melamine-cured acrylic topcoats over polyester/melamine-cured primers (surfaces) is the result of coatings containing reactive functional groups such as hydroxyl or carboxyl moieties over substrates containing similar groups.

When a substrate contains reactive hydroxyl groups that can react with diisocyanate groups contained in thermoset polyurethane coatings, chemical bonding also takes place (see Figure 3.4). Other chemical bonding combinations are also known to take place.

Paint Diffusion

When two phases of coating and polymeric substrate attain molecular contact by wetting, segments of the macromolecules will diffuse across the interface. The extent of the migration will depend on the material properties and curing conditions. Auto adhesion is a two stage process: wetting followed by diffusion of chain segments across the interface to reestablish the entangled network. Dissimilar polymers are usually incompatible because of their long-chain nature and low diffusion coefficients.

ADHESION TESTING

Because a specification for the degree of adhesion must be provided in almost every paint formulation, methods for routine measurement of that key quantity have been established. The two primary test procedures are the cross-cut test and pull-off methods. Both methods have been standardized nationally and internationally.

Cross-Cut Test

The ASTM D-3359 Tape Test is the most commonly used qualitative adhesion test method. There are two versions of the test. In version A, an X cut is made in the film to the substrate, and pressure-sensitive tape is applied over the cut and then removed at an angle close to 180°. The adhesion is assessed qualitatively on a 0 to 5 scale. In version B, a lattice pattern is cut to the substrate using a multiple cutting tool consisting of a set of six or eleven "knives" 1 or 2 mm apart in each direction (Figure 3.5). Pressure-sensitive tape is applied over the lattice and then removed. Adhesion is evaluated by comparison with description and illustrations.

The classification is based on estimating the amount of paint flakes separated from the substrate. The ISO recommends standard considering the test for "go/no-go" statements. In such a case, class 0 would indicate perfect adhesion whereas class 2 or even class 1 should be interpreted as an objectionable result.

The tape test has the advantages of being simple and economical to perform and lends itself to job site application. However, there are several drawbacks, including poor reproducibility and high subjectivity. Although the ASTM specifies the type of tape to use, tapes, like most products, can vary in properties between lots. The test actually measures the quality of adhesion between the coating and the tacky adhesive on the tape. A less tacky tape can produce erroneous results.

Because the tape test is operator sensitive, the burden of accuracy and reproducibility depends on the skill of the operator. Key steps that directly reflect the importance of operator skill include the visual assessment of the tested sample and the angle and rate of tape removal.

Tensile Methods

The pull-off method has been standardized internationally. This test utilizes stress patterns caused by loads acting either normal or parallel to the plane of contact. ASTM Test Method D-5179 is for measuring adhesion of organic coatings to substrates. ISO 4624 is a similar pull-off test. In either case, a metallic stud (either aluminum or steel) is glued with the coating to the substrate and is subjected to axial tension until detachment of the paint film occurs. The adhesion strength is the maximum tensile stress possible at the interface. Adhesive strength is affected by the coating thickness and the solvent retention when solvents containing coatings are used. Figure 3.6 illustrates the effect of coating thickness. It is noted that the breaking strength is reduced as the coating film thickness increases.

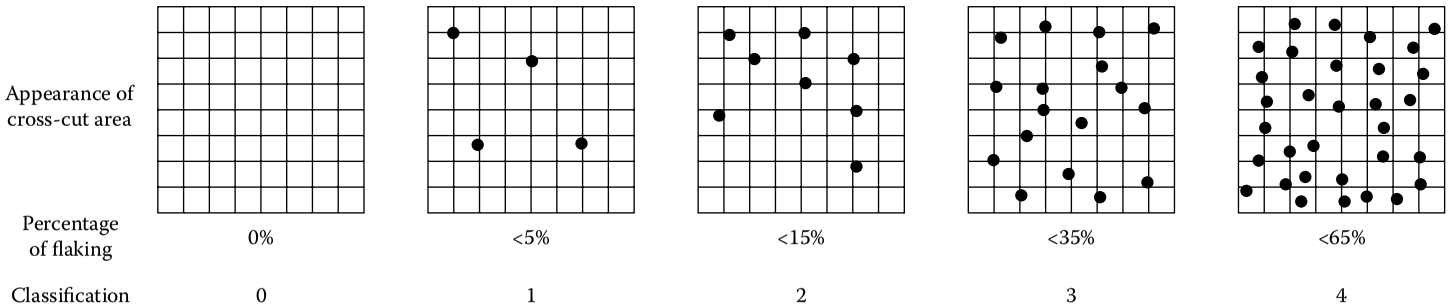


FIGURE 3.5 Cross-cut test paint film classification.

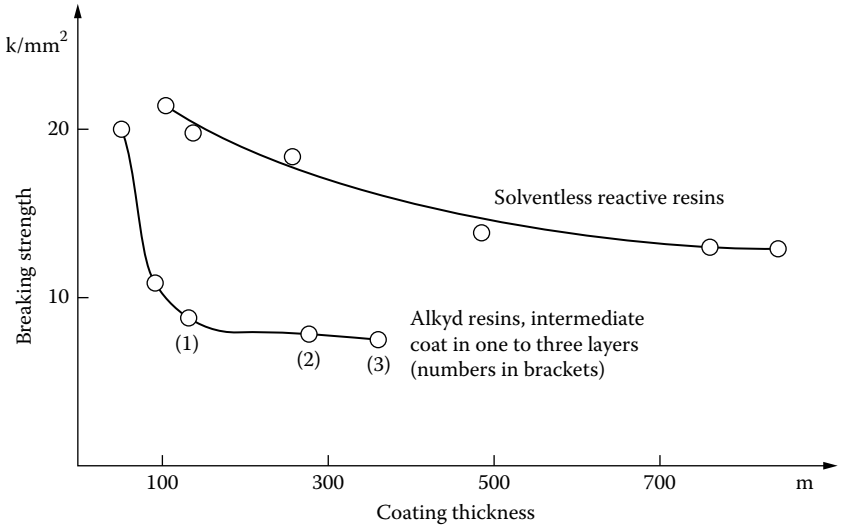


FIGURE 3.6 Effect of coating thickness on bonding strength.

When a torque is applied about the axis or the stud, the process of detachment indicates the maximum shear stress that can be attained at the interface. This is also a measure of adhesion.

The values of adhesion strength obtained from both methods are of the same order of magnitude. However, there is a tendency to obtain results with the torque principle in the case of cohesive failure, but lower results for adhesive failure (Figure 3.7).

It is important that an appropriate adhesive be used to firmly attach the stud to the test area. In general, the fast-hardening cyanoacrylates or the solventless epoxy resin adhesives cured with polyamines can be used for this purpose. The constituents of the adhesive must not interact with the coating in a manner that causes complete swelling.

Indentation Debonding

When a needle-like indenter is pressed perpendicularly into the surface of a coating that is bonded to a virtually undeformable substrate, most of the deformation will take place within the film, but there will also be some debonding at the interface.

Referring to Figure 3.8, it is noted that a peeling moment can be calculated that will serve as a measure of the film's ability to withstand delamination in the area of the indentation site.

Optical devices can be used to monitor the gradually increasing area of debonding, especially on thin coatings, on the basis of Newton's rings. Indenters of other typical shapes, in addition to needle-like indenters, have been used successfully.

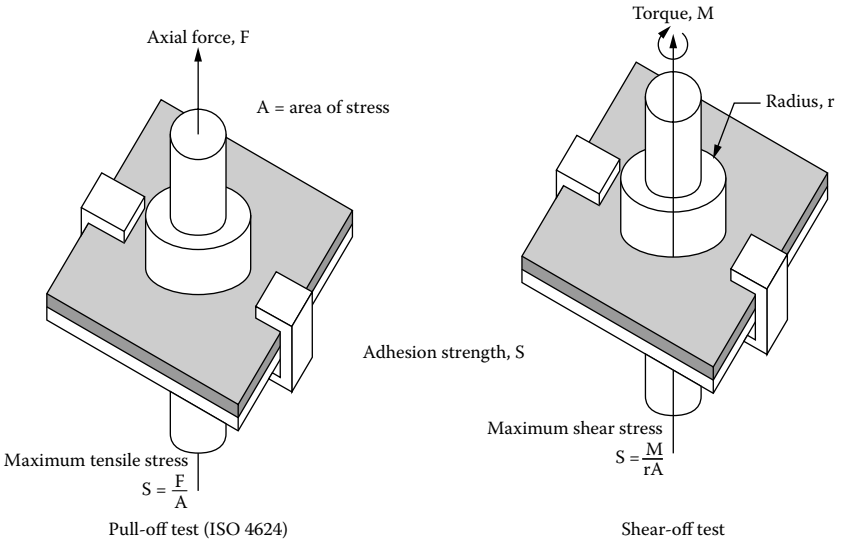


FIGURE 3.7 Determination of adhesive strength.

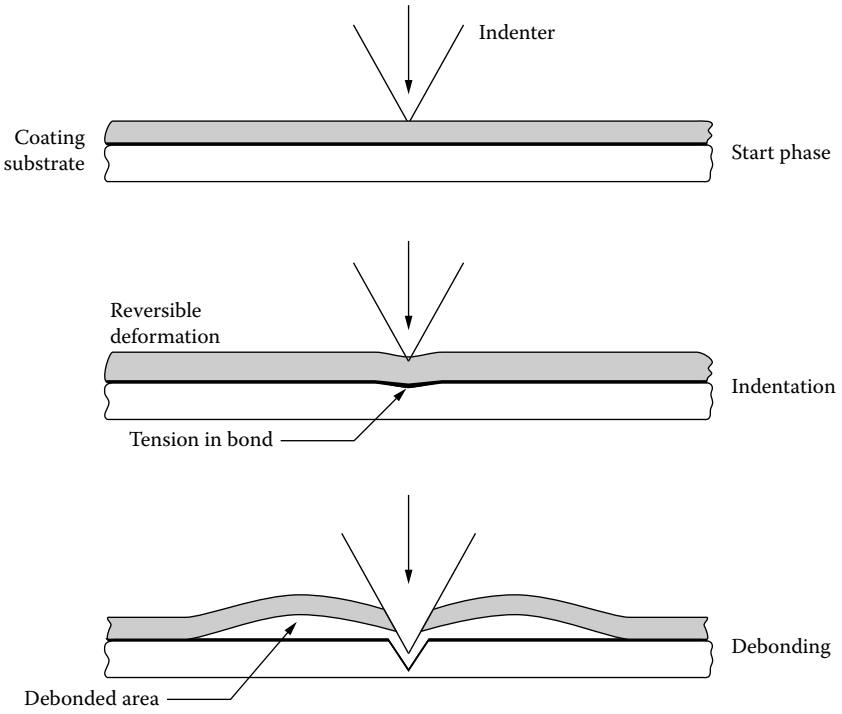


FIGURE 3.8 Principle of the indentation process.

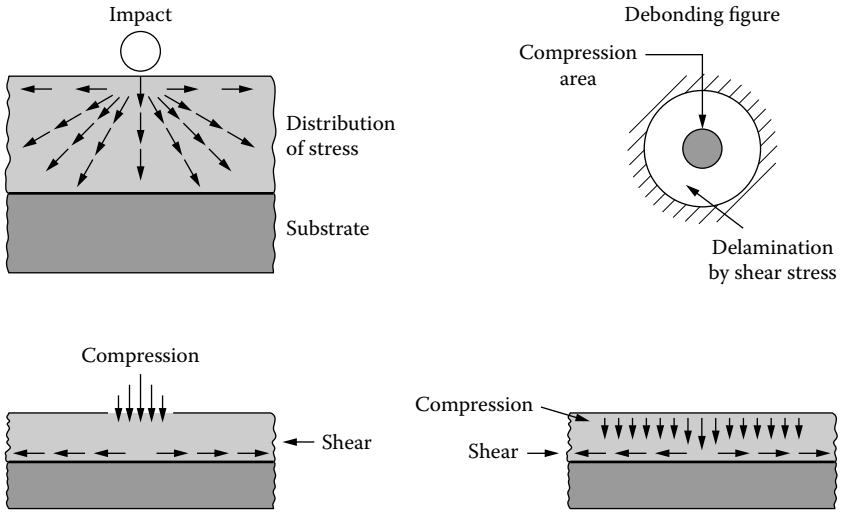


FIGURE 3.9 Impact effect on interface adhesion.

A 60° angle cone has proven optimal for taking into account boundary conditions at the interface. A particular advantage of the indentation test is that it yields values for bond strength in absolute terms, as well as information about the durability of the bond between the coating and substrate.

Impact Tests

An impact test is used to determine the stone-chip resistance of a coating. The value of adhesion at the interface is of primary concern. A steel ball impinging on the test piece can duplicate the situation encountered in actual practice (Figure 3.9).

As a first approximation, the transfer of forces through the film is equal to the case of static loading, and can be calculated in essentially the same way as for an indentation test.

In the debonding area, negative tensile (compressive) stress is present in the center of the detachment site and sheer stress is present in the annular region. The maximum diameter of the bonding area can serve as a measure of adhesion at the interface. The diameter, and better yet the area of the debonding zone, both serve as (reciprocal) measures of adhesion. An extended debonded site is an indication of a low adhesion level.

Delamination Tests

In the previous tests, the primary concern was stress conditions at the interface. Delamination is the result of peeling forces that attack the bond between the paint

film and substrate. The attack occurs either at well-defined lines, so that the coating is detached in strips, or at one point only, causing delamination to progress rapidly in the form of a blister. Both conditions occur in practice.

Three types of tests have been developed to test for delamination.

Knife Cutting Method

In this method, film separation is obtained by means of a sharp knife pushed along the interface with a measured force.[1] The process of detachment comprises both tensile and shear stresses, which eventually cause detachment of the film. In this method, a particular system of forces becomes effective. It is determined by the rake angle of the knife, coating thickness, friction between the cutting tool and coating as well as substrate, amount of energy elastically in the film and energy losses caused by plastic deformation, fracture energy occurring during decomposition within the film, and other effects of lesser importance.

All these factors must be either strictly controlled or their influence estimated as accurately as possible. As shown in Figure 3.10, the details of the separation process indicate how much importance can be attributed to the various factors.

Peel Test

Quite often, a coating fails due gradual peeling either from a sparsely covered edge or from a line-shaped damaged area. Because of this, it is appropriate that a suitable test procedure be utilized to investigate this condition.

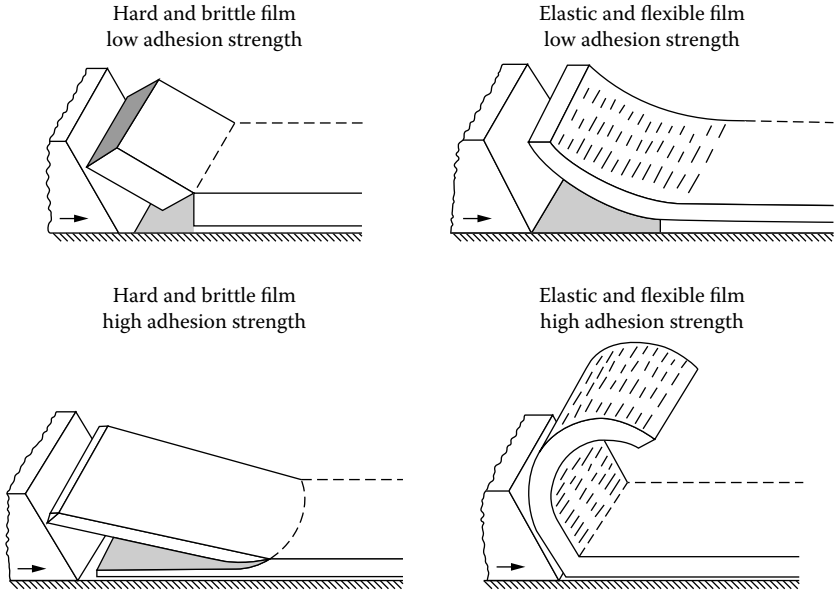


FIGURE 3.10 Influence of mechanical paint film properties on the results of knife cutting test.

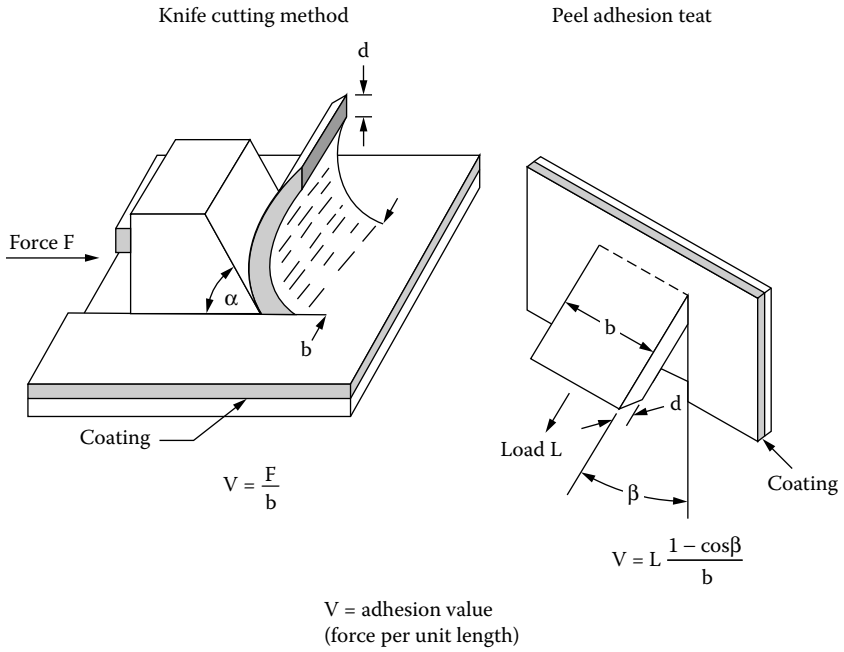


FIGURE 3.11 Devices for measuring adhesion on the basis of delamination.

Detachment of the film is the result of the combined effects of both positive and negative tensile stresses and shear stress. To conduct the test, a strip of sufficient width is marked on the sample by two parallel cuts of adequate length. As shown in Figure 3.11, the angle under which the load is applied has a bearing on the results.[2] The details of the separation process are quite complicated, although at first glance the process might appear relatively simple.[3]

The viscoelastic nature of the film is a contributing factor and this property is also affected by the amount of pigmentation in the film.[4] Because of the viscoelasticity of the film, the test results also depend on the velocity of the detachment process.

Although the peel test is a practical method, the results cannot be interpreted in terms of the bonding mechanism.

Blister Method

Usually, the first indication that a coating designed for protection against corrosion is deteriorating occurs when a blister forms. The following test has been developed to investigate this type of failure.

A hole is bored into the substrate prior to applying the paint coating. The hole is plugged with a nonwetting material such as Teflon. This will permit easy removal of the plug after the substrate has been painted (Figure 3.12).

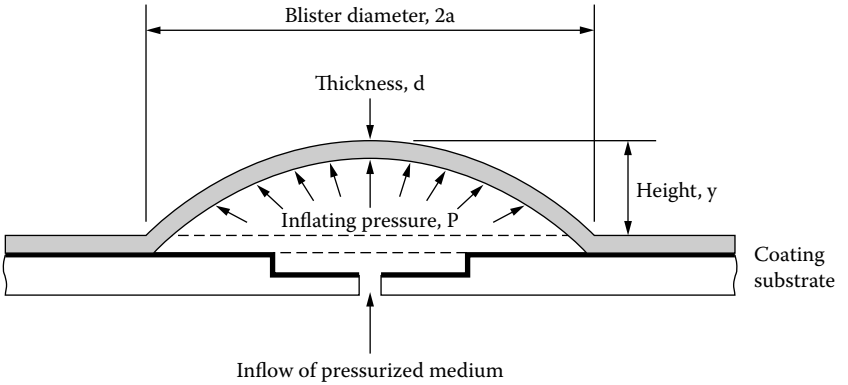


FIGURE 3.12 Test for measuring adhesion based on blister dimensions.

Hydrostatic pressure is applied in the hole, either with a fluid (oil, mercury, etc.) or with pressurized air. The pressure is the primary measure of the debonding process. The height and diameter of the blister are measured to obtain the maximum stress or bonding energy (work of adhesion). From this geometrical data, together with the tensile modulus of the film and its thickness, a critical pressure value can be calculated:

$$P = 4.75E\frac{dy^3}{d^4} \tag{3.1}$$

It is this process that causes the blister to grow; therefore, this pressure serves as the basis for determining the adhesive strength W:

$$W = 0.65Pd \tag{3.2}$$

FLAW DETECTION METHODS

Once a coating has been applied, and throughout its lifetime, it is necessary to determine any deterioration of the bonding strength between the film and the substrate. However, quantitative details of the bonding strength are not required. These tests provide a means of detecting the first signs of adhesion failure.

The nondestructive measurement of adhesion quality has gained popularity in recent years. Extensive work has been successfully applied to the general rise in nondestructive methods to predict adhesive bond quality.

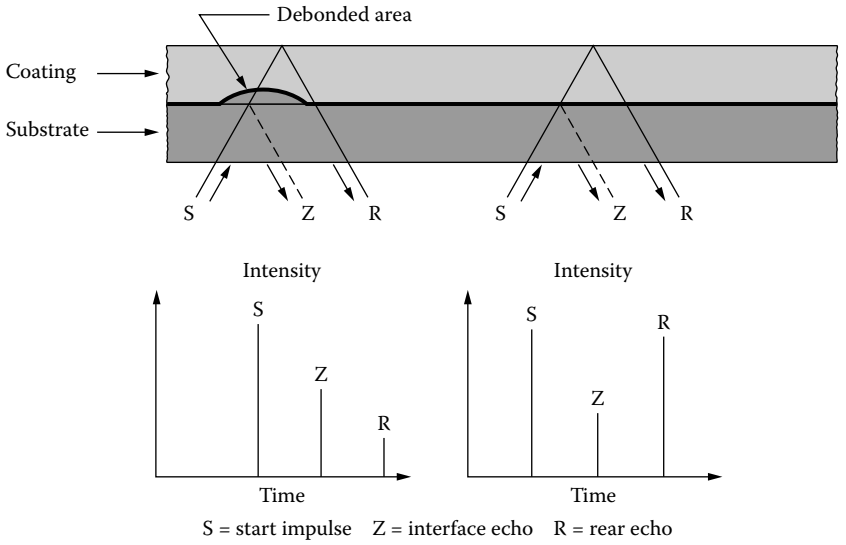


FIGURE 3.13 Ultrasonic pulse-echo technique.

Ultrasonic Pulse-Echo System

Referring to Figure 3.13, it is seen that an incident of ultrasound will be partially reflected and transmitted at each interface of the test piece, including the backing. It is the pulse partially transmitted at each interface of the test piece, including the backing. It is the pulse partially transmitted at the interface that undergoes more or less total reflection at this free surface.

When the bonding at the interface is intact, the amplitude of the reflected pulse will be fairly low, in contrast to the amplitude of the transmitted pulse that travels through the substrate and is reflected at its free boundary. If a defect is present at the interface containing air, or indicating another way that the joint has been disbanded, the amplitude of the related ultrasonic pulse will show an increase. This increase is due to the very low acoustic impedance at the site.

Thermographic Detection

Heat flux passing through a coated substrate will provide a uniform temperature on the surface, providing there is no flaw or debonded area of the coating. When a flaw or debonded site is present, the flow of heat flux is interrupted and a decrease in temperature is detected on the surface. The actual shape of the area where the temperature decreases is made visible at the surface by in infrared sensor. This can be seen in Figure 3.14.

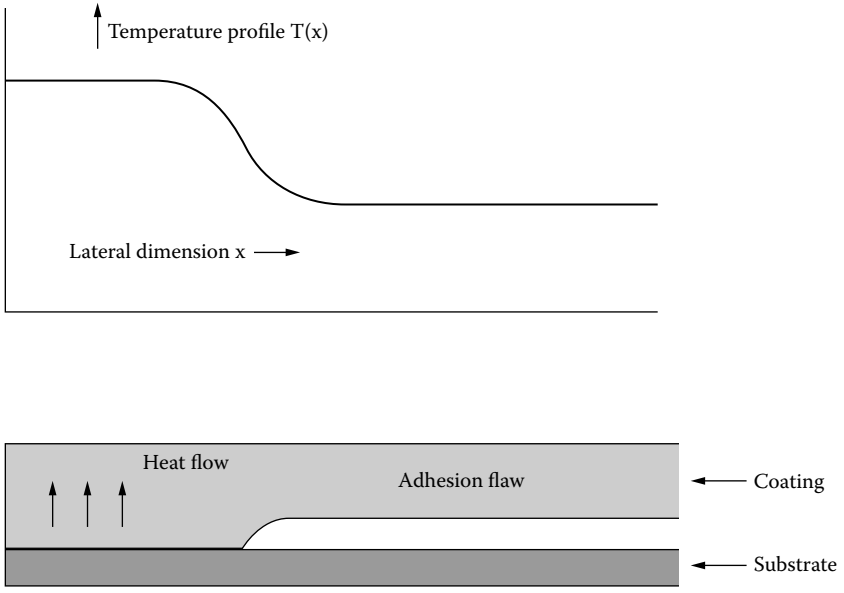


FIGURE 3.14 Thermographic detection of debonding areas.

The primary advantage of thermographic detection methods is the fact that they yield remote mapping of the distribution of temperature on a surface, whatever the cause may have been. This principle has been applied successfully to the detection of subsurface flaws, which may occur as a consequence of any deterioration in the bonding quality of coating and substrate.

Acoustic Emission Analysis

Because it has been observed that by means of very sensitive acoustical sensors, that any debonding effects within an originally uniform and coherent material are accompanied by a specific burst of (misty ultrasonic) pulses, this principle has also been proposed for monitoring the behavior of adhesive joints under load.

With slight modifications, this method can be applied to examine the extent of debonding phenomena taking place in a coating system on a given substrate, if the entire test piece is subjected to gradual stretching, normally in one dimension. The acoustic signals obtained are related to individual fracture events in the test system. Refer to Figure 3.15. Normally, it will be the detachment of the film that is indicated in this way. It is also possible that any separation within the film (e.g., between binder matrix and pigment) could also cause acoustic signals, but in all probability on a lower level of intensity.

This procedure appears to provide a potentially promising method of detecting flaws in a coating system. However, a great deal of information is required if the preliminary results are to be interpreted correctly.

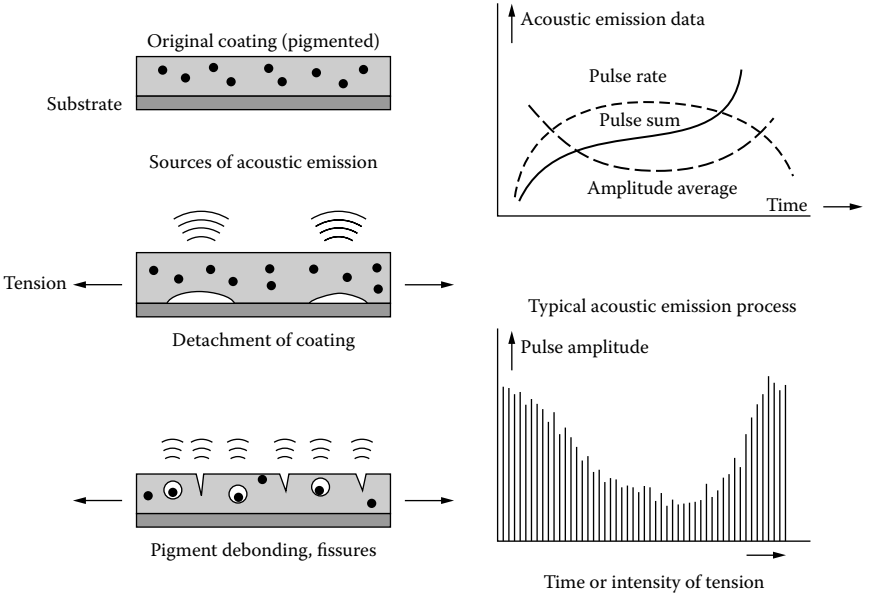


FIGURE 3.15 Application of acoustic emission analysis for monitoring the outset of coating detachment.

CAUSES OF BOND AND COATING FAILURES

Bond and coating failures can result from any one or a combination of the following causes:

1. Poor or inadequate surface preparation and/or application of the paint to the substrate
2. Atmospheric effects
3. Structural defects in a paint film
4. Stresses between the bond and the substrate
5. Corrosion

Surface Preparation and Application

Coating failures typical of surface preparation and application problems include:

1. *Cracking, checking, alligatoring.* These types of failures develop with the aging of the paint film. Shrinkage within the film during aging causes cracking and checking. Alligatoring is a film rupture, usually caused by application of a hard, brittle film over a more flexible film.

2. *Peeling, flaking, delamination.* These failures are caused by poor adhesion. When peeling or flaking occurs between coats, it is called delamination.
3. *Rusting.* Failure of a coated surface may appear as (a) spot rusting in minute areas, (b) pinhole rusting in minute areas, (c) rust nodules breaking through the coating, or (d) underfilm rusting, which eventually causes peeling and flaking of the coating.
4. *Lifting and wrinkling.* When the solvent of a succeeding coat of paint too rapidly softens the previous coat, lifting results. Rapid surface drying of a coating without uniform drying throughout the rest of the film results in a phenomenon known as wrinkling.
5. *Failures around weld areas.* Coating adhesion can be hampered by weld flux, which can also accelerate corrosion under the film. Relatively large projections of weld spatter cause possible gaps and cavities that may not be coated sufficiently to provide protection.
6. *Edge failures.* Edge failures usually take the form of rusting through the film at the edge where the coating is normally the thinnest. This is usually followed by eventual rust creepage under the film.
7. *Pinholing.* These are tiny holes that expose the substrate, and are caused by improper paint spray atomization or segregation of resin in the coating. If practical during application, brush out the coating. After application and proper care, apply additional coating.

Atmospheric Effects

Polymeric coatings are exposed to environmental constituents. The primary factors promoting degradation are thermal, mechanical, radiant, and chemical in nature. Polymers can also be degraded by living organisms such as mildew. Any atmospheric environment is subject to dry and wet cycles. Because water and moisture have a decided effect on the degradation of a coating, the duration of wetness of a coating is important. Moisture and water that attack organic films derive from rain, fog, dew, snow, and water vapors in the atmosphere. Relative humidity is a particularly important factor. As exposure time is increased in 100% relative humidity, the bond strength of the paint coating is reduced. This is shown in Table 3.1.

Temperature fluctuations and longer durations of wetness tend to produce clustered water, which increases the acceleration of degradation of the organic film, particularly in a marine atmosphere. The most severe natural atmosphere for a paint film is that of a seashore environment.

The mode of degradation may involve depolymerization, generally caused by heating, splitting out of constituents in the polymer, chain scission, cross-linking, oxidation, and hydrolysis. Polymers are subject to cracking upon application of a tensile force, particularly when exposed to certain liquid environments. This phenomenon is known as environmental stress cracking or corrosion cracking.

TABLE 3.1
Relationship of Bond Strength to Exposure Time in 100% Relative Humidity

Exposure Time (hr)	Bond Strength (psi)		
	Epoxy Ester	Polyurethane	Thermosetting Acrylic
Initial	4790	3410	5700
24	1640	1500	3650
48	1500	1430	3420
120	—	1390	2400
195	1400	1130	1850
500	1390	670	480

Polymeric materials in outdoor applications are exposed to weather extremes that can be extremely deleterious to such materials. The most harmful weather component, exposure to ultraviolet (UV) radiation, can cause embrittlement, fading, surface cracking, and chalking. After exposure to direct sunlight for a period of years, most polymers exhibit reduced impact resistance, lower overall mechanical performance, and a change in appearance.

The electromagnetic energy of sunlight is normally divided into ultraviolet (UV) light, visible light, and infrared energy. Infrared energy consists of wavelengths longer than visible red wavelengths and starts above 760 nanometers (nm). Visible light is defined as radiation between 400 and 760 nm. Ultraviolet light consists of radiation below 400 nm. The UV portion of the spectrum is further subdivided into UV-A, UV-B, and UV-C. The effects of the various wavelengths are shown in Table 3.2.

Because UV light is easily filtered by air masses, cloud cover, pollution, and other factors, the amount and spectrum of natural UV exposure is extremely variable. Because the sun is lower in the sky during the winter months, it is filtered through a greater air mass. This creates two important differences between

TABLE 3.2
Wavelength Region of the UV

Region	Wavelength (nm)	Characteristics
UV-A	400–315	Causes polymer damage
UV-B	315–200	Includes the shortest wavelengths found at the earth's surface Causes severe polymer damage Absorbed by window glass
UV-C	280–100	Filtered out by the earth's atmosphere Found only in outer space

summer and winter sunlight hours. During the winter months, much of the damaging short-wavelength UV light is filtered out. For example, the intensity of UV light at 320 nm changes about 8 to 1 from summer to winter. In addition, that short-wavelength solar cutoff shifts from approximately 295 nm in summer to approximately 310 nm in winter. As a result, materials sensitive to UV below 320 nm would degrade only slightly, if at all, during the winter months.

Photochemical degradation is caused by photons or light breaking chemical bonds. For each type of chemical bond, there is a critical threshold wavelength of light with enough energy to cause a reaction. Light of any wavelength shorter than the threshold can break a bond, but longer wavelengths of light cannot break it. Therefore, the short wavelength cutoff of a light source is of critical importance. If a particular polymer is sensitive only to UV light below 295 nm (the solar cutoff point), it will never experience photochemical deterioration outdoors.

The ability to withstand weathering varies with the polymer type and within grades of a particular resin. Many resin grades are available with UV-absorbing additives to improve weatherability. However, the higher molecular weight grades of a resin generally exhibit better weatherability than the lower molecular weight grades with comparable additives. In addition, some colors tend to weather better than others.

Several artificial light sources have been developed to simulate direct sunlight. In the discussion of accelerated weathering light sources, the problems of light stability, the effects of moisture and humidity, the effects of cycles, or the reproducibility of results are not taken into account. Simulations of direct sunlight should be compared to what is known as the solar maximum condition — global moon sunlight on the summer solstice at normal incidence. The most severe condition that can be encountered in outdoor service is the solar maximum, which controls the failure of materials. It is misleading to compare light sources against "average optimum sunlight," which is an average of the much less damaging March 21st and September 21st equinox readings.

Arc-Type Sources

Enclosed Carbon Arc (ASTM G-23)

Since 1918 the enclosed carbon arc has been used as a solar simulator in accelerated weathering and lightfastness tests, and is still specified in many test methods. The UV output of the enclosed carbon arc consists primarily of two large spikes of energy, with very little output below 350 nm. As pointed out previously, the shortest UV wavelengths are the most damaging; consequently, the enclosed carbon arc gives very slow tests on most materials and poor correlation on materials sensitive to short-wavelength UV light.

Sunshine Carbon Arc (open flame carbon arc: ASTM G-23)

In 1933, the sunshine carbon arc was introduced. Although it presented an advantage over the enclosed carbon arc, there were still some problems. While the

match of sunlight is superior to that of the enclosed carbon arc, there is still a large spike of energy much greater than sunlight at about 390 nm.

A more serious problem exists in the shorter wavelengths. The sunshine carbon arc emits a great deal of energy in the UV-C portion of the spectrum, well below the normal solar cutoff point of 295 nm. These short wavelengths can cause unrealistic degradation when compared to natural sources because radiation of this type is found in outer space, not on the earth's surface.

Xenon Arc (ASTM G–26)

In 1954, Germany adapted the xenon arc for accelerated weather testing. To reduce unwanted radiation, xenon arcs require a combination of filters. Borosilicate inner and outer filters are the most widely used due to borosilicate's giving a close approximation to sunlight by providing a cutoff wavelength of approximately 280 nm, which is relatively close to sunlight cutoff of 295 nm.

Irradiance settings of 0.35 or 0.55 W/m^2 at 340 nm are the most common. The 0.35 setting compares to winter sunlight, whereas the 0.55 setting compares to summer sunlight. However, for practical reasons, the 0.35 setting is more commonly used.

Fluorescent UV Lamps

The fluorescent UV testers make use of different lamps with different spectra for different exposure applications. Developed in the 1970s, they use an approach different from that of the arc testers. The fluorescent UV testers do not attempt to reproduce sunlight itself, but rather only the damaging effects of sunlight. Because short-wavelength UV causes all of the damage to durable materials exposed outdoors, this approach is effective. Consequently, fluorescent testers confine their primary light emission to the UV portion of the spectrum.

FS-40 Lamp (F40–UVB) (ASTM G-53)

The FS-40 became the first fluorescent UV lamp to be widely used during the early 1970s. The majority of the output of the FS-40 is in the UV-B portion of the UV spectrum, with some output in the UV-A spectrum. Good correlation to outdoor exposures has been achieved with this lamp for the material integrity of plastics. However, the short-wavelength output below the solar cutoff can occasionally cause abnormal results, especially for color retention.

UVB-313 Lamp (ASTM G-53)

The UVB-313 lamp was introduced in 1984. It is essentially a second-generation FS-40 having the same SED (Spectral Energy Distribution), but its output is higher and more stable. As a result of its higher output, the UVB-313 lamp provides greater acceleration over the FS-40 for most materials.

UVA-340 Lamp (ASTM G-53)

Introduced in 1987, the UVA-340 lamp enhances the correlation of G-53 devices. This lamp provides excellent simulation of sunlight in the critical short-wavelength UV region, from approximately 365 nm down to the solar cutoff of 295 nm. This lamp shows more realistic testing than the other lamps because the UVA-340 lamp eliminates the short-wavelength output that can cause unnatural results, thereby allowing more realistic testing than many other commonly used light sources. The UVA-340 lamp has been tested on plastics and greatly improves the correlation possible with the fluorescent UV and condensation devices.

TYPES OF FAILURES

Factors in the atmosphere that cause corrosion or degradation of the coating include UV light, temperature, oxygen, ozone, pollutants, and wind. The types of failures resulting from these causes include:

1. *Chalking.* UV light, oxygen, and chemicals degrade the coating, resulting in chalk. This can be corrected by providing an additional topcoat with the proper UV inhibitor.
2. *Color fading or color change.* This may be caused by chalk on the surface or by breakdown of the colored pigments. Pigments can be decomposed or degraded by UV light or reaction with chemicals.
3. *Blistering.* Blistering may be caused by:
   a. Inadequate release of solvent during both applications and drying of the coating system
   b. Moisture vapor that passes through the film and condenses at a point of low paint adhesion
   c. Poor surface preparation
   d. Poor adhesion of the coating to the substrate or poor intercoat adhesion
   e. A coat within the paint system that is not resistant to the environment
   f. Application of a relatively fast-drying coating over a relatively porous surface
   g. Failures due to chemical or solvent attack (when a coating is not resistant to its chemical or solvent environment, there is apparent disintegration of the film)
4. *Erosion (coating worn away).* Loss of coating due to inadequate erosion protection. Provide material with greater resistance to erosion.

Strength of Paint Film

Paint films require hardness, flexibility, brittleness resistance, abrasion resistance, mar resistance, and sag resistance. Paint coatings are formulated to provide a balance of these mechanical properties. The mechanical strength of a paint film is described by the words “hardness” and “plasticity,” which correspond to the modulus of

TABLE 3.3
Tensile Properties of Typical Paint Films

Paints	Tensile Strength (g/mm)	Elongation at Break (%)
Linseed oil	14–492	2–40
Alkyd resin varnish (16% PA)	141–1266	30–50
Amino-alkyd resin varnish (A/W = 7/3)	2180–2602	—
NC lacquer	844–2622	2–28
Methyl-*n*-butyl-*meta*-acrylic resin	1758–2532	19–49

elasticity and to the elongation at break obtained from the stress-strain curve of a paint film. Typical paint films have tensile properties as shown in Table 3.3. The mechanical properties of paint coatings vary, depending on the type of pigment, baking temperatures, and aging times. As baking temperatures rise, the curing of paint films is promoted and elongation is reduced. Tensile strength is improved by curing and the elongation at breaks is reduced with increased drying time.

Structural defects in a paint film cause failings that are determined by environmental conditions such as thermal reaction, oxidation, photooxidation, and photothermal reaction. An important factor in controlling the physical properties of a paint film is the glass transition temperature T_g. In the temperature range higher than T_g, the motion of the resin molecules becomes active, such that the hardness, plasticity, and permeability of water and oxygen vary greatly. Table 3.4 lists the glass transition temperatures of organic films.

TABLE 3.4
Glass Transition Temperature of Organic Films

Organic Film	Glass Transition Temperature, T_g (°C)
Phthalic acid resin	50
Acrylic lacquer	80–90
Chlorinated rubber	50
Bake type melamine resin	90–100
Anionic resin	80
Cationic resin	120
Epoxy resin	80
Tar epoxy resin	70
Polyurethane resin	40–60
Unsaturated polyester	80–90
Acrylic powder paint	100

Deterioration of paint films is promoted by photolysis, photooxidation, or photothermal reaction as a result of exposure to natural light. As explained previously, UV light ($\lambda = 40$ to 400 nm) decomposes some polymer structures. Polymer films such as vinyl chloride resins are gradually decomposed by absorbing the energy of UV light. The T_g of a polymer is of critical importance in the photolysis process. Radicals formed by photolysis are trapped in the matrix, but they diffuse and react at temperatures higher than T_g. The principal chains of polymers with ketone groups form radicals:

$$\begin{array}{lll} \text{RCOR}' & \text{R} + \text{COR}' & \text{CO} + \text{R}' \\ \text{ROCOR}' & \text{OCOR}' & \text{CO}_2 + \text{R}' \end{array}$$

The resultant radicals accelerate the degradation of the polymer and, in some cases, HCl (from polyvinyl chloride) or CH_4 is produced.

Cohesive Failure

In chemical terms, there is a similarity between paints on one side and adhesives or glue on the other (see Figure 3.16). Both materials appear in the form of organic coatings. A paint coating is, in essence, a polymer consisting of more or less cross-linked macromolecules, and certain amounts of pigments and fillers. Metals, woods, plastics, paper, leather, concrete, or masonry to name only the most important materials can form the substrate for the coating.

It is important to keep in mind that these substrate materials can inhibit a rigidity higher than that of the coating. Under such conditions, fracture will occur

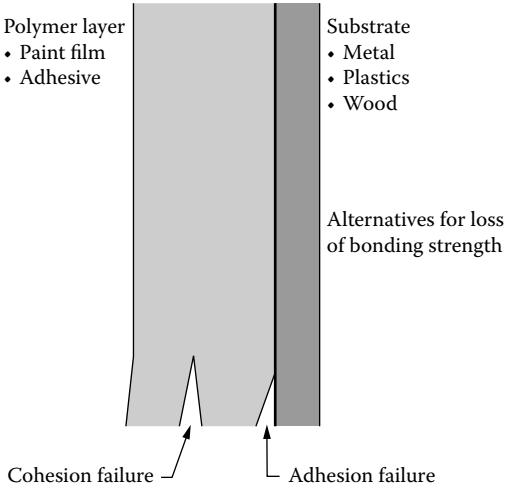


FIGURE 3.16 Bonding situation at the interface of polymer layer and substrate.

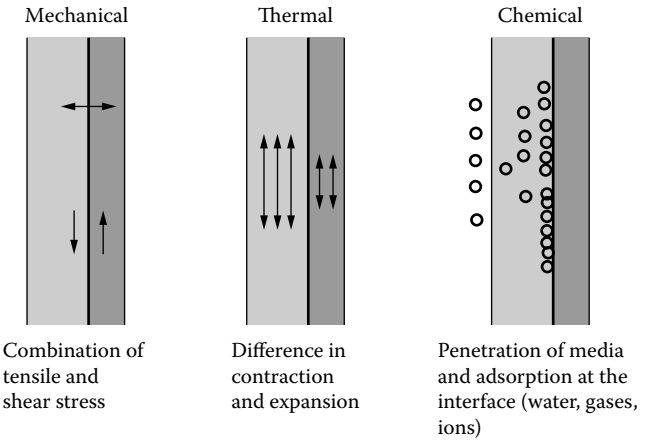


FIGURE 3.17 Mechanical (a), thermal (b), and chemical bond (c) failure.

within the coating if the system experiences an external force of sufficient intensity. Cohesive failure will result if the adhesion at the interface exceeds the cohesion of the paint layer. Otherwise, adhesive failure is the result, indicating a definite separation between the coating and substrate.

Both types of failure are encountered in practice. The existence of cohesive failure indicates the attainment of an optimal adhesion strength.

Stress and Chemical Failures

Several external factors can induce stress between the bond and the coating, causing eventual failure. These factors can act individually or in combination (refer to Figure 3.17).

First may be regular mechanical stress, which not only affects the bulk of the materials, but also the bond strength at the interface. The stress may be tensile stress that acts perpendicular to the interface, or shear stress that acts along the plane of contact.

Because coatings can undergo changes in temperature, and sometimes rapidly, any difference in the coefficient of expansion can cause stress concentrations at the interface. These stresses may be of such magnitude that the paint film detaches from the substrate. Temperature effects tend to be less obvious than the mechanical and chemical factors.

In certain environments, the presence of a chemical can penetrate the coating and become absorbed at the interface, causing loss of adhesion.

Any testing done to measure the adhesion of a coating should take into account these effects so that the method employed will reproduce the end-use conditions.

TYPES OF CORROSION UNDER ORGANIC COATINGS

For corrosion to take place on a metal surface under a coating, it is necessary for an electrochemical double layer to be established. For this to take place, it is necessary for the adhesion between the substrate and coating to be broken. This permits a separate thin water layer to form at the interface from water that has permeated the coating. As mentioned previously, all organic coatings are permeable to water to some extent.

The permeability of a coating is often given in terms of the permeation coefficient P. This is defined as the product of the solubility of water in the coating (S kg/cm^3), the diffusion coefficient of water in the coating (Dm^2/s), and the specific mass of water (p kg/m^2). Therefore, different coatings can have the same permeation coefficient, although the solubility and diffusion coefficient, both being material constants, are very different. This limits the usefulness of the permeation coefficient.

Water permeation takes place under the influence of several driving forces, including:

1. A concentration gradient during immersion or during exposure to a humid atmosphere resulting in true diffusion through the polymer
2. Capillary forces in the coating resulting from poor curing, improper solvent evaporation, bad interaction between binder and additives, or entrapment of air during application
3. Osmosis due to impurities or corrosion products at the interface between the metal and the coating

Given sufficient time, a coating system that is exposed to an aqueous solution or a humid atmosphere will be permeated. Water molecules will eventually reach the coating/substrate interface. Saturation will occur after a relatively short period of time (on the order of 1 hour), depending on the values for D and S and the thickness of the layer. Typical values for D and S are 10^{-13} m^2/s and 3%, respectively. Periods of saturation under atmospheric exposure are determined by the actual cyclic behavior of the temperature and the humidity. In any case, situations will develop in which water molecules reach the coating/metal interface where they can interfere with the bonding between the coating and the substrate, eventually resulting in loss of adhesion and corrosion initiation, providing that a cathodic reaction can take place. A constant supply of water or oxygen is required for the corrosion reaction to proceed. Water permeation can also result in the build-up of high osmotic pressures, resulting in blistering and delamination.

Wet Adhesion

Adhesion between the coating and the substrate can be affected when water molecules have reached the substrate/coating interface. The degree to which permeated

water can change the adhesion properties of a coated system is referred to as *wet adhesion*. Two different theories have been proposed for the mechanism for the loss of adhesion due to water:

1. *Chemical disbondment* resulting from the chemical interaction of water molecules with covalent hydrogen, or polar bonds between polymer and metal (oxide)
2. *Mechanical or hydrodynamic disbondment* as a result of forces caused by accumulation of water and osmotic pressure

For chemical disbondment to take place, it is not necessary that there be any sites of poorly bonded coating. This is not the case for mechanical disbanding, where water is supposed to condense at existing sites of bad adhesion. The water volume at the interface may subsequently increase due to osmosis. As the water volume increases under the coating, hydrodynamic stresses develop. These stresses eventually result in an increase in the nonadherent surface area.

Osmosis

Osmotic pressure can result from one or more of the following:

1. Pressure of soluble salts as contaminants at the original metal surface
2. Inhomogeneities in the metal surface such as precipitates, grain boundaries, or particles from blasting pretreatment
3. Surface roughness due to abrasion

Once corrosion has started at the interface, the corrosion products produced can be responsible for the increase in osmotic pressure.

Blistering

Various phenomena can be responsible for the formation of blisters and the start of underfilm corrosion. These include the presence of voids, wet adhesion problems, swelling of the coating during water uptake, gas inclusions, impurity ions in the coating, poor general adhesion properties, and defects in the coating.

When a coating is exposed to an aqueous solution, water vapor molecules and some oxygen diffuse into the film and end up at the substrate interface. Eventually, a thin film of water may develop at the sites of poor adhesion or at the site where wet adhesion problems arise. A corrosion reaction can start with the presence of an aqueous electrolyte with an electrochemical double layer, oxygen, and the metal. This reaction will cause the formation of macroscopic blisters. Depending on the specific materials and circumstances, the blisters may grow out because of the hydrodynamic pressure in combination with one of the

chemical propagation mechanisms such as cathodic delamination and anodic undermining.

Cathodic Delamination

When cathodic protection is applied to a coated metal, loss of adhesion between the substrate and paint film, adjacent to defects, often takes place. This loss of adhesion is known as *cathodic delamination*. Such delamination can also occur in the absence of applied potential. Separation of anodic and cathodic reaction sites under the coating results in the same driving force as during external polarization. The propagation of a blister due to cathodic delamination under an undamaged coating on a steel substrate is schematically illustrated in Figure 3.18. Under an intact coating, corrosion may be initiated locally at sites of poor adhesion.

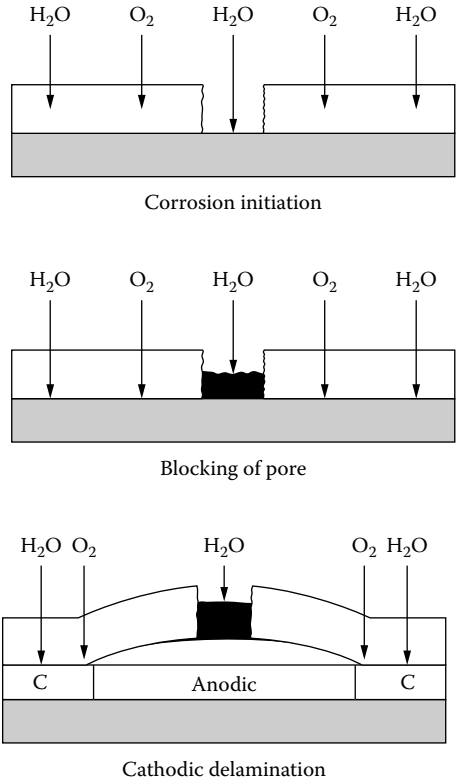


FIGURE 3.18 Blister initiation and propagation under a defective coating (cathodic delamination).

A similar situation develops in the case of corrosion under a defective coating. When there is a small defect in the coating, part of the substrate is directly exposed to the corrosive environment. Corrosion products are formed immediately and block the damaged site from oxygen. The defect in the coating is sealed by corrosion products, after which corrosion propagation takes place according to the same mechanism as for the initially damaged coating. Refer to Figure 3.18 for the sequence of events.

Anodic Undermining

Anodic undermining results from the loss of adhesion caused by anodic dissolution of the substrate metal or its oxide. In contrast to cathodic delamination, the metal is anodic at the blister edges. Coating defects may cause anodic undermining, but in most cases it is associated with a corrosion-sensitive site under the coating, such as a particle from a cleaning or blasting procedure, or a site on the metal surface with potentially increased corrosion activity (e.g., scratches). These sites become active once the corrodent has penetrated to the metal surface. The initial corrosion rate is low. However, an osmotic pressure is caused by the soluble corrosion products that stimulates blister growth. Once formed, the blister will grow due to a type of anodic corrosion at the edge of the blister.

Coated aluminum is very sensitive to anodic undermining, while steel is more sensitive to cathodic delamination.

Filiform Corrosion

Metals with semipermeable coatings or films may undergo a type of corrosion resulting in numerous meandering thread-like filaments of corrosion beneath the coatings or films. Conditions that promote this type of corrosion include:

1. High relative humidity (60 to 95% at room temperature)
2. Coating is permeable to water
3. Contaminants (salts, etc.) are present on or in the coating, or at the coating/substrate interface
4. Coating has defects (e.g., mechanical damage, pores, insufficient coverage of localized areas, air bubbles)

Filiform corrosion under organic coatings is common on steel, aluminum, magnesium, and zinc (galvanized steel). It has also been observed under electroplated silver plate, gold plate, and phosphate coatings.

This form of corrosion is more prevalent under organic coatings on aluminum than on other metallic surfaces, being a special form of anodic undermining. A differential aeration cell is the basic driving force. The filaments have considerable length but little width and depth and consist of two parts: a head and a tail. The primary corrosion reactions, and subsequently the delamination process of the paint

film, take place in the active head, while the tail is filled with the resulting corrosion products. As the head of the filiform moves, the filiform grows in length.

Early Rusting

When a latex paint is applied to a cold steel substrate under high moisture conditions, a measles-like appearance may develop immediately when the coating is touch-dry. This corrosion takes place when the following conditions are met:

1. The air humidity is high.
2. The substrate temperature is low.
3. A thin (up to 40 μm) latex coating is applied.

Flash Rusting

Flash rusting refers to the appearance of brown stains on a blasted steel surface immediately after applying a water-based primer. Contaminants remaining on the metal surface after blast cleaning are responsible for this corrosion. The grit on the surface provides crevices or local galvanic cells that activate the corrosion process as soon as the surface is wetted by the water-based primer.

STAGES OF CORROSION

To prevent excessive corrosion, good inspection procedures and preventative maintenance practices are required. Proper design considerations are also necessary, as well as selection of the proper coating system. Regular inspections of coatings should be conducted. Because corrosion of substrates under coatings takes place in stages, early detection will permit correction of the problem, thereby preventing ultimate failure.

First Stages of Corrosion

The first stages of corrosion are indicated by rust spotting or the appearance of a few small blisters. Rust spotting is the very earliest stage of corrosion and in many cases is left unattended. Standards have been established for evaluating the degree of rust spotting and these can be found in ASTM 610-68 or Steel Structures Painting Council Vis-2. One rust spot in 1 square foot may provide a 9+ rating but three or four rust spots drop the rating to 8. If the rust spots go unattended, a mechanism for further corrosion is provided.

Blistering is another form of early corrosion. Frequently, blistering occurs without any external evidence of rusting or corrosion. The mechanism of blistering is attributed to osmotic attack or a dilution of the coating film at the interface with the steel under the influence of moisture. Water and gases pass through the film and dissolve ionic material from either the film or the substrate, causing an osmotic pressure greater than that of the external face of the coating. This produces a solution

concentration gradient, with water building up at these sites until the film eventually blisters. Visual blistering standards are found in ASTM D-714-56.

Electrochemical reactions also assist in the formation of blisters. Water diffuses through a coating also by an electroendosmotic gradient. Once corrosion has started, moisture is pulled through the coating by an electrical potential gradient between the corroding areas and the protected areas that are in electrical contact. Therefore, osmosis starts the blistering; and once corrosion begins, electroendosmotic reactions accelerate the corrosion process. The addition of heat and acidic chemicals increases the rate of breakdown. Temperatures of 150°F to 200°F (66°C to 93°C) accelerate the chemical reaction. Under these conditions, steel will literally dissolve in a chemical environment. Moisture is always present and afterward condenses on the surface behind the blister. This condensation offers a solute for gaseous penetrants to dissolve. When the environment is acidic, the pH of the water behind the blister can be as low as 1.0 or 2.0, thus subjecting the steel to severe attack.

Second Stage of Corrosion

After observing the initial one or two rust spots, or after having found a few blisters, a general rusting in the form of multiple rust develops. This rusting is predominately Fe_2O_3, a red rust. In atmospheres lacking sufficient oxygen, such as in sulfur dioxide scrubbers, a black FeO rust develops. Once the unit has been shut down and more oxygen becomes available, the FeO will eventually convert to Fe_2O_3.

Third Stage of Corrosion

This advanced stage of corrosion is the total disbondment of the coating from the substrate, exposing the substrate directly to the corrodents. Corrosion can occur at an uninhibited rate because the coating is no longer protecting the steel.

Fourth Stage of Corrosion

Attack of the metal substrate after removal of the coating is not usually of a uniform nature but rather that of a localized attack, resulting in pitting.

Fifth Stage of Corrosion

Deep pits formed in the substrate during the fourth stage of attack can eventually penetrate completely to cause holes. Within the corrosion cell, pitting has occurred to such a degree that undercutting, flaking, and delamination of the substrate take place. As the small hole develops, the electrolyte has access to the reverse side and corrosion now takes place on both sides of the substrate.

Final Stage of Corrosion

Corrosion is now taking place at its most rapid and aggressive rate. Large gaping holes are formed, causing severe structural damage.

REFERENCES

1. Asbeck, W.K., The measurement of adhesion in absolute units by knife-cutting methods: the hesiometer. Presented at the *Eleventh FATIPEC Congress,* Congress Book, Brussels, 1972, pp. 78–87.
2. Gent, A.N. and Hamed, G.R., Peel mechanics, *J. Adhes.,* 7, 91–95, 1975.
3. Crocombe, A.D. and Adams, R.D., Peel analysis using the finite element method, *J. Adhes.,* 12, 127–139, 1981.
4. Heertjes, P.M. and deJong, J., The peeling off of paint film, *J. Oil Color Chem. Assoc.,* 35, 1096–1106, 1972.

4 Surface Preparation and Application

INTRODUCTION

Surface preparation, which includes cleaning and pretreatment, is the most important step in any coating operation. For coatings to adhere, surfaces must be free from oily soils, corrosion products, and loose particulates. While new wood surfaces may be coated without cleaning, old wood surfaces must be cleaned to remove any loose, flaky coatings and oily soils. Chemicals are used to remove mold released from plastics. Metals are cleaned using solvents, or aqueous chemicals, or by media blasting, sanding, and brushing. The choice of cleaning method depends on the substrate and the size and shape of the object.

To improve coating adhesion, pretreatments are applied after cleaning. In the case of metals, these pretreatments also provide some corrosion resistance. Wood surfaces may require the priming of knots and the filling of nail holes. Acids are used to remove loosely adhering contaminants and to passivate cementitous and masonry surfaces. Some plastic surfaces may be painted after cleaning to remove mold release but others may require additional pretreatments to ensure coating adhesion.

This chapter provides a detailed discussion of the cleaning and pretreatment of various substrates.

METAL SUBSTRATE PREPARATION

Initially, a "pre-surface-preparation inspection" should be made. This inspection is to determine if additional work needs to be done by other crafts before the start of surface preparation for painting. Such other work might include grinding and rounding of edges and welds; removal of weld spatter, heavy deposits of oil, grease, cement spatter, or other contaminants; moving equipment out of the work area; masking or otherwise protecting equipment or items not to be painted in the work area; and other such preliminary activities. Only after this is done can the painters then begin to work effectively.

Oily soils must be removed before any other surface preparation is undertaken. Otherwise, these soils might spread over the surface. These soils can also contaminate abrasive cleaning media and tools. Oily soils can be removed faster using liquid cleaners that impinge on the surface or in agitation immersion baths. It is often necessary to heat liquid cleaners to facilitate soil removal.

TABLE 4.1
Summary of Surface Preparation Specifications

SSPC Specification	Description
SP 1: Solvent cleaning	Removal of oil, grease, dirt, soil, salts, and contaminants by cleaning with solvent, vapor, alkali, emulsion, or steam
SP 2: Hand-tool cleaning	Removal of loose rust, mill scale, and paint to degree specified by hand chipping, scraping, sanding, and wire brushing
SP 3: Power-tool cleaning	Removal of loose rust, mill scale, and paint to degree specified by power tool chipping, descaling, sanding, wire brushing, and grinding
SP 5: White-metal blast cleaning	Removal of all visible rust, mill scale, paint, and foreign matter by blast cleaning by wheel or nozzle (dry or wet), using sand, grit, or shot (for very corrosive atmospheres where high cost of cleaning is warranted)
SP 6: Commercial blast cleaning	Blast cleaning until at least two thirds of the surface area is free of all visible residues (for rather severe conditions of exposure)
SP 7: Brush-off blast cleaning	Blast cleaning of all except tightly adhering residues of mill scale, rust, and coatings, exposing numerous evenly distributed flecks of underlying metal
SP 8: Pickling	Complete removal of rust and mill scale by acid pickling, duplex pickling, or electrolytic pickling
SP 10: Near-white blast cleaning	Blast cleaning nearly to white-metal cleanliness, until at least 95% of the surface area is free of all visible residues (for high-humidity, chemical atmosphere, marine, or other corrosive environments)

Coating application, in the most basic terms, is the preparation of the surface to receive paint and the application of the paint in the proper manner to the specified thickness. The surface preparation specified is predicated by the coating system to be applied. It is usually a good idea to specify a "standard" surface preparation method. The most common standard methods are those defined by the Steel Structures Painting Council (SSPC). Table 4.1 summarizes the SSPC surface preparation methods. These standards, and others prepared by the National Association of Corrosion Engineers, the Society of Naval Architects and Marine Engineers, various highway departments, and private corporations, are almost always final appearance standards. These standards give the desired end product but do not describe in detail the means to achieve this end. It is important, therefore, that the painter or person doing the surface preparation be knowledgeable. It is important that the various pieces of equipment be sized properly; that air and abrasives (if used) be cleaned, graded, and free of moisture, oil, and other contaminants; and that ambient conditions be controlled, or at least closely monitored.

Surface preparation techniques have changed drastically. Silica sand has been banned in virtually all Western countries except the United States and Canada (although there is a strong movement to ban it in these countries as well) as a blast cleaning abrasive. To prevent environmental damage caused by the leaching into water supplies of lead, chromate, and other toxic paint pigments removed during the course of blast cleaning, many localities require the safe containment and safe disposal of spent blast-cleaning abrasives. Although a paint layer over a properly cleaned surface still acts as a barrier against a corrosive environment, in may cases the components that form this barrier have changed considerably.

In some environments, certain surface preparation and coating application techniques are not permissible. For example, many companies do not permit open blast cleaning where there is a prevalence of electrical motors or hydraulic equipment. Refineries, as a general rule, do not permit open blast cleaning — or for that matter, any method of surface preparation that might result in the possibility of a spark, static electricity build-up, or an explosion hazard. During the course of construction or erection, many areas requiring protection are enclosed or covered, or so positioned that access is difficult or impossible. Consideration must be given to painting these structures prior to installation.

Some methods of coating must be done at a specialized facility because the equipment used is not readily transportable to field sites. Typical methods include most chemical cleaning, including pickling and acid etching, automatic rotary wheel blast cleaning, and automatic spraying, electrostatic, or high-speed roller coating application.

Abrasive Cleaning

Abrasive cleaning is undertaken after oily soils have been removed. Rust and corrosion are removed by media blasting, hand or power sanding, and hand or power blasting. Media blasting is accomplished by propelling, under pressure, materials such as sand, metallic shot, nut shells, plastic pellets, or dry ice crystals so that they impinge on the surfaces to be cleaned. High-pressure water jet cleaning is similar to media blasting.

Detergent Cleaning

Aqueous solutions of detergents are used to remove oily soils. They are applied to metals by immersion or spray. After cleaning, the surfaces are rinsed with clean water to remove the detergent. Detergents will not remove rust and corrosion.

Alkaline Cleaning

Aqueous solutions of alkaline phosphates, borates, and hydroxides are used to remove oily soils in much the same way as detergents. After cleaning, they are washed away with clear water.

Emulsion Cleaning

Aqueous emulsions of organic solvents such as mineral spirits and kerosene are used to remove heavy oily soils and greases. After dissolving the oily soils, the emulsions are flushed away with hot water. Any remaining oily residue is removed using clean solvent, detergent, or alkaline cleaners.

Solvent Cleaning

Organic solvents are effective in removing oily soils. Hand wiping, spraying, or immersion methods can be employed. The solvents and wipers will become contaminated with these soils and therefore must be changed frequently to prevent oily residues from remaining on the surface. Because of the hazardous nature of these solvents, safe handling practices must be employed.

Vapor Degreasing

Boiling solvent condenses on the cool surface to be cleaned and flushes away oily soils but does not remove particulates. Although once very popular, the use of this process is declining. The process employs chlorinated solvents that are under regulatory scrutiny by governmental agencies.

Steam Cleaning

The application of detergent and alkaline cleaners using steam cleaners is an effective degreasing method. Heavy greases and waxes are dissolved and flushed away by the impingement of steam and the action of the chemicals. Hot-water spray cleaning using chemicals is almost as effective as steam cleaning.

METAL SURFACE PRETREATMENT

Because abrasive cleaning removes corrosion, it is also considered a pretreatment. The impingement of blasting media and the action of brushes and abrasive pads roughen the substrate and thereby improve adhesion. The other cleaning methods that remove oily soils do not generally remove rust and corrosion from the substrates.

Other pretreatments use aqueous chemical solutions that are applied by immersion or spray techniques. These chemicals prepare the substrate surface to accept the coating and improve the adhesion. Different metals are treated in different ways.

Aluminum

After the aluminum substrate has been cleaned to remove oily soils and corrosion products, it is pretreated using chromate conversion coating and anodizing. A phosphoric-acid-activated vinyl wash primer, which is also a pretreatment, must be applied directly to the metal and not over other pretreatments.

Copper

After cleaning by solvents and chemicals, the surface is abraded to remove corrosion; bright dipping in acids will also remove corrosion. Chromates and vinyl wash primers are used to pretreat the cleaned surfaces.

Galvanized Steel

To prevent white corrosion, the mill applies oil and wax to the galvanized steel surface, which must be removed. After cleaning, chromates and phosphates are used to pretreat the surface. If no other pretreatment has been utilized, a vinyl wash primer can be used.

Steel

Phosphate pretreatment is usually applied to steel to provide corrosion resistance after cleaning to remove rust and oily soils. Chromates and wash primers are possible alternative pretreatments.

Stainless Steel

Under normal circumstances, stainless steel is not usually coated because of its corrosion resistance. If it is to be coated, oily soils must be removed and the surface abraded to produce roughness. Wash primers will improve adhesion.

Titanium

Cleaned titanium is pretreated the same as stainless steel (see above).

Zinc and Cadmium

Zinc and cadmium substrates are treated the same as galvanized steel (see above).

PLASTIC SUBSTRATE PREPARATION

As with metallic substrates, surface preparation has the greatest impact on film adhesion. Film adhesion to a plastic is primarily a surface phenomenon and requires intimate contact between the substrate surfaces and the coating. Without appropriate conditioning and cleaning, intimate contact with the plastic surface is not possible.

Plastic surfaces present a number of unique problems. Many plastics, such as polyethylene and fluorinated polymers, have a low surface energy, which means that few materials will readily adhere to the surface. Plastic materials are often formulations of one or more polymer types, or have various amounts of inorganic fillers. In addition, the coefficient of thermal expansion is usually quite high for plastic compounds and can vary widely, depending on polymer blend, filler content, and filler type. The flexibility of plastic materials puts more stress on

the coating, and serious problems can develop if film adhesion is low as a result of poor surface preparation.

Surface preparation, depending on the polymer, is required to:

1. Remove process oils, dirt, grime, waxes, mold release agents, and poorly retained plasticizers
2. Match the finish on the plastic to the coating viscosity for improved film adhesion
3. Convert the surface of the plastic to provide an interface that is more like, or more compatible with, the chemical structure of the coating
4. Promote oxide formation to produce a higher level of surface activity
5. Control absorbed water, which can interfere with adhesion

There are as many procedures for cleaning and preparing plastic surfaces as there are polymer types. Most plastic types have recommended procedures for achieving the best finish for coating. Many polymers can be blended together to achieve specific properties. Fillers and plasticizers are also included in the resin matrix to yield certain characteristics. The same preparation procedure may not be suitable in each of these cases.

Advice as to the appropriate surface preparation procedure to use should be available from the manufactures of both the plastic *and* the coating. However, because of the possible unique need of the user, even the manufacturers may not have a definite answer. Experimentation may be required to identify the most suitable technique for a specific application.

The procedures described concentrate on the technique and not the plastic. In some cases, certain techniques are recommended for specific polymers.

It must be noted that many of the surface preparation processes involve the use of hazardous, corrosive, toxic, flammable, or poisonous chemicals. It is essential that appropriate control procedures and safe handling methods be employed to minimize risk in the work environment.

Solvent Cleaning

The easiest and most common procedure used to remove surface contamination is by means of solvent action, which removes surface contamination by dissolving the unwanted substance. Organic solvents and water are used for this purpose.

Organic solvents may be either flammable or nonflammable. The most commonly used are acetone, methyl ethyl ketone, toluol, 1,1,1,-trichloroethane, naphtha, and, on occasion, Freon (either by itself or blended with another solvent).

Although water is inexpensive and plentiful, it often has trace levels of impurities that can contaminate surfaces. Consequently, distilled or deionized water is recommended. Water is frequently used as a rinse for other surface preparation procedures.

These solvents can be applied in one of several methods, including simple wiping with a dampened cloth, immersion in a swirling bath with heat applied

to speed the solvent action, and spray cleaning. Spray cleaning has the advantage of flushing off the contamination with the force of the spray. Vapor degreasing is also employed. In this case, the plastic part is suspended over a boiling tank of solvent. As the vapors condense on the part, the constant flow over the surface washes it clean. High-frequency vibration from sonic waves in a solvent bath is also used to remove contaminants.

Before use, the compatibility of the solvent with the plastic must be verified. Regardless of the process used, frequent changing or filtering of the solvents is recommended to prevent residue build-up and recontamination. When using heat to dry the parts after washing, care must be taken because heat can very easily distort thermoplastics.

Detergent Cleaning

Emulsification of oils, greases, and some mold releases is easily achieved in either hot- or cold-water solutions of detergents or soaps. Recommended materials include Ivory soap, Ajax, Borax, and trisodium phosphate in various cleaning operations.

Unless the plastic is water sensitive, an immersion wash is effective. Scouring with a medium-to-stiff bristle brush works quite well for dislodging many contaminants.

Because soaps can act as a contaminant, it is essential that a thorough rinse be applied using clean water. Thorough drying at elevated temperatures is recommended. Detergent cleaning is often used as a preliminary step to mechanical treatments.

Mechanical Treatments

A solvent or detergent cleaning process must precede a mechanical treatment to prevent scrubbing surface contaminants into the roughened surface. Physical scrubbing of plastic surfaces removes oxides and contaminated layers.

A commonly used procedure is either wet or dry sanding, using a grit of 40 to 400. The grit size depends on the amount of surface to be removed and the surface finish desired. Softer plastics are more susceptible to damage.

Grit blasting, either wet or dry, and wire brushing are appropriate techniques to use on parts that have complex configurations. Grit size and type can be varied to obtain the proper finish.

Regardless of the method employed, the roughened surface should be vacuumed or air-blasted to remove residual dust or grit. It is recommended that this be followed by a solvent wipe or water rinse, followed by elevated drying.

Chemical Treatment

A chemical etch of the plastic to be coated is, in general, the most effective surface preparation technique. Both physical and chemical characteristics of the plastic can be modified to improve wet-out and film adhesion. To reduce

surface contamination and to obtain optimum interaction between the chemical and the substrate, one or more of the cleaning operations must be employed prior to the chemical treatment.

Chemical treatment involves the surface being washed or immersed in a bath containing an acid, base, oxidizing agent, chlorinating agent, or other highly active chemical. Regardless of the agent being used, it is necessary to control the parts by weight of the active ingredient, the temperature of the solution, and the elapsed time of immersion. Some procedures have a wide range of ingredient ratios, while others are quite specific. The temperature of the solution is inversely proportional to the time of immersion — the higher the temperature, the shorter the immersion time. It is important that solution strength be monitored and renewed as required.

All chemical etch procedures require a water rinse and elevated temperature drying.

Sulfuric Acid–Dichromate Etch

The sulfuric acid–dichromate etch is recommended for use on acrylonitrile-butadiene-styrene (ABS), acetal, melamine or urea, polyolefins, polyphenylene oxide, polystyrene, polysulfone, and styrene-acrylonitrile (SAN). A different ingredient ratio, immersion temperature, and immersion time is recommended for each plastic. Table 4.2 shows the parameters of the sulfuric acid–dichromate etch bath.

Sodium Etch

Highly reactive chemicals must be used to etch such difficult surfaces to coat as the various fluoroplastics and some thermoplastic polyesters. A typical solution used contains 2 to 4 parts metallic sodium dispersed in a mixture of 10 to 12 parts naphthalene and 85 to 87 parts tetrahydrofuran.

Immersion time is 15 minutes at ambient temperatures, followed by a thorough rinsing with a ketone solvent and rinsing with water.

TABLE 4.2
Parameters of Sulfuric Acid-Dichromate Etch Bath

Ingredient	Parts (by weight)	Range
Potassium or sodium dichromate	5	0.5–10.0
Concentrated sulfuric acid	85	65.0–96.5
Water	10	0–27.5
Time	10 seconds–90 minutes	
Temperature	Room temp.–to 160°F (71°C)	

Sodium Hydroxide

Thermoplastic polyesters, polyamides, and polysulfone can be effectively treated using a mixture of 20 parts (by weight) sodium hydroxide and 80 parts (by weight) water. The plastic is immersed in the 175–200°F (24–93°C) bath for a period of 2 to 10 minutes.

Satinizing

DuPont developed this process for the treatment of its homopolymer-grade acetal (U.S. Patent 3,235,426). A heated solution of dioxane, *para*-toluene sulfonic acid, perchlorethylene, and a thickening agent is prepared, into which parts are dipped. After the dip cycle, parts are heat-treated, rinsed, and dried in accordance with a prescribed procedure.

Phenol

An 80% solution of phenol in water is used to etch nylon. The solution is brushed onto the surface at room temperature and then allowed to dry for approximately 20 minutes at 150°F (66°C).

Sodium Hypochlorite

The newer thermoplastic rubbers and several of the thermoplastic polymers can be chlorinated on the surface by applying the following solution (parts by weight):

15% Sodium hypochlorite	2–3
Concentrated hydrochloric acid	1–2
Water	95–97

The solution can be brushed onto the surface and allowed to remain for 5 to 10 minutes or immersed for the same period of time.

Other Treatments

Procedures have been developed specifically for plastic processing to overcome the low surface activity of many of these materials. Prior removal of surface contamination by solvent or detergent cleaning is necessary is most cases to achieve optimal results.

Primers

The application of a primer coating is used to develop better adhesion of the final coating to the plastic substrate. A variety of chemical types can be used as primers, including urethane polymers, silicones, nitrile phenolics, vinyl, or isocyanates. The primer is applied to the surface as soon as possible after other surface preparation procedures have been completed in order to protect the surface from recontamination.

Flame Treatment

The surface of many plastics, such as acetals, polyolefins, fluoropolymers, and polycarbonates, are oxidized by the impingement of a flame. The oxidation

provides a higher level of surface energy and better film adhesion. This process is particularly effective on complex shapes and molded parts. Super-heated air at 1000°F (538°C) is just as effective.

Exposure to Ultraviolet Radiation

An ionized or highly polar surface results after exposure to high-intensity ultraviolet radiation.

Drying

Over-drying can be effective on plastic formulations that absorb atmospheric moisture.

Plasma Treatment

Plasma treatments are effective for most plastics. Parts are exposed to gases such as neon, helium, oxygen, and moisture vapor, which are ionized by radio-frequency or microwave discharge. Although very effective in improving surface conditions that promote better film adhesion, this process is limited to smaller components and parts because of equipment size.

Corona Discharge

Surface tension can be improved by passing film or thin-gauge plastics between two electrodes. This treatment is suitable for high-speed operations.

Testing of Prepared Surface

The effectiveness of a surface preparation technique being used for the first time on a specific plastic formulation must be determined. Several tests have been developed for this purpose.

Water Break Test

When poured onto a clean surface, water will sheet across the face. If the surface is oily or poorly treated, beads will form. This test is not recommended for surfaces that absorb moisture and has limited effectiveness on low-polarity surfaces such as fluoroplastics and polyolefins.

Tape Test

A flexible tape is applied to the surface under controlled conditions with standardized pressure and a defined dwell time, after which a peel test is conducted. The type, width, and brand of tape should remain constant for consistent results. (Refer to Chapter 3.)

Quick Strip Test

After coating and conditioning a part, a grid pattern of cuts is made through the coating. A standard tape is applied with constant pressure to the surface and then

quickly stripped. An indication of the film adhesion is determined by counting the number of squares that were removed. (Refer to Chapter 3.)

Contact Angle Test

Well-prepared surfaces are easier to wet and will exhibit a lower contact angle than an unprepared or poorly prepared surface. A drip of a standardized reference fluid will have a defined contact angle at the edge of the drop.

Environmental Testing

The effectiveness of the coated part in meeting end-use conditions can be determined by exposing it to a series of heat cycling, weatherometer, stress tests, and various exposure tests.

APPLICATION OF COATINGS

Over the years there have been many changes in the formulation of coatings that have affected the methods by which they are applied to a substrate. Several of these changes have resulted from governmental regulations.

The Occupational Safety and Health Act (OSHA) and the Toxic Substances Control Act (TOSCA) regulate the environment in the workplace and limit workers' contact with hazardous materials. These Acts made it necessary to use alternate coating materials and to modify application procedures in order to comply.

In the late 1940s, smoke control laws were enacted to reduce airborne particulates that led to air pollution. During this period, a condition known as "photochemical smog" developed as a result of the increased automobile usage and industrial expansion. The smog was created by the reaction of chemicals in the atmosphere to sunlight. Los Angeles Country officials, recognizing that automobile exhaust and VOC (volatile organic compound) emissions were major sources of smog, enacted an air pollution regulation called Rule 66. Under Rule 66, specific solvents that produced photochemical smog were banned from use. At the same time, they published a list of acceptable solvents that could be used in coating. The EPA conducted additional studies that indicated that these so-called "acceptable" solvents, given enough time, would also produce photochemical smog in the atmosphere.

The EPA established national air quality standards (in its Clean Air Act of 1970 and its 1990 amendments) that regulate the amounts of solvents that can be emitted. Many local standards are more stringent than the national standard. Consequently, specific coatings may not comply with regulations in all areas. Waterborne, powder, high-solids, electrophoretic, and radiation-cured coatings will comply in all areas.

In addition, certain types of paints, primarily those containing lead and asbestos, have been outlawed by federal and local jurisdictions. Potentially harmful pigments

or other constituents are causing the restriction of other paints containing these ingredients.

It is important that, during the application of any coating, adequate ventilation for the removal of solvents be provided, as well as suitable and safe access to the work being painted.

APPLICATION METHODS

The method of application of a corrosion resistant paint will depend on:

1. Purpose for which coated product is to be used
2. Environment to which the coating will be exposed
3. The type of paint
4. The shape and size of the object to be painted
5. The period of application process
6. Cost

Application methods vary from the traditional paint brush or roller to various spray techniques, powder coating, and electrodeposition. Exact procedures will depend on the specific coating used and the object to be coated.

Brushing

Brushing is an effective, relatively simple method of paint application, particularly with primers, because of the ability to work the paint into pores and surface irregularities. Because brushing is slow, it is used primarily for smaller jobs, surfaces with complex configurations (edges, corners, cuts, etc.), or where overspray might pose a serious problem.

Brushing was once the main coating method; but at the present, spray coating is more widely used. Brush coating has the following advantages:

1. Applicators are simple and inexpensive.
2. Complicated forms and shapes can be coated.
3. Thick films are obtained with one coat.
4. Particularly useful for applying an anti-rust coating.

The disadvantage of brushing results from the nonuniformity of coating layers, especially coating layers of rapidly drying paints.

Rolling

The advantage of using rollers is found when used on large, flat areas that do not require the smoothness or uniformity that can be obtained by spraying. They are also used in interior areas where overspray presents a cleaning and masking problem. Because of the difficulties in penetrating pores, cracks, and other surface

irregularities, the use of a brush is preferred when applying primers. When using a roller, air mixes with the paint and leaves points where moisture can penetrate the cured film. Rolling is best used when used to apply a topcoat over a primer that has been applied by some other method.

Roller Coating

Roller coating is a process to coat coils and sheets by passing them through two preset rollers. The quantity of paint consumed is reduced by approximately 50% of that used in other coating methods. The thickness of paint film is controlled by adjusting the rollers. One-side or both-side coatings are possible.

Spray Painting

A more uniform and smoother surface can be achieved with spray painting than with brushing or rolling because the latter methods tend to leave brush or stipple marks and irregular thickness. The most common methods of spray painting are conventional and airless.

The conventional spray method relies on air for paint atomization. Jets of compressed air, introduced into the stream of paint at the nozzle, break the stream into tiny droplets that are carried to the surface by the air current. Paint losses from bounce-back or overspray can be high because large amounts of air are mixed with the paint during application. Such losses have been estimated to be as much as 30 to 40%.

Some of the disadvantages of conventional air spray applications include:

1. It is slower than airless application.
2. More overspray results than with other methods.
3. It is difficult to coat corners, crevices, etc. because of blowback.

An airless spray system consists of:

1. A plunger pump that supplies high pressure to the paint
2. An airless spray gun
3. A high-pressure-resistant hose

High-viscosity paints are warmed before spraying. This technique has the following advantages over an air spray system:

1. The sticking ratio of paint is increased by 25 to 40%.
2. A thicker film can be applied.
3. The running of paint on the substrate is reduced.
4. Because there is only one hose, it is easier for the operator to use.
5. Higher viscosity paints can be applied.
6. Clean up is easier.

Because the airless spray process is more efficient than brushing, it is suitable for coating steel structures and bridge girders in the factory. However, paint loss using the airless spray process is 30 to 40% greater than that of brushing. The disadvantages of the airless spray system include:

1. Reliance on dangerous high pressure
2. Fan pattern is not adjustable
3. Additional working parts that can cause difficulty
4. Higher initial cost than other spraying techniques
5. A need to exercise extra care to avoid excessive build-up of paint that causes solvent entrapment, pinholes, runs, sags, and wrinkles

Powder Coating

Powder coatings have grown in popularity as anti-pollution coatings because of the absence of solvents. Coating thicknesses of 25 to 250 μm can be obtained.

Automotive bodies' electric components, housing materials, wires, and cables make use of this process. Polyethylene and epoxy resins are the predominant types of paints used. At the present time, the following 11 procedures are used in the coating process:

1. Pouring method (flock coating)
2. Rotational coating of pipes
3. Fluidized bed
4. Dipping in nonfluidizing powders
5. Centrifugal casting
6. Rotational molding
7. Electrostatic powder spraying
8. Electrostatic fluidized bed
9. Pouring or flowing of fluidized powder
10. Electrogas dynamics powder spraying
11. Flame spraying of thermoplastic powders

Powder coating was developed in the 1950s and is a method for applying finely divided, dry, solid, resinous coatings by dipping products in a fluidized bed or by spraying them electrostatically. The fluidized bed is essentially a modified dip tank. During the electrostatic spraying method, charged particles adhere to grounded parts until fused and cured. In all cases, the powder coating is heated to its melt temperature, where a phase change occurs, causing it to adhere to the product and fuse to form a continuous coating.

Fluidized bed powder coating is a dipping process using dry, finely divided plastic materials; a tank having a porous bottom plate forms the fluidized bed. The plenum below the porous plate supplies low-pressure air uniformly across

the plate, which suspends the finely divided plastic powder particles. Products that are preheated above the melt temperature of the material are dipped into the bed, where the powder melts and fuses into a continuous coating. Thermosetting powders often require additional heat to cure the film on the product.

Fluidized bed powder coating has the advantage of producing a uniform and reproducible film thickness. It also has the advantage of producing a heavy coating in one dip. The disadvantage of this method is the 3-mil minimum film thickness required to form a continuous coating.

An electrostatic fluidized-bed coater is essentially a fluidized bed with a high-voltage DC grid installed above the porous plate to charge the finely divided particles. The charged particles repel the grid and each other, forming a cloud. These particles are attracted to and coat products that are at ground potential. Film thicknesses of 1.5 to 5 mil are possible on cold parts and 20 to 25 mil are possible on heated parts.

The advantage of this method is that small parts, such as electrical components, can be coated uniformly and quickly. The disadvantage is that the product size is limited and inside corners have low film thicknesses.

Electrostatic spray powder coating is a method for applying finely divided, electrostatically charged particles to products that are at ground potential. A powder/air mixture from a small fluidized bed in the powder reservoir is supplied by hose to a spray gun, which has a charged electrode in the nozzle fed by a high-voltage DC power pack. The spray guns can be manual or automatic and mounted in a conveyorized spray booth. Film thicknesses of 1.5 to 5 mil can be obtained on cold substrates. A 20- to 25-mil film thickness can be obtained on heated substrates. The advantage of this method is that coatings using many resin types can be achieved, in thicknesses of 1.5 to 3 mil, with no VOC emissions. Disadvantages include the difficulty in obtaining a continuous coating of less than 1 mil; and because of the complex powder reclaiming systems, color changes are more difficult to make than with liquid spray systems.

Electrodeposition of Polymers

The electrodeposition of polymers is an extension of painting techniques into the field of plating and, like plating, is a dip coating process. In the case of ionizable polymers, the deposition reaction is:

$$R_3NH^+OH^- + lF \rightarrow R_3N + H_2O$$

or the conversion of water-dispersed ammonium-type ions into ammonia-type, water-insoluble polymers known as cathodic deposition. Alternatively, a large number of installations utilize the anodic deposition process:

$$RCOO^- + H^+ \text{ less } lF \rightarrow RCOOH$$

R symbolizes any of the widely used polymers (such as acrylics, epoxies, alkyds, etc.). The electrodeposition process ids defined as the utilization of synthetic, water-dispersed, electrodepositable macroions.

Metal ions, typically $0.5Ni^{2+}$, show an electrical equivalent weight equal to approximately 29.5 g while the polymeric ions typically used for electrodeposition exhibit a gram equivalent weight (GEW) of approximately 1600. Therefore, 1F plates out 30 g nickel and deposits 1600 g macroions.

The formation of uniformly thick coats on all surfaces of a formed workpiece, including the extreme recesses, as the inside of car doors, is probably the reason for the rapid industrial growth of this process. The ability to extend coats into recesses is known as *throwing power*.

Another advantage is the very small emission of volatile organic compounds (VOCs), making electrodeposition with powder coating and radiation cure the least polluting coating processes.

The anodic deposition process for paint coating systems was introduced in the early 1960s, and the cathodic deposition process in 1972. Electrodeposition processes are widely used because they possess the advantages of unmanned coating, automation, energy savings, and lower environmental pollution. This process is used to apply coatings to automotive bodies and parts, domestic

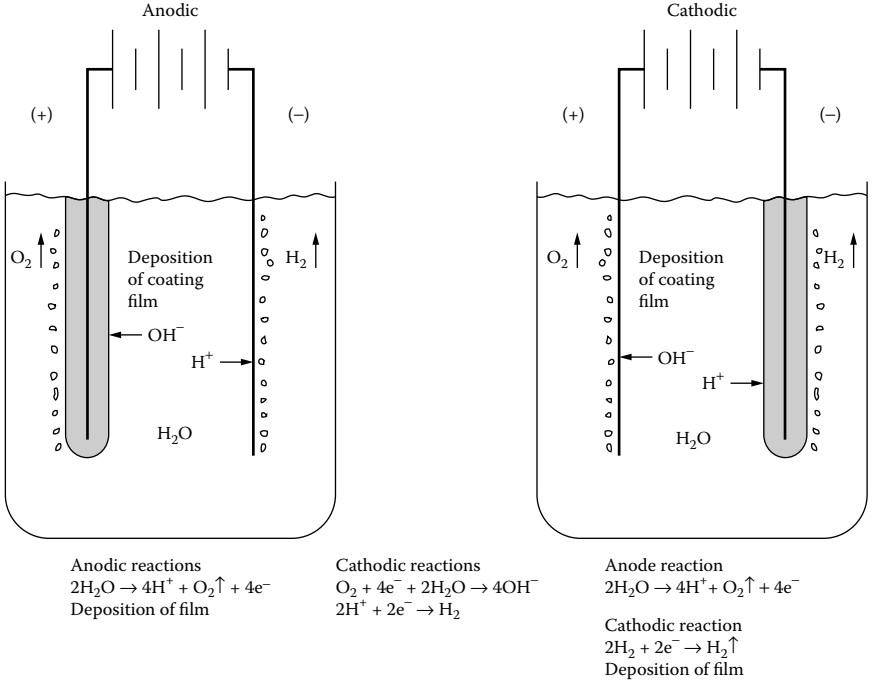


FIGURE 4.1 Anodic (a) and cathodic (b) electrodeposition of paints.

electrical components, machine parts, and architecturals such as window frames. Schematic illustrations of anodic and cathodic electrodeposition of paints are shown in Figure 4.1.

The primary paints used in the electrodeposition process are anionic-type resins with a carboxyl group (RCOOH polybutadiene resin) and cationic-type resins ($R\text{-}NH_2$ epoxy resin). Hydrophilic groups and neutralizing agents are added to the water-insoluble or undispersed prepolymers to convert them to soluble or dispersed materials.

The dissolution of metal substrate in the cathodic process is much less than that in the anodic process. The primary resins used in the cathodic process are epoxy; and because epoxy resins provide good water and alkali resistance as well as adhesion, cationic paint coatings are superior to anodic paint coatings.

Multilayer Coatings

The thicker a coating layer is, the better its protective ability. However, the thickness of a single coat is restricted because thick paint films tend to crack as a result of internal stress. When a product is to be used for an extended period of time in a severe environment, multilayer paint coating systems are usually employed. Automotive bodies and steel structures are typical products receiving multilayer coatings. A two- or three-coat system is employed for automotive bodies, and a general or heavy-duty coating system is adopted for steel structures. A typical paint coating system for an automotive body is as follows:

1. Pretreatment (degreasing and phosphating by dipping or spraying)
2. Primer coating by cathodic electrodeposition
3. Sealing by blow gun or undercoating by air spray
4. Surface conditioning by flatting
5. Intermediate paint coating by auto-electrostatic powder process or spraying
6. Surface conditioning by flatting and wax injection
7. Top paint coating by auto-electrostatic powder process as by spray

The paint system for auto bodies is composed of a combination of various types of paints and effective coating processes, thereby providing optimal corrosion protection and decorative appearance.

The paint system for a steel structure is selected based on the required service life and environmental conditions under which the steel structure must exist. Structures in mild environments are commonly coated with general coating systems. Those in severe environments are treated with heavy-duty coating systems. Typical paint coating systems for steel structures are given in Table 4.3.

TABLE 4.3
Application Examples of Multistage Paint Coating Systems to Steel Structures

	General Coating System		
	A	**B**	**C**
1st coat	Etching primer	Etching primer	Zinc-rich primer
2nd coat	Oil corrosion preventive paint	Oil corrosion preventive paint	Chlorinated rubber system primer
3rd coat	Oil corrosion preventive paint	Oil corrosion preventive paint	Chlorinated rubber system primer
4th coat	Long oil alkyd resin paint	Phenolic resin system M10 paint	Chlorinated rubber system paint
5th coat	Long oil alkyd resin paint	Chlorinated rubber system paint	Chlorinated rubber system paint
6th coat		Chlorinated rubber system paint	

	Heavy Coating System			
	D	**E**	**F**	**G**
1st coat	Zinc spray or zinc-rich paint	Thick-type zinc-rich paint	Thick-type zinc-rich paint	Zinc-rich primer
2nd coat	Etching primer	Thick-type vinyl or chlorinated rubber system paint	Thick-type epoxy primer	Tar epoxy resin paint
3rd coat	Zinc chromate primer	Thick-type vinyl or chlorinated rubber system paint	Thick-type epoxy primer	Tar epoxy resin paint
4th coat	Phenolic resin system M10 paint	Vinyl or chlorinated rubber system paint	Epoxy resin system paint	Tar epoxy paint
5th coat	Chlorinated rubber system paint	Vinyl or chlorinated rubber system paint	Epoxy or polyurethane resin system paint	
6th coat	Chlorinated rubber system paint			

CURING

For a coating to be effective, it must be properly cured. Unless this is allowed to take place, the coating will not provide the protection required nor have the expected lifetime.

TABLE 4.4
Solvents that Affect Organic Resins

Resin	Heat-Distortion Point (°F)	Solvents that Affect Surface
Acetal	338	None
Methyl methacrylate	169–195	Ketones, esters, aromatics
Modified acrylic	170–190	Ketones, esters, aromatics
Cellulose acetate	110–209	Ketones, some esters
Cellulose propionate	110–250	Ketones, esters, aromatics, alcohols
Cellulose acetate butyrate	115–227	Ketones, esters, aromatics, alcohols
Nylon	260–360	None
Polyethylene:		
High density	140–180	None
Med. density	120–150	
Low density	105–121	
Polypropylene	210–230	None
Polycarbonate	210–290	Ketones, esters, aromatics
Polystyrene (G.P. high heat)	150–195	Some aliphatics, ketones, esters, aromatics
Polystyrene (impact, heat-resistant)	148–200	Ketones, esters, aromatics, some aliphatics
ABS	165–225	Ketones, esters, aromatics, alcohol

Most organic resins are liquid, which cure or dry to form solid films. They are classified as thermoplastic or thermosetting. Thermoplastic resins dry by solvent evaporation and will soften when heated and harden when cooled. Thermosetting resins will not soften when heated after they are cured. Most organic resins are affected by solvents. Table 4.4 lists organic resins and the solvents that affect them.

Coatings are also classified by their various film-forming mechanisms, such as solvent evaporation, coalescing, phase change, and conversion. Additionally, they are classified as room-temperature curing (sometimes called air drying) or heat curing (generally referred to as baking or force drying), which uses elevated temperatures to accelerate air-drying. Thermoplastic and thermosetting coatings can be both air-drying and baking.

Air Drying

Air-drying coatings cure at room or ambient temperatures, forming films. The films are formed by one of three mechanisms:

1. *Solvent evaporation.* Shellac and lacquers such as nitrocellulose, acrylic, styrene-butadiene, and cellulose acetate thermoplastic resins form films by solvent evaporation.

2. *Conversion.* As solvents evaporate, films are formed that are cured by oxidation, catalysis, or cross-linking. Thermosetting coatings cross-link to form film at room temperature by catalysis or oxidation. The addition of catalysts will accelerate the oxidative curing of drying oils and oil-modified resins. Monomeric materials can form films and cure by cross-linking with polymers in the presence of catalysts, as in the case of styrene monomers and polyester resins. Epoxy resins will cross-link with polyamine resins to form films and cure. Airborne moisture starts a reaction in the vehicle of polyurethane resin coating systems resulting in film formation and cure.
3. *Coalescing.* Emulsion or latex coatings, such as styrene-butadiene, acrylic ester, and vinyl acetate acrylic, form films by coalescing and dry by solvent evaporation.

Baking

Coatings requiring baking will form films at room temperature but require elevated temperatures of 300 to 372°F (150 to 200°C) to cure. Curing is either by conversion or phase change.

Conversion

Heating accelerates the cure of many oxidative thermosetting coatings. In resin systems such as thermosetting acrylics and alkyd melamines, the reactions will not take place below a temperature of 275°F (135°C). Coatings that require heat for curing are generally tougher than air-drying coatings. In some cases, the cured films are so hard that they must be modified with other resins.

Phase Change

Polyolefins, waxes, and polyamides are thermoplastic coatings that form films by phase changes — generally from solid to liquid, then back to solid. Plastisols and organisols undergo phase changes during film formation. Fluidized bed powder coatings, both thermoplastic and thermosetting, also undergo changes during film formation and cure.

Force Drying

The cure rate of many thermoplastic and thermosetting coatings can be accelerated by exposure to elevated temperatures that are below those considered as baking temperatures.

Reflowing

Certain thermoplastic coating films will soften and flow, becoming smooth and glossy at elevated temperatures. The automotive industry uses this technique on acrylic lacquers to eliminate buffing.

Radiation Curing

Bombardment with ultraviolet and electron-beam radiation with little increase in temperature will form and cure films. However, infrared radiation increases the surface temperature and is therefore considered a baking process.

Vapor Curing

This method is used for two-component coatings. The substrate is coated with one component of the coating in the conventional manner. It is then placed in an enclosure filled with the other component — a curing agent in vapor form — where the catalysis or cross-linking conversion takes place.

Inspection

The most important part of a coating operation is to guarantee that the coating has been properly applied. It is better to have a less effective coating applied properly than the best coating applied poorly.

There are a wide variety of aids, standards, and inspection instruments available to check the quality of the coating system. These include devices for checking the cleanliness of a prepared surface; the depth of a blast-cleaning anchor pattern or profile; and various magnetic, eddy current, and non-destructive thickness gauges (capable of measuring the total coating thickness or the thickness of each coat in a multicoat system). In addition, there are instruments available to monitor temperature, humidity, and dew point on a continuous basis.

After application, adhesion tests and holiday tests (for pinholes and other discontinuities) can also be specified.

It is also important to realize that even if properly applied, the coating does not last forever. During the first 6 to 12 months after application, visual inspection will be able to detect inadvertent misses, thin spots, or weak areas in the coating. Repair, if required, should be done at this time.

As time passes, the coating will break down and deteriorate as a result of the environment. Because of this, scheduled inspections should be conducted. Localized areas of failure should be touched up before deterioration of the entire surface occurs.

If a scheduled maintenance program of periodic touch-up, followed occasionally by a full coat over the entire area, is followed, the expensive costs of total surface preparation (such as complete media blasting for removal of all old coating) can be avoided, sometimes for a period of 30 years or more.

Corrosion protection by coatings can be economically achieved for long periods of time if the entire coating procedure is followed from beginning to end, starting with a definition of the environment, selection of the proper coating system, proper surface preparation and application, inspection, and periodic maintenance and repair.

5 Composition of Paint

INTRODUCTION

The most commonly used organic coating is paint. When applied for corrosion protection, paints are referred to as coatings. Paints consist of binders, pigments, fillers, additives, and solvents.

Organic coatings can protect metal structures against a specific or otherwise corrosive environment in a relatively economical way. The degree of protection depends on a number of properties of the total coated system, which consists of paint film, the metal substrate, and its pretreatment.

Paints and coatings are based on naturally occurring compounds, synthetic materials, or a mixture of both. The natural type systems are based on asphaltic, bituminous materials, or on natural oils, such as those produced from rice, fish, etc. The latter group is composed of the original "oleoresinous" paints although the term has much broader meaning today. The older systems are much more tolerant of poor surface preparation and contamination than the more modern synthetic paints.

Coating systems are classified according to the generic type of binder or resin, and are grouped according to the curing or hardening mechanism inherent in that generic type. Although the resin or organic binder of the coating material has the predominant effect on the resistances and properties of the paint, the type and quantity of pigments, solvents, and additives have an influence on the application properties and protective ability of the applied film. In addition, systems can be formulated that are crosses between the categories. For example, the acrylic monomer or prepolymer can be incorporated with practically any other generic resin to produce a product having properties that are a compromise between the acrylic and original polymer.

Modern synthetic coatings are based on a variety of chemistries. They usually require more sophisticated surface preparation and application than the natural type systems.

Today's paints and coatings must be in compliance with volatile organic compounds (VOC) restrictions and U.S. OSHA regulations. Some states and local municipalities have imposed even stricter limits.

As indicated, the composition of the paint film itself has a major influence on the corrosion protection provided by the coating. This chapter discusses the major constituents of organic systems. More detailed information can be found in References 1 and 2.

BINDER

The binder or resin forms the matrix of the coating, the continuous polymeric phase in which all other components can be incorporated. The resin is the film-forming agent of the paint. Its density and composition are primarily responsible for determining the permeability, chemical resistance, and ultraviolet (UV) resistance of the coating.

A continuous film is formed either by physical curing, chemical curing, or a combination of the two. A typical physical curing process is the sintering of thermoplastic powder coatings. Prior to application, this type of paint consists of a large number of small binder particles. After depositing these particles on a metal surface, they are baked in an oven to form a continuous film by sintering.

Chemical curing involves film formation through chemical reaction. These reactions can either be reactive curing or oxidative curing. In reactive curing, a polymer network is formed through polycondensation or polyaddition reactions. This may be the case with multicomponent coatings where the binder reacts with cross-linkers. In oxidative curing, oxygen from the atmosphere reacts with the binder monomers, causing polymerization.

It is not uncommon for both physical and chemical curing to take place, as in the case with the film formation of thermosetting powders. At elevated temperatures, physical sintering of the particles takes place, followed by chemical reactions between different components in the powder. Another example is film formation of solvent-based reactive coatings, such as common house paints. With these paints, the solvent physically evaporates from the curing film, causing the binder molecules to coalesce and start chemical polymerization reactions.

PIGMENTS

The addition of pigments serves two purposes. First, they provide color to the coating system to improve its aesthetic appeal; and second, they can be added to improve the corrosion protection properties of the coating. This latter improvement can be obtained, for example, by incorporating flake-shaped pigments parallel to the substrate surface. When a large volume concentration is used, the flakes will hinder the permeation of corrosive media into the coating by elongating their diffusion pathways.

Alternatively, anti-corrosion pigments can be added that will provide active protection against corrosive attack. These pigments tend to dissolve slowly in the coating and provide protection by covering corrosion-sensitive sites under the coating; by sacrificially corroding themselves, thereby protecting the substrate metal; or by passivating the surface.

Blocking pigments can adsorb at the active metal surface, thereby reducing the active area for corrosion and forming a transport barrier for ionic species to and from the substrate. Typical of this type is a group of alkaline pigments such as lead carbonate, lead sulfate, and zinc oxide. These can form soaps via interaction with organic oils.

Galvanic pigments are metal particles that are non-noble relative to the metal substrate. On exposure, these particles (zinc dust on steel) corrode preferentially, while at the original metal surface only the cathodic reaction takes place.

Passivating pigments reconstruct and stabilize the oxide film on the exposed metal substrate. Chromates (e.g., zinc chromate, strontium chromate) with limited water solubility are used for this purpose. In aqueous systems they may cause anodic passivation of a metal surface with a very stable chromium-and-oxygen containing layer.

Color or hiding pigments are selected to provide aesthetic value, retention of gloss and color, as well as help with film structure and impermeability. Examples include iron oxides, titanium dioxide, carbon or lampblack, and others.

Pigments must be compatible with the resin and should also be somewhat resistant to the environment; for example, calcium carbonate, which is attacked by acid, should not be used in an acidic environment. Water-soluble salts are corrosion promoters, so that special low-salt-containing pigments are used as primers for steel.

For special protective properties, primers contain one of three kinds of pigments as follows:

1. *Inert or chemically resistant.* These are for use in barrier coatings in severe environments such as conditions below an acidity of pH 5 or above an alkalinity of pH 10, or as a nonreactive extender, hiding or color pigments in neutral environments.
2. *Active.* Leads, chromates, or other inhibitive pigments are used in linseed oil/alkyd primers.
3. *Galvanically sacrificial.* Zinc is employed at high concentrations to obtain electrical contact for galvanic protection in environments between pH 5 and 10.

Types and characteristics of these pigments are presented in Table 5.1.

SOLVENTS

The purpose of the solvent is to reduce the viscosity of the binder and other components so as to enable their homogeneous mixing. In addition, the reduced viscosity makes it possible to apply the coating as a thin, smooth, continuous film on a specific surface. The roles of the solvent in a coating prior to application and after application are contradictory. In the liquid state, before application, paint should form a solution or a stable dispersion or emulsion of binder, pigments, and additives in the solvent. All solid components should remain more or less homogeneously distributed in the liquid phase. This requires high compatibility between solvents and components and the presence of repulsive forces between components to avoid clustering. In contrast, after the paint has been applied, a major attractive force between the components is necessary for the formation of a continuous film. The interaction with the solvent should decrease

TABLE 5.1
Characteristics of Pigments for Metal Protective Paints

Pigment	Specific Gravity	Color	Opacity	Specific Contribution to Corrosion Resistance
		Active Pigments		
Red lead	8.8	Orange	Fair	Neutralizes film acids, insolubilizes sulfates and chlorides, renders water noncorrosive
Basic silicon lead chromate	3.9	Orange	Poor	Neutralizes film acids, insolubilizes sulfates and chlorides, renders water noncorrosive
Zinc yellow (chromate)	3.3	Yellow	Fair	Neutralizes film acids, anodic passivater, renders water noncorrosive
Zinc oxide (French process)	5.5	White	—	Neutralizes film acids, renders water noncorrosive
Zinc dust at low concentration in coatings for steel	7.1	Gray	Good	Neutralizes film acids
		Galvanically Protective Pigments		
Zinc dust sacrificial at high concentration	7.1	Gray	Good	Makes electrical contact, galvanically sacrificial
		Barrier Pigments		
Quartz	2.6	Nil	Translucent	Insert, compatible with vinyl ester additives
		Extenders		
Mica	2.8	Nil	Translucent	Impermeability and inertness
Talc	2.8	Nil	Translucent	Impermeability and inertness
Asbestine	2.8	Nil	Translucent	Impermeability and inertness
Barytes	4.1	Nil	Translucent	Impermeability and inertness
Silica	2.3	Nil	Translucent	Impermeability and inertness
Iron oxide	4.1	Red	—	Impermeability and inertness
Iron oxide	4.1	Ochre	—	Impermeability and inertness
Iron oxide	4.1	Black	—	Impermeability and inertness
Titanium dioxide	4.1	White	Excellent	Impermeability and inertness
Carbon black	1.8	Black	Good	Impermeability and inertness

Note: Titanium dioxide has better "hiding" than any other pigment.

Source: Tator, K.B., "Coating," in Schweitzer, P.A., Ed., *Corrosion and Corrosion Protection Handbook*, *2nd ed.*, Marcel Dekker, New York, 1989, pp. 466–467.

to enable the solvent to evaporate from the curing film. To achieve optimum storage and application properties, a correct choice of additives is vital. Correct material selection for coating formulation is often a complicated operation, where elaborate practical experience is a requirement.

Organic solvents (water is considered either a solvent or an emulsifier) usually are required only to apply the coating and, after application, are designed to evaporate from the wet paint film. The rate at which the solvents evaporate strongly influences the application characteristics of the coating; and if the solvents are partially retained and do not completely evaporate, quite often the coating will fail prematurely due to blistering and pinholing. As a general rule, the synthetic resins (vinyls, epoxies, chlorinated rubbers, etc.) are more polar and therefore more readily dissolve in polar solvents. However, polar solvents are more apt to be retained by a polar resin system and therefore, when using such resins, particularly in immersion service, it is imperative that sufficient time is allowed for the coating to cure or dry. Because these resins depend more on solvents for penetration and flow, they require a greater degree of surface preparation than do oleoresinous or oil-modified coatings.

Coatings are usually formulated to be applied at ambient conditions of approximately 75°F (24°C) and 50% relative humidity. If ambient conditions are considerably higher or lower than these optimum ranges, then the solvent balance should be modified to provide for better coating application and solvent release. In colder weather, faster evaporating solvents should be used; and conversely in hot weather, slower evaporating solvents are required. Classes and characteristics of some common solvents are shown in Table 5.2.

In some cases, organic paint can be mixed and applied without the presence of solvents. These paint systems are referred to as "solvent-free." Examples of this are low-viscosity, two-component epoxies and powder coatings. The application and curing of powder coatings was discussed previously. The epoxy coatings can be mixed and applied without the use of a solvent, as the two components typically have low viscosity. Mixing and application of these coatings are often done at elevated temperatures to reduce the viscosity as much as possible.

ADDITIVES

Most additives are formulated into paint often in trace amounts to provide a specific function. For example, cobalt and manganese naphthanates are used as dryers for alkyds and other oil-based coatings to facilitate surface and thorough drying. These drying additives are added to the paint in amounts usually less than 0.1%.

Other additives are incorporated into the formula for different purposes. For example, zinc oxide can be added to retard deterioration of the resin by heat and actinic rays of the sun. Mildew inhibitors (phenylmercury, zinc, and cuprous compounds) are commonly added to oil-based and latex paints. Latex paints (water emulsion) invariably have a number of additives acting as surfactants, coalescing aids, emulsion stabilizers, etc. Vinyl paints often have a 1% carboxylic acid (generally maleic acid) modification to the vinyl resin to promote adhesion

TABLE 5.2
Characteristics of Solvent Classes

Class	Solvent Name	Strength/Solvency	Polarity	Specific Gravity	Boiling Range (°F)	Flash Point of TCC	Evaporation Rate[a]
Aliphatic	VM & P naphtha	Low (32 KB)[b]	Nonpolar	0.74	246–278	52	24.5
	Mineral spirits	Low (28 KB)	Nonpolar	0.76	351–395	128	9.0
Aromatic	Toluene	High (105 KB)[c]	Intermediate polarity	0.87	230–233	45	4.5
	Xylene	High (98 KB)	Intermediate polarity	0.87	280–288	80	9.5
	High solvency	High (90 KB)	Intermediate polarity	0.87	360–400	140	11.6
Ketone	Methyl ethyl ketone (MEK)	Strong	High polarity	0.81	172–176	24	2.7
	Methyl isobutyl ketone (MIBK)	Strong	High polarity	0.80	252–266	67	9.4
	Cyclohexanone	Strong	High polarity	0.95	313–316	112	4.1
Ester	Ethyl acetate	Intermediate	Intermediate polarity	0.90	168–172	26	2.7
Alcohol	Ethanol	Weak	Intermediate polarity	0.79	167–178	50	6.8
Unsaturated aromatic	Styrene	Strong	Intermediate polarity	0.90			
Glycol	Cellosolve	Strong	High polarity	0.93	273–277	110	0.3
ethers	Butyl cellosolve	Strong	High polarity	0.90	336–343	137	0.06

[a] Butyl acetate equals 1.

[b] KB, Kauri-Butanol; a measure of solvent power of petroleum thinners (milliliters of thinner required to produce cloudiness when added to 20 g of a solution of karigum in butyl alcohol).

[c] TCC-TAE closed up.

to metals. Conversely, hydroxyl modification (generally an alcohol) aids in adhesion of vinyls to organic primers. The use of a particular additive can be critical to the performance of the paint; and because additives are usually added in trace amounts, they may be most difficult to detect upon analysis of the paint.

FILLERS (EXTENDERS)

The primary function of fillers in organic coatings is to increase the volume of the coating through the incorporation of low-cost materials such as chalk or wood dust. They can also be used to improve coating properties such as impact and abrasion resistance and water permeability.

In addition to lowering the cost, extenders also provide sag resistance to the liquid paint so that the edges remain covered. When the paint has dried, they reduce the permeability to water and oxygen and provide reinforcing structure within the film. Talc and mica are used extensively as extenders. Mica is limited to approximately 10% of the total pigment. Both talc and mica, but particularly mica, reduce the permeability through the film as plate-like particles block permeation, forcing water and oxygen to seek a longer path through the binder around the particle.

REFERENCES

1. R.A. Dickie, R.A., *ACS, Symp. Ser.,* 285, 773, 1985.
2. Wilson, A.D., Nicholson, J.W., and Prosser, H.Y., Eds. *Surface Coatings 1 and 2,* Elsevier Applied Science, Amsterdam, 1985.

6 Coating Materials (Paints)

Coating systems are defined by generic type of binder or resin, and are grouped according to the curing or hardening mechanism of that generic type. The organic binder or resin of the coating material is primarily responsible for determining the properties and resistances of the paint. However, the type and amount of pigments, solvents, and additives also have an influence on the application properties and protective properties of the applied film, as discussed in the previous chapter.

In addition, hybrid systems can be formulated that are crosses between generic categories. For example, the acrylic monomer or prepolymer can be incorporated with practically any other generic type of resin to produce a paint with properties that are a compromise between the acrylic and the original polymer. This is advantageous in many cases, such as the mixing of vinyls and acrylics or heat-curing alkyds and acrylics.

Distinction should be made between zinc-pigmented paints and zinc-rich paints. In the former, pigments constitute approximately 80% of the paint, of which 20% is ZnO_2. Zinc-rich coatings have loadings of zinc dust, usually over 90% by weight. These coatings provide excellent galvanic protection in aggressive environments. They are available as inorganic or organic zinc, the difference being the vehicle in which the zinc fillers are carried. Silicates are common vehicles for inorganics. Chlorinated rubber, catalyzed epoxy, polystyrene, and polyurethane are the recommended organic vehicles for zinc. Zinc-rich coatings have a long life and are more economical than some other high-quality three-coat systems. They are used to protect ship hull superstructures, marine structures, highway bridges, chemical plant equipment, and other installations exposed to high humidity and salt.

Paints are broadly classified as primers and topcoats. Primers are applied directly to the metal surface. They contain pigments of zinc and perform the primary job of corrosion protection. Topcoats are applied over the primer, mainly for the sake of appearance. However, they also provide a diffusion barrier and close the pores in the primary coat. Pores, or "holidays," are the starting points of paint failures. The application of topcoats minimizes these potential points of failure. Three to five topcoats are often recommended for industrial and marine atmospheres.

As mentioned previously, paints, whether primers or topcoats, are classified according to the type of resin used as the vehicle in the paint formulation. Among the most commonly used synthetics are alkyds, phenolics, chlorinated rubber, vinyls, and epoxies. Alkyd resins find wide application in the protection of home appliances and machinery due to their fast drying property and durability in atmospheric exposures. Phenolic finishes have excellent resistance to acids, chemicals, moisture, and cold alkalies. Vinyls and chlorinated rubber have the widest range of resistance to corrosives, from strong acids to strong alkalies, and have good resistance to penetration by water. Epoxies are also resistant to alkalies and many other chemical media. Table 6.1

TABLE 6.1
Properties of Paints

Coating Type	Resistance to: UV	Weather	Acid	Alkali	Moisture	Salt Solutions	Comments
Vinyls dissolved in esters, aromatics, or ketones			R	R	R	R	Adhesion may be poor until all solvents have vaporized from the coating
Chlorinated rubbers dissolved in hydrocarbon solvents	N		R	R	R		Excellent adhesion to metals, concrete, and masonry Used on structures exposed to water and marine atmospheres
Epoxies, polyamine plus epoxy resin	N		PR	PR	R	PR	Harder and less flexible than other epoxies Greatest chemical resistance of the epoxies
Polyamide plus epoxy resin (polyamide epoxy)	N		PR	PR	R	PR	Chemical resistance inferior to that of the polyamine epoxies
Aliphatic polyamine			PR	PR		PR	Flexible film
Esters of epoxies and fatty acids (epoxy esters)	R	R	PR	N		PR	On surfaces requiring the properties of a high quality oil-based paint
Coal tar plus epoxy resin	N	N	R		R		Used on clean, blast-cleaned steel for immersion or below grade service Attacked by organic solvents
Oil-based coatings with vehicle (alkyd epoxy, urethane)	R	R		N			Lower cost than most coatings Used on exterior wood surfaces
Urethane, moisture cured	R	R	Weak R	Weak R	R		May yellow under UV light High gloss and ease of cleaning
Urethanes catalyzed	R	R	R	R	R	R	Expensive Used as coating on steel in highly corrosive areas

Silicones, water repellent in water or solvent	R	R	N	N	R		Used on masonry surfaces
Silicones, water-based aqueous emulsions of polyvinyl acetate, acrylic or styrene-butadiene latex	R	R	N	N			May flash rust as a primer on steel Not chemically resistant
Polyesters, organic acids combined with polybasic alcohols Styrene is a reaction diluent	PR	R	R	N			Must be applied with special equipment Not suitable for use with most aromatic solvents
Coal tar	N	N	Weak R	Weak R	R		Used submerged or buried steel
Asphalt. Solids from crude oil refining in aliphatic solvents	R	R	Weak R	Weak R	R	Weak R	Used in above-ground weathering environments and chemical fume atmospheres
Zinc-rich metallic zinc in an organic or inorganic vehicle							Provides galvanic protection as a primer
Acrylic-resin water emulsion base	R	R	Weak R	Weak R			Limited penetrating power May flash rust as a primer over bare steel Not suitable for immersion service. Soluble in ketones, esters, aliphatic chlorinated hydrocarbons, and aromatic hydrocarbons

Note: R, resistant; N, not resistant; Pr, poor resistance

shows the resistance of various coatings exposed to several environments. The various types of paint/coating systems in current use have temperature limitations as shown in Table 6.2.

The most commonly used paint systems are covered in detail in the following sections.

ETCHING PRIMER (WASH PRIMER)

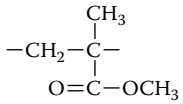
An etching primer is used to improve the adhesion of a paint over-coat. A typical etching primer composition is as follows:

Main Ingredients	**Wt. %**
Polyvinylbutyral resin	7.2
ZTO type zinc chromate	6.9
Talc alcohol	1.1
99% Isopropanol or 95% ethane	48.7
Butyl alcohol	16.1
Additives	
Phosphoric acid	3.6
Water	3.2
Isopropanol	13.2

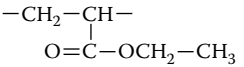
Chromic acid ions are reduced to form complex chromium phosphate compounds in the paint. Chromium phosphate compounds combine with polyvinylbutyral and then form chromium-containing polymers. The structure of etching primer coated steel is: steel substrate–iron oxide–zinc phosphate (at defects in iron oxide film), chromium phosphate–composite of chromium, and polyvinylbutyral–polyvinylbutyral.

ACRYLICS

Acrylics can be formulated as thermoplastic resins, thermosetting resins, and as a water emulsion latex. The resins are formed from polymers of acrylate esters, predominantly polymethyl methacrylate and polyethyl acrylate. The acrylate resins do not contain tertiary hydrogens attached directly to the polymer backbone chain and, as a result, are exceptionally stable to oxygen and ultraviolet light deterioration. The repeating units of the acrylic backbone are joined to make long polymer chains. The repeating units for the methacrylate and the acrylate are as follows:



Polymethylmethacrylate



Polyethylacrylate

TABLE 6.2
Temperature Limitations of Paints

	Maximum Temperature (°F/°C)	
Paint	**Dry**	**Wet**
Alkyds	225/105	150/66
Chlorinated rubber	200/93	120/49
Coal tar epoxy	225/107	150/66
Oil based paints	225/107	150/66
Polyamine epoxy	225/107	190/90
Aliphatic amine epoxy	225/107	150/66
Polyamide epoxy	225/105	150/66
Urethanes:		
Moisture cured	250/121	150/66
Catalyzed	225/107	150/66
Polyesters	180/82	180/82
Vinyls	180/82	140/60
Water soluble resins	150/66	150/66
Emulsion coatings	150/66	150/66
Zinc rich	>700/370	700/370
Silicones:		
Aluminum formulation	1200/649	—
Phenolics	150/66	—

A wide range of monomers is available for use in designing a specific acrylic system. Typically, mixtures of monomers are chosen for the properties they impart to the polymer. The glass transition temperature T_g of the polymer can be varied by selecting the proper monomers. This permits a varied area of application. Table 6.3 illustrates the wide range of T_g values resulting from the different monomer compositions for emulsion acrylics.

TABLE 6.3
Glass Transition Temperature vs. Application Area

T_g (°C/°F)	Application Area
80–100/176–212	High heat resistant coatings
50–65/122–149	Floor care coatings
35–50/95–122	General industrial coatings
10–40/50–100	Decorative paints

Acrylics can be formulated as lacquers, enamels, and emulsions. Lacquers and baking enamels are used as automotive and appliance finishes. In both of these, acrylics are used as topcoats in multicoat finishing systems.

Thermosetting acrylics have replaced alkyds in applications requiring greater mar resistance, such as appliance finishes. Acrylic lacquers are brittle and therefore have poor impact resistance but their outstanding weather resistance allowed them to replace nitrocellulose lacquers in automotive finishes for many years. Acrylics and modified acrylic emulsions have been used as architectural coatings and also on industrial products. These medium-priced resins can be formulated to have excellent hardness and adhesion, as well as abrasion, chemical, and mar resistance. When acrylic resins are used to modify other resins, their properties are imparted to the resulting resin system.

Acrylic resins, particularly the methacrylates, are somewhat resistant to acids, bases, weak and moderately strong oxidizing agents, and many corrosive industrial gases and fumes. This resistance is mostly because the polymer backbone comprises only carbon atoms. However, pendant side-chain ester groups, although quite resistant to hydrolysis, preclude the use of these resins in immersion service or in strong chemical environments. The resins are generally soluble in moderately hydrogen-bonded solvents such as ketones, esters, aliphatic chlorinated hydrocarbons, and aromatic hydrocarbons.

Acrylics exhibit excellent light and ultraviolet stability, gloss and color retention, good chemical resistance, and excellent weathering resistance. They are also resistant to chemical fumes, and occasional mild chemical splash and spillage. Upon prolonged exposure to ultraviolet light, they will show minimum chalking and little, if any, darkening.

Acrylic resins are generally quite compatible with most other resins (depending on the type of acrylic) and the properties of many other resinous materials (such as alkyds, chlorinated rubbers, epoxies, and amino resins) are often modified with the acrylic to improve application, lightfastness, gloss, and/or color retention.

Thermoplastic and water emulsion acrylics are not suitable for any immersion service or any substantial acid or alkaline chemical exposure. Most acrylic coatings are used as topcoats in atmospheric service. With cross-linking, greater chemical resistance can be achieved. Cross-linked acrylics are the most common automotive finish.

ALKYD RESINS

Alkyd resin-based coatings were introduced in the 1930s as replacements for nitrocellulose lacquers and oleoresinous-based coatings. These resins have good durability at relatively low cost and are still used for finishing a wide variety of products, either alone or modified with oils or other resins. Their final properties are determined by the degree and type of modification. Until the 1960s they were used extensively by the automotive and appliance industries. Although the alkyds are used in outdoor exposure, they are not as durable in long-term exposure, and their color and gloss retention is inferior to that of the acrylics.

Alkyds are synthesized from three basic components: polybasic acids, polyols, and (except for oil-free alkyds) fatty acids. The nature and proportion of these components control the properties of the resin. The number of combinations is enormous and specifications of an alkyd resin must involve several parameters.

Depending on the weight percent of fatty acid in the resin, alkyds are referred to as short oil (<45%), medium oil (>55%), or long oil (≥60%). Some confusion exists regarding the percentage of triglyceride, in which case fatty acid content must be recalculated into triglyceride. The second approach can be converted into the first by dividing by 1.045.

The type of fatty acid used also governs the properties of the alkyds. The resins are classified as drying, semidrying, and nondrying, depending on the degree of unsaturation in the fatty acid residues (iodine numbers of >140, 125–140, and <125, respectively).

Oxidative drying of alkyds, which involves air oxidation of polyene structures in fatty acid residues, is at maximum around 50% oil length. After drying, film hardness is inversely proportional to the degree of fatty acid modification.

Short oil alkyds generally give films of high quality with regard to color and gloss retention but low flexibility and with poor adhesion. Long oil alkyds are usually superior in terms of pigment dispersion, rheological properties, and storage stability.

Once the mainstay of organic coatings, alkyds are still used for finishing metal and wood products. Their durability in interior exposures is generally good, but their exterior durability is only fair. Drying types provide good weathering resistance and good adhesion to a wide variety of substrates, but relatively poor resistance to chemical attack. They have a maximum temperature resistance of 225°F (107°C) dry and 150°F (66°C) wet. These paints are used on exterior wood surfaces for primers requiring penetrability and in less severe chemical environments.

Alkyd resins as a group are characterized by good adhesion and drying properties. The films produced have good flexibility and durability. By various modifications, specific properties can be improved. A weak point of alkyds is their susceptibility to alkaline hydrolysis.

Long oil alkyds are soluble in aliphatic solvents. Normally applied by brush, they are used in exterior trim paints and wall paints, as well as in marine and metal maintenance paints. They are also widely used in clear lacquers.

Medium oil alkyds are soluble in aliphatic/aromatic solvent blends. The air-drying type is used as the standard vehicle for industrial applications such as primers and undercoatings, maintenance paints, and metal finishes. The nonoxidizing type is often used as an external plasticizer in nitrocellulose lacquers.

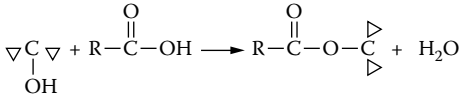
Short oil alkyds are soluble in aromatic but not aliphatic solvents. The air-drying type is used in baking primers and enamels, either as the sole binder or together with other resins, such as urea or melamine resins. The nondrying type is mainly used as plasticizing resin in nitrocellulose lacquers and in combination with urea or melamine resins in stoving and acid curing finishes.

AUTOOXIDATIVE CROSS-LINKING COATINGS

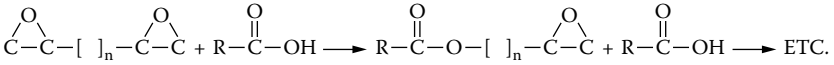
Autooxidative cross-linking coatings rely on a drying oil with oxygen to introduce crosslinking within the resin and attainment of the final film properties. The final coating is formed as a result of the drying oil reacting with the resin, which is combined with pigments and solvents. The paint is packaged in a single can, which can be opened, mixed, and the paint applied. Because oxygen reacts with the coating introducing additional cross-linking, final film properties can take weeks, or even months to attain.

Autooxidative cross-linking-type paints include alkyds, epoxy esters, oil-modified urethanes, etc. These are commonly used, when properly formulated, to resist moisture and chemical fume environments. They can be applied over wood, metal, or masonry substrates.

An example of an autooxidative coating is the epoxy ester, which is made as follows:

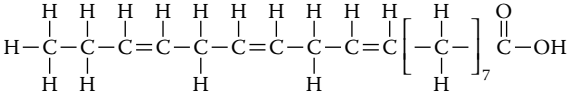


Epoxy resin Fatty acid Reaction thru hydroxyl



Reaction thru terminal epoxy

Where R is a fatty acid such as linolenic-



Or a polybasic acid (more than one carboxyl group)

The result is a large, bulky epoxy ester molecule with ester linkages in both the backbone and pendant side chains.

The major advantages of these coatings include their ease of application, great versatility, excellent adhesion (wetting by virtue of the oil modification), relatively good environmental resistance (in all but immersion and high chemical fume environments), widespread availability, and tolerance for poorer surface preparation than any of the coating systems based on synthetic resins. Their major disadvantage is the lessened moisture and chemical resistance compared with other synthetic resin coating systems.

BITUMINOUS

The bituminous systems comprise asphaltic- or coal tar-based resins, including both natural and combination natural/synthetic mixes. Coal tar coatings have good moisture resistance (which can be improved by formulating with epoxies), but are not very good in weather and have poor resistance to sunlight. Bituminous coatings are used primarily for underground protection.

Coal tar is a distilled coking by-product in an aromatic solvent. It exhibits excellent water resistance, and good resistance to acids, alkalies, and mineral, animal, and vegetable oils.

Unless cross-linked with another resin, it is thermoplastic and will flow at temperatures of 100°F (38°C) or less. It will harden and embrittle in cold weather. Available only in black color, it will alligator and crack upon prolonged exposure to sunlight, although it remains protective.

Coal tar finds application as a moisture-resistant coating in immersion and underground services. It is widely used for pipeline exterior and interior coatings below grade. And, it is relatively inexpensive.

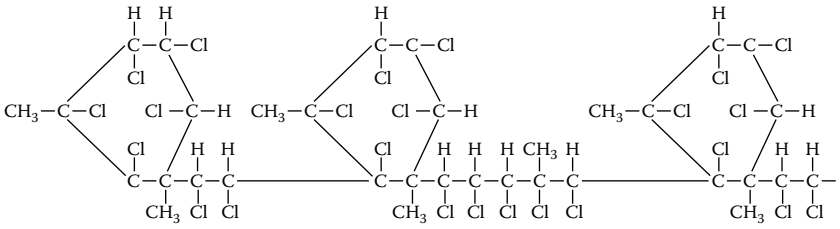
Asphalt paint consists of solids from crude oil refining suspended in aliphatic solvents. It exhibits good water resistance and ultraviolet light stability, and will not crack or degrade in sunlight. Being nontoxic, it is suitable for exposure to food products. It is resistant to mineral salts and alkalies up to 30% concentration.

Poor resistance is shown to hydrocarbon solvents, oil, fats, and some organic solvents. It does not have the moisture resistance of coal tar, can embrittle after prolonged exposure to dry environments or temperatures above 300°F (150°C), and can soften and flow at temperatures as low as 100°F (38°C). It is available only in black color.

Asphalt paint is often used as a relatively inexpensive coating in atmospheric service where coal tars cannot be used.

CHLORINATED RUBBER

Originally, chlorinated rubber resins were produced by chlorinating natural rubber. Today, the term also includes the chlorination of synthetic rubbers. The addition of chlorine to unsaturated double bonds occurs until the final product contains approximately 65% chlorine. The chemical structure of a segment of the chlorinated rubber resin is as follows:



The result is a hard, brittle material with poor adhesion and elasticity. A plasticizer must be added to produce a surface coating. Many materials can be used as a plasticizer but a nonsaponifiable plasticizer, usually of the chlorinated paraffin or chlorinated diphenyl types, is primarily used. The type and amount of plasticizer used in the chlorinated rubber are instrumental in determining the final resistance and properties of the chlorinated rubber paint. Chlorinated rubber resins are generally soluble in most organic solvents, all but aliphatic hydrocarbons and alcohols. Chlorinated rubber resins have good compatibility with a variety of other resins, including alkyds, phenolics (and medium to short oil resin modifications of each), acrylics, melamine, urea formaldehyde resins, and many other natural or synthetic resins. The addition of these materials can enhance the ease of application but might also reduce the chemical resistance. Unmodified chlorinated rubber resins are generally formulated at a high molecular weight and, accordingly, are somewhat difficult to apply by spraying. "Cob-webbing" often occurs when spraying, and brushing or roller application results in a noticeable "dray."

The volume of solids of the coating dissolved in hydrocarbon solvent is somewhat higher than that of a vinyl; therefore, a suitably protective chlorinated rubber system often consists of only three coats.

Chlorinated rubber coatings are widely used on masonry surfaces and as swimming pool paints. They, like vinyls, exhibit very good adhesion after initial through-drying (usually 3 or 4 days, up to 2 weeks after application); and the same care must be taken for solvent evaporation as described for the vinyls. The high chlorine content accounts for its inertness, its good adhesion, and its fire-retardant nature.

Chlorinated rubber paints find application in rural and mountain areas with high humidity and much snow, in urban atmospheres because of their resistance to automobile exhausts and waste gases from factories, and in marine atmospheres because of their resistance to salt spray. The chlorinated rubber paints are degraded by UV light.

Chlorinated rubber paints are chemically resistant to acids and alkalies, have a low permeability to water vapor, and are abrasion and fire resistant and nontoxic. Limitations include being degraded by UV high and being attacked by hydrocarbons.

COAL TAR EPOXY

Amine- and polyamide-cured epoxies, when combined with approximately 50% refined coal tar, are one of the least water permeable coatings available. Coal tar epoxies, because of the UV light sensitivity of coal tar pitch, are normally not used in atmospheric exposures. However, for below-grade protection (e.g., buried pipe lines) and in immersion service, they are considered excellent.

The coal tar epoxies exhibit excellent resistance to saltwater/freshwater immersion and good resistance to both acids and alkalies. Solvent resistance is also good but immersion in strong solvents may leach the coal tar.

These coatings will embrittle upon exposure to cold or UV light. Cold weather abrasion is also poor. Topcoats should be applied within 48 hours to avoid intercoat adhesion problems. Coal tar epoxy has a temperature resistance of 225°F (105°C) dry and 150°F (66°C) wet. It will not cure below a temperature of 50°F (10°C) and is available in black or dark colors only.

These coatings find applications on clean blasted steel and concrete for immersion service or below-grade service. They can be applied without a primer in thicknesses of 10.0 mil (0.25 mm) per coat.

NITROCELLULOSE

When most people think of nitrocellulose, they think of guncotton, a material that was developed for explosives or gun propellant. But they are only partially correct. Nitrocellulose is one of the oldest and most widely used film formers adaptable to a number of uses. It is derived from cellulose, a material from plants, and therefore a renewable source. Soluble nitrocellulose possesses a unique combination of properties such as toughness, durability, solubility, gloss, and rapid solvent release.

As the film former in lacquer systems, it affords protective and decorative coatings for wood and metal.

Nitrocellulose is the common name for the nitration product of cellulose. Other names include cellulose (tri)nitrate and greencotton. The commercial product is made by reacting cellulose with nitric acid. Cellulose is composed of a large number of anhydroglucose units, six-membered rings having three hydroxyl (–OH) groups attached to them. In chemically purified cellulose, the number of anhydroglucose units in the typical cellulose chain ranges from 500 to 2500.

Nitric acid can react with the three hydroxyl groups of the anhydroglucose units to form the nitrate ester. Fully nitrated cellulose would them be a trinitrate — that is, a nitrate having a degree of substitution of three. At this level, nitrocellulose does not possess properties that are useful for use as a coating. Film-forming properties are better at degrees of substitution between 1.8 and 2.3.

Nitrocellulose is divided into types according to the nitrogen content of the product, which reflects higher or lower degrees of substitution. The type containing an average of 12% nitrogen (11.8 to 12.2%) is the one used for coatings. It is available in a wide range of viscosity grades from 18 to 25 cP to 2000 seconds. This type is more tolerant of aromatic hydrocarbons, such as toluene, and less tolerant of aliphatic hydrocarbons. It is used in coatings for wood and metal, for lacquer emulsions for wood and metal, and for architectural finishes.

The generally used method of formulating nitrocellulose coating systems is to dissolve the nitrocellulose and its modifiers in a volatile solvent to form a homogenous system (with the exception of pigments and fillers). The resulting formulation can be applied to the substrate by brushing, spraying, or curtain coating. The solvent evaporates, leaving a solid film on the substrate.

True solvents are liquids that will dissolve nitrocellulose completely. For 12% nitrogen nitrocellulose, these are ketones, esters, amides, and nitroparaffin. Some solvents such as ethanol or isopropanol will not dissolve nitrocellulose on their own. They can be added to true solvents without precipitating the nitrocellulose. These are called “co-solvents.” Aliphatic and aromatic hydrocarbons are non-solvents. Termed “diluents,” they can be added in limited amounts without precipitation to lower cost and improve the solubility of resin modifiers. Aromatics can usually be added to a greater extent than aliphatics.

Resins are added in nitrocellulose coating compositions to improve the degree of film build by increasing the solids content at a given viscosity. Depth, gloss, and adhesion can also be improved by the addition of resin.

Pigments are added for producing opaque, colored finishes. Because nitrocellulose tends to be degraded in sunlight, some pigments extend the service life of films exposed to sunlight. Certain pigments should be avoided because they show alkaline reactions, which causes nitrocellulose degradation.

Unplasticized clear nitrocellulose film has the following chemical and physical properties:

Moisture absorption at 21°C in 24 hours in 80% relative humidity	1%
Water vapor permeability at 21°C	2.8 $g/cm^2/H \times 10^6$
Sunlight:	
Effect on discoloration	Moderate
Effect on embrittlement	Moderate
Aging effect of water:	
Cold	nil
Hot	nil
General resistance:	
Acids, weak	Fair
Acids, strong	Poor
Alkalies, weak	Poor
Alkalies, strong	Poor
Alcohols	Partly soluble
Ketones	Soluble
Esters	Soluble
Hydrocarbons:	
Aromatic	Good
Aliphatic	Excellent
Oils:	
Mineral	Excellent
Vegetable	Fair to Good
Animal	Good

OIL-BASED PAINTS

These paints are mixtures of pigment and boiled linseed oil or soybean oil, or other similar materials. This paint is used as a ready-mixed paint, particularly on wood surfaces because of its penetrating power. It is resistant to weather but has relatively poor chemical resistance and will be attacked by alkalies. Its temperature limitations are 225°F (108°C) dry and 150°F (66°C) wet.

Oil-based paints are used on exterior wood surfaces, for primers requiring penetrability and in less severe chemical environments.

TABLE 6.4
Properties of Nylon Coatings

Property	Nylon 11	Nylon 6/6	Nylon 6
Elongation (73°F), %	120	90	50–200
Tensile strength (73°F), lb/in.^{2}	8500	10,500	10,500
Modulus of elasticity (73°F), lb/in.$^2 \times 10^3$	175	400	350
Rockwell hardness, R	100.5	118	112–118
Specific gravity	1.04	1.14	1.14
Moisture absorption, % ASTM D-570	0.4	1.5	1.5–2.3
Thermal conductivity, Btu/ft^{2}h/°F/in.	1.5	1.7	1.2–1.3
Dielectric strength (short term), V/mil	430	385	440
Dielectric constant (10 Hz)	3.5	4	4.8
Effect of:			
Weak acids	None	None	None
Strong acids	Attack	Attack	Attack
Strong alkalies	None	None	None
Alcohols	None	None	None
Esters	None	None	None
Hydrocarbons	None	None	None

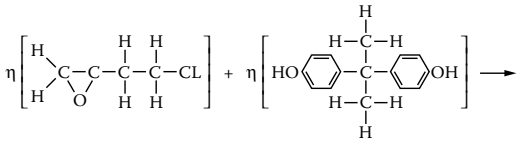
POLYAMIDES

One of the more notable polyamide resins is nylon, which is tough, wear-resistant, and has a relatively low coefficient of friction. Application can be as a powder coating by fluidized bed, electrostatic spray, or flame spray. Nylon coatings usually require a primer. Film properties can be adjusted by selecting the appropriate polyamide. Table 6.4 compares the properties of three types of nylon polymers used in coatings.

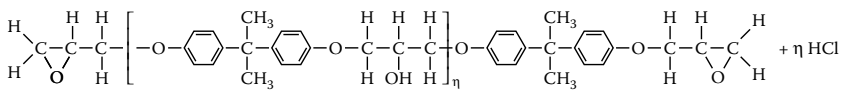
Polyamide coatings are used to provide a high degree of toughness and mechanical durability to office furniture.

EPOXIES

The epoxy resin itself is a common condensation product of epichlorhydrin and bisphenol acetone.



Epichlorhydrin Bisphenol acetone

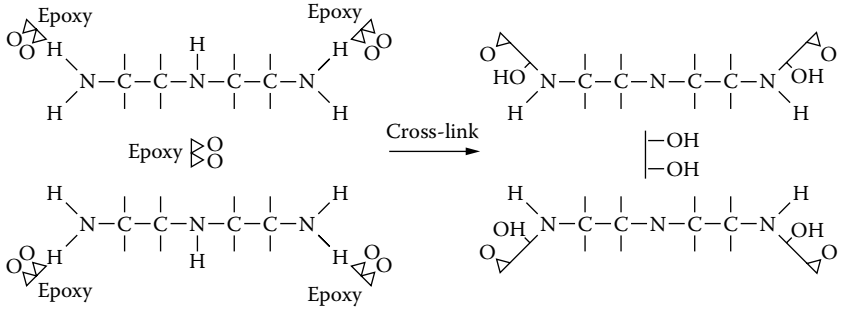


Epoxy resins themselves are not suitable for protective coatings because when pigmented and applied, they dry to a hard, brittle film with very poor chemical resistance. However, when properly co-polymerized with other resins (particularly those of the amine or polyamine family) or esterified with fatty acids, epoxy resins will form a durable protective coating.

The epoxy resin can react through pendant hydroxyl groups or the terminal oxirane ring. The properties of the final film will depend on the molecular weight of the expoxy used, the co-reacting resin, and modifiers such as phenolic resins or coal tar.

Polyamine Epoxies

Amine resins, usually diethylene triamine or triethylene tetramine, or similar aliphatic polyamines react to give a relatively highly cross-linked chemically resistant but hard-curing and relatively inflexible film. The following structure is that of an epoxy cross-linked with amine (e.g., diethyltriamine).



Active hydrogens from the amine nitrogen react to open epoxy rings forming hydroxyl groups, thereby cross-linking the nitrogen atom with the epoxy carbon.

Amine-cured epoxies have the widest range of chemical and solvent resistance of any of the epoxies. They exhibit excellent resistance to alkalies, most organic and inorganic acids, water, and aqueous salt solutions. Resistance to solvents and oxidizing agents is good as long as not continually wetted. These epoxies are harder and less flexible than other epoxies and are intolerant of moisture during application. Coating will chalk on exposure to UV light. Strong solvents may lift coatings. Temperature limitations are 225°F (105°C) dry and 190°F (90°C) wet. The resin will not cure below 40°F (5°C) and should be topcoated within 72 hours to avoid intercoat delamination. Maximum properties require a curing time of 7 days.

Aliphatic Amines

The hydroxyl groups of the polyamine epoxy may also open the epoxy ring to further cross-linking and eliminate H_2O. Note that there are no ester links. Increased

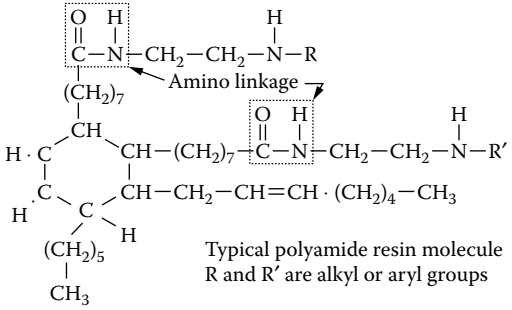
flexibility with only a slight loss of chemical resistance can be achieved by prereacting some of the epoxy resin with an aliphatic polyamine during paint manufacture. At the time of application, the prereacted resin is mixed with additional amine and applied. Paints formulated in this way are called amine adducts.

These amines are partially resistant to acids, acid salts, and organic solvents, with a temperature limitation of 225°F (108°C) dry and 150°F (66°C) wet. The film formed has greater permeability than that of the other epoxies. These paints are used for protection against mild atmospheric corrosion.

Polyamide Epoxies

Polyamide resins can also react with epoxies to form durable protective coatings. These resins are somewhat bulkier than the amines by virtue of their fatty acid modification. Consequently, they impart more flexibility to the cross-linked resin. Polyamide-cured epoxies are also more resistant to chalking, and are more receptive to top-coating after extended periods of time than are amine-cured epoxies.

Polyamide adducts can be made in a manner similar to that described for amine adducts. Cross-linking takes place by opening the epoxy ring with active hydrogens from the polyamide nitrogen in the manner illustrated for amine epoxies. A typical polyamide with epoxy resin is as follows:



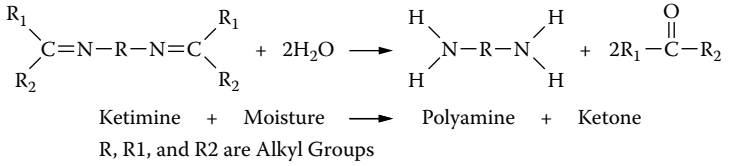
Typical polyamide resin molecule
R and R′ are alkyl or aryl groups

Polyamide epoxies exhibit inferior chemical resistance to that of the polyamine epoxies. They are only partially resistant to acids, acid salts, alkalies, and organic solvents. However, they do have superior water resistance.

The polyamide epoxies are more flexible and tougher than the polyamines, have excellent adhesion, gloss, hardness, impact, and abrasion resistance with a temperature limitation of 225°F (105°C) dry and 150°F (66°C) wet. They are not resistant to UV light.

Ketimine-cured epoxies enable the application of a solventless or 95 to 100% high-solids epoxy coating with standard spray application equipment. A ketimine under dry conditions reacts very slowly with epoxy resins; but in the

presence of water or humidity, the ketimine reacts to decompose into polyamine and a ketone.



The ketone evaporates and the polyamine then reacts with the epoxy resin in normal fashion. Ketimine-cured epoxies should not be applied at thicknesses greater than 8 mil or so, and in one coat to allow moisture access and complete curing.

POLYVINYL BUTYRAL

The inherent properties of adhesion to a wide variety of surfaces, film toughness, and chemical/solvent resistance, and film clarity of the polyvinyl butyral resins make them the vehicle of choice in a wide variety of specialty coating applications. They adhere tenaciously to most polar surfaces, including wood, glass, metals, ceramics, pigments, etc. Their high binding efficiency allows their use at very high pigment loadings.

Polyvinyl butyrals are used extensively as wood coatings, where their resistance to natural wood oils makes them a primary choice for sealers and wash coats. An example of an application is the Western Pine Association's Knot Sealer number WP578.

Polyvinyl butyrals are also used in the manufacture of wash primers for the priming of metal surfaces to be used in hostile environments (e.g., the hulls of naval vessels). There are a number of formulations available, both single- and two-package systems. Another example of a metal coating based on polyvinyl butyral is metal coating 2009, which can be applied by spray or roller.

POLYVINYL FORMAL

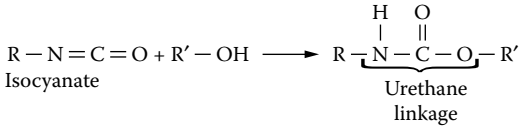
Polyvinyl formal, available in several viscosity grades from Monsanto as Formvar, is widely used as an oil-resistant insulating coating for magnetic wire. For this application, it is normally cross-linked by formulating with phenolic, epoxy, or urethane resins to enhance properties. These coatings are tough, strongly adhering, abrasion resistant, and totally impervious to hydrocarbon oils and lubricants.

In general, polyvinyl formal is higher in modulus and less susceptible to solvent attack than polyvinyl butyral. Films are somewhat yellow, thereby reducing their utility in applications calling for a colorless film.

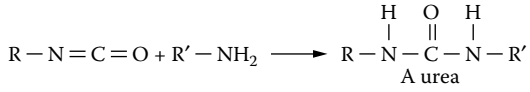
POLYURETHANES

Urethanes are reaction products of isocyanates with materials possessing hydroxyl groups, and simply contain a large number of urethane groups, regardless of what the rest of the molecule may be.

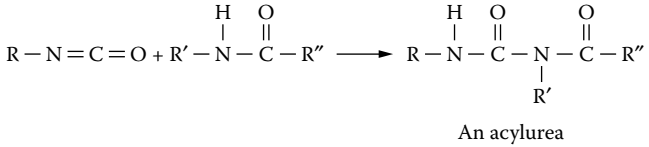
1. With hydroxyl-bearing polyesters, polyethers, epoxies, etc.:



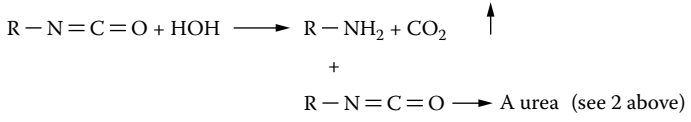
2. With an amine:



3. With an amide:



4. With moisture:



The polyol side (hydroxyl containing) may consist of a number of materials, including water (moisture-cured urethanes), as well as epoxies, polyesters, acrylics, and drying oils. Epoxy and polyesters polyols are more chemical and moisture resistant than acrylic polyols. The acrylic polyol, however, when suitably reacted to form a urethane coating, is entirely satisfactory for most weathering environments. The isocyanate can be either aliphatic or aromatic.

Polyurethane resin-based coatings are very versatile. They are higher priced than alkyds but lower in price than epoxies. Polyurethane resins are available as oil modified, moisture curing, blocked, two-component, and lacquers. Table 6.5 is a selection guide for polyurethane coatings. Two-component polyurethanes can

TABLE 6.5
Properties of Urethane Coatings

	One-Component				
Property	Urethane Oil	Moisture	Blocked	Two-Component	Lacquer
Abrasion resistance	Fair–Good	Excellent	Good–Excellent	Excellent	Fair
Hardness	Medium	Medium–Hard	Medium–Hard	Soft–Very Hard	Soft–Medium
Flexibility	Fair–good	Good–Excellent	Good	Good–Excellent	Excellent
Impact resistance	Good	Excellent	Good–Excellent	Excellent	Excellent
Solvent resistance	Fair	Poor–Fair	Good	Excellent	Poor
Chemical resistance	Fair	Fair	Good	Excellent	Fair–Good
Corrosion resistance	Fair	Fair	Good	Excellent	Good–Excellent
Adhesion	Good	Fair-Good	Fair	Excellent	Fair–Good
Toughness	Good	Excellent	Good	Excellent	Good–Excellent
Elongation	Poor	Poor	Poor	Excellent	Excellent
Tensile	Fair	Good	Fair–Good	Good–Excellent	Excellent
Cure rate	Slow	Slow	Fast	Fast	None
Cure temperature	Room	Room	300–390°F (149–199°C)	212°F (100°C)	150–225°F (66–108°C)

be formulated in a wide range of hardnesses. They can be abrasion resistant and weather resistant. Polyurethanes can be combined with resins to reinforce or adopt their properties. Urethane-modified acrylics have excellent outdoor weathering properties. They can also be applied as air-drying, forced-dried, and baking liquid finishes, as well as powder coatings.

Moisture-cured types require humidity during application and may yellow under UV light. They have a temperature resistance of 250°F (121°C) dry and 150°F (66°C) wet. Catalyzed (two-component) urethanes exhibit very good chemical resistance. They are not recommended for immersion service or exposure to strong acids/alkalies. They have a temperature resistance of 225°F (105°C) dry and 150°F (66°C) wet.

The formulation of urethane coatings is important, as the isocyanate will, to some degree, always react with moisture in the air. The reaction is accelerated by high humidity and, in the presence of sunlight or heat, will liberate carbon dioxide gas. Poorly formulated coatings may foam, bubble, or gas, and the dried film may have numerous pinholes or voids.

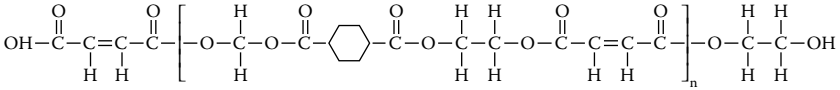
Polyurethanes find wide application in the transportation industry. They are applied on aircraft, automobiles, railroad cars, trucks, and ships. As a result of

their chemical resistance and ease of decontamination from chemical, biological, and radiological warfare agents, they are widely used for painting military land vehicles, ships, and aircraft. Polyurethanes are used on automobiles as coatings for plastic parts and as clear topcoats in the basecoat–clearcoat finish systems. Low-temperature baking polyurethanes are used as mar-resistant finishes for products that must be packaged while still warm.

Urethane coatings are not suitable for immersion service or for prolonged exposure to water or strong chemical environments.

POLYESTERS

In the coating industry, polyesters are characterized by resins based on components that introduce unsaturation (–C=C–) directly into the polymer backbone. The following structure shows an isophthalic polyester resin:



n = 3 to 6

This unsaturation must be capable of direct addition co-polymerization with vinyl monomers (usually styrene). The most common polyester resins are polymerization products of maleic or isophthalic anhydride or their acids. In producing paint, the polyester resin is dissolved in styrene monomer, together with pigment and small amounts of inhibitor. A free radical initiator (commonly a peroxide) and additional styrene are packaged in another container. When applied, the containers are mixed. Sometimes, because of the fast initiating reaction (short pot life), they are mixed in an externally mixing or dual-headed spray gun. After being mixed and applied, a relatively fast reaction takes place, resulting in crosslinking and polymerization of the monomeric styrene with the polyester resin.

Polyester coatings exhibit high shrinkage after application. The effect of high shrinkage can be reduced by proper pigmentation, which reinforces the coating and reduces the effect of the shrinkage.

Polyester coatings are also available in single-package forms, sometimes called oil-free alkyds, which are self-curing, usually at elevated temperatures. In either case, the resin formulator can adjust the properties to meet most exposure conditions. Polyesters are also available to be applied as powder coatings.

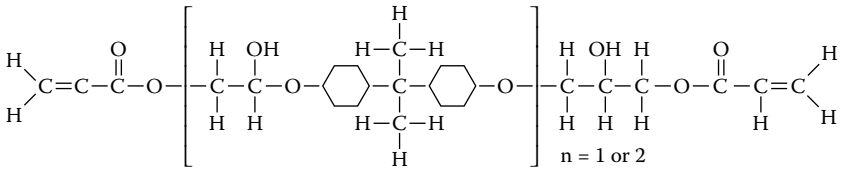
Polyester coatings possess excellent resistance to acids and aliphatic solvents, with good resistance to weathering. They have a temperature resistance of 180°F (82°C) dry or wet.

Polyesters are not suitable for use with alkalies and most aromatic solvents because they swell and soften these coatings.

These coatings find application as coatings for tanks and chemical process equipment.

VINYL ESTERS

Vinyl esters have a higher temperature and greater acid resistance than the polyesters. They are formulated in a similar manner and have the same application limitations. Instead of using a polyester resin, the vinyl esters derive from a resin based on a reactive end vinyl group that can open and polymerize. The chemical structure is:



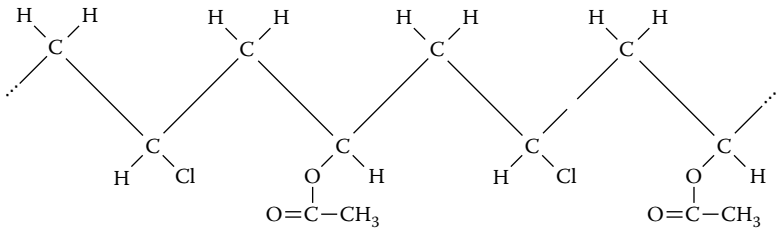
Note that there are fewer ester groups in the molecular structure of a vinyl ester than in a polyester. Additionally, there is C═C saturation and a more symmetrical molecular structure, with less polarity. Consequently, the vinyl ester has better moisture and chemical resistance and is more stable than the polyester.

When applying the vinyl ester (or the polyester), it is essential that the surface be dry; moisture may inhibit the curing reaction.

Excessive thicknesses should not be applied. Two or three thin coats are better than one thick coat. For proper adhesion, the steel substrate must have a high anchor pattern of blast-cleaned steel. Concrete surfaces must have a broom finish or otherwise roughened surface.

VINYLS

Vinyl is a general term denoting any compound containing the vinyl linkage ($-CH{=}CH_2$) group. However, this group is contained in many compounds not commonly thought of as vinyl coatings (such as styrene, diallylphathalate, vinyl toluene, propylene), and many others in the ethylene family of olefins. Vinyl coatings are considered co-polymers of vinyl chloride and vinyl acetate co-polymerized in approximately 86% vinyl chloride to 14% vinyl acetate. The chemical structure of a vinyl chloride/vinyl acetate co-polymer is as follows:



Frequently, approximately 1% of the carboxylic acid or anhydride (usually maleic acid or anhydride) is added to improve adhesion to the metal surfaces. For improving adhesion to other previously applied coatings, 1% of a hydroxyl modifier is added, usually in the form of an alcohol.

Because a relatively high amount of solvent (ketones and esters) is required to dissolve a vinyl co-polymer high in vinyl chloride content, the volume of solids in solution is relatively low. Because of this, most vinyl coatings must be applied thinly (1 to 1.5 mil per coat). Accordingly, a vinyl coating system may require five or more coats. Although the protection is generally excellent in the proper environment, the system is considered highly labor intensive. High-build vinyls have been formulated, permitting application of the coating 2 to 2.5 mil or more per coat. This advantage comes at the expense of reduced protection because the thixotropes, fillers, and additives used to provide greater thickness are also more susceptible to environmental and moisture permeation.

Vinyls find wide application in water immersion service because of their extreme toughness and impermeability. However, it is essential that all solvents have evaporated before placing a vinyl-coated object in immersion service. The high polarity of the resin tends to retain the solvents used to dissolve the resin. Solvent evaporation retardation has the resultant effect of solvent voids within the vinyl coating, pinholes penetrating through a coat or more than one coat, and blistering caused by volatilization of retained solvents upon heating — or water-filled blisters because of hydrogen-bonding attraction of water by the retained solvents in the coating.

Polyvinyls dissolved in aromatics, ketones, or esters have the following properties:

1. Resistance: insoluble in oils, greases, aliphatic hydrocarbons, and alcohols; resistant to water, salt solutions at room temperature, and inorganic acids and alkalies; fire resistant
2. Temperature resistance: 180°F (82°C) dry and 140°F (60°C) wet
3. Features: tasteless and odorless
4. Applications: used on surfaces exposed to potable water, as well as for immersion service, sanitary equipment, and widely used as industrial coatings

WATER-SOLUBLE RESINS AND EMULSION COATINGS

Any type of resin can be made water soluble by introducing sufficient carboxyl groups into the polymer. These groups are then neutralized with a volatile base such as ammonia or an amine, rendering the resin a polymeric salt, soluble in water or water/ether-alcohol mixtures. The main disadvantage to such resins is that the polymers designed to be dissolved in water will remain permanently sensitive to water. Because of this, they are not widely used industrially.

However, water emulsion coatings are widely accepted. The water-based latex emulsions are formulated with high-molecular-weight resins in the form of microscopically fine particles of high molecular weight copolymers of polyvinyl chloride, or polyvinyl acetate, styrene-butadiene, acrylic esters, or other resins combined with pigments, plasticizers, UV stabilizers, and other ingredients. Water-based epoxy formulations are also available. The epoxy resin and a polyamide copolymer are emulsified and packaged in separate containers. After mixing, coalescence, and ultimate drying, the polyamide reacts with the epoxy to form the final film.

Emulsion coatings initially form a film by water evaporation. As the water evaporates, the emulsified particles come closer together until they touch each other. The latex particles, with the aid of a coalescing agent (usually a slow-evaporating solvent), ultimately merge to form a relatively continuous film. Because of irregularities in the physical packing of the emulsion particles, latex films are not noted for their impermeabililty. Also, initial adhesion may be relatively poor as the water continues to evaporate and coalescing acids, solvents, and surfactants evaporate or are leached from the "curing" film. Later, from as little as a few days to as long as a few months after application, the latex coating attains its final adhesion and environmentally resistant properties.

The major advantage of the emulsion coatings is their ease of cleanup. These coatings are resistant to water, mild chemical fumes, and weathering. They have a temperature resistance of 150°F (66°C) wet or dry.

These coatings must be stored above freezing. They will not penetrate chalky surfaces. Their chemical and weather resistance is not as good as solvent or oil-based coatings. They are not suitable for immersion services.

ZINC-RICH PAINTS

Zinc-rich paints owe their protection to galvanic action. While all of the preceding coatings owe their final film properties, corrosion resistance, and environmental resistance to the composition of their binder, rather than their pigment, the high amount of zinc dust metal pigment in zinc-rich paints determines these coatings' fundamental property: galvanic action. Many of the previous coatings, chlorinated rubber and epoxies in particular, are formulated as zinc-rich coatings. In so doing, the high pigment content changes the properties of the formulated coating.

Zinc-rich coatings can be classified as organic or inorganic. The organic zinc-riches have organic binders, with polyamide epoxies and chlorinated rubber binders being the most common. Other types such as urethane zinc-rich are also available. These latter coatings are more easily applied than the other zinc-rich coatings.

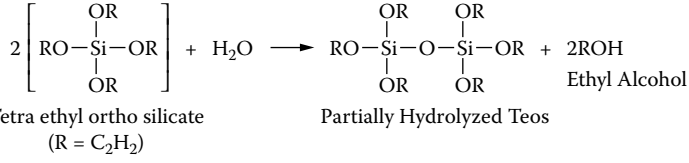
Organic zinc-rich coatings can also be formulated with other binders, and formulations using alkyds and epoxy esters are widely used in the automotive industry (but are not recommended as suitable vehicles for field applied, air-dried industrial, or maintenance primers). Vinyl and styrene-butadiene resins have also been used for zinc-rich coatings; although some vinyl zinc-rich coatings are still available, styrene-butadiene is no longer used.

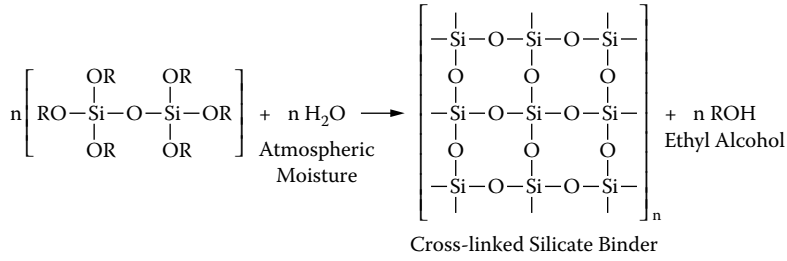
The advantages offered by the organic zinc-rich paints lie in the galvanic protection afforded by the zinc content, with chemical and moisture resistance similar to that of the organic binder. These paints should be top-coated in chemical environments having a pH outside the range of 5 to 10. Compared to the inorganic zinc-rich paints, the organic zinc-rich paints are more tolerant of surface preparation.

The organic zinc-rich coatings generally have lower service performance than the inorganic zinc-rich coatings, but ease of application and surface preparation tolerance make them increasingly popular.

These coatings are widely used in Europe and the Far East, while inorganic zinc-rich coatings are most common in North America. The organic binder can be closely tailored to topcoats (for example, epoxy topcoats or epoxy zinc-rich coatings) for a more compatible system. Organic zinc-rich coatings are often used to repair galvanized or inorganic zinc-rich coatings.

Inorganic zinc-rich binders are based on silicate solutions, which after curing or drying, crystallize and form an inorganic matrix, holding zinc dust particles together and to the steel substrate. The ethyl silicate zinc-rich primer-curing reaction is:





The first zinc-rich coatings were post-cured (by the application of heat or acid) water-based sodium silicate solutions; and later lithium, potassium, ammonium, and other alkali silicates were used. The post-cured inorganic zinc-rich silicates appear to provide the best binder and the longest protection of any zinc-rich primer. However, they are rather difficult to apply and somewhat labor intensive because, after application, a curing solution must be applied and — if topcoated — brushed off. Consequently, self-curing inorganic silicates have been developed based on some of these same alkali silicates and, additionally, alkyl silicates (notably ethyl silicate). These organic silicates, upon curing, react with atmospheric moisture to form alcohol, which evaporates. The resulting film is inorganic and essentially

the same as that of the alkali silicate. Single-package materials are based on ethyl silicate or polyalcohol silicate binders.

Inorganic zinc-rich coatings provide excellent long-term protection against pitting in neutral and near-neutral atmospheric and some immersion services. Abrasion resistance is excellent and dry heat resistance exceeds 700°F (370°C). Water-based inorganic silicates are available for confined spaces and VOC compliance.

The inorganic nature requires thorough blast-cleaning surface preparation and results in difficulty when topcoating with organic topcoats. Zinc dust is reactive outside the pH range of 5 to 10, and topcoating is necessary in chemical fume environments.

Ethyl silicate zinc-rich coatings require atmospheric moisture to cure and are the most common type. Applications include wide usage as a primer on bridges, offshore structures, and steel in the building and chemical processing industries. It is also used as a weldable preconstruction primer in the automotive and ship-building industries. Its use eliminates pitting and corrosion.

For a coating to be considered zinc-rich, it must contain at least 75% by weight of zinc dust in the dry film. This may change because conductive extenders (notably di-iron phosphite) have been added to improve weldability and burn-through, with supposedly equivalent protection at lower zinc loadings.

The primary advantage of zinc-rich coatings is their ability to provide galvanic protection. The zinc pigment in the coating preferentially sacrifices itself in the electrochemical corrosion reaction to protect the underlying steel. This galvanic action, together with the filling and sealing effect of zinc reaction products (primarily zinc carbonate, zinc hydroxide, and complex zinc salts), provides more effective corrosion protection to steel substrates than does any other type of coating. Zinc-rich coatings cannot be used outside the pH range of 6 to 10.5.

PHENOLICS

Phenolics are available either as a baked coating or as an air-drying maintenance coating. As an air-drying coating, it has a dry temperature resistance of 150°F (66°C). These resins supply solvent and moisture resistance. These paint coatings can be formulated for excellent resistance to alkalies, solvents, fresh water, salty deionized water, and mild acid resistance. However, the prime application of phenolic coatings is as baked coatings, which are discussed in Chapter 8.

SILICONE

Technically, these silicone resins are inorganic materials but are an important paint material and therefore are included. Silicone resins are high priced and are used alone or as modifiers to upgrade other resins. They are noted for their high temperature resistance, moisture resistance, and weatherability. They can be hard or elastomeric, baked or room-temperature cured. They are based on silicon compounds (which have silicon rather than carbon linkages in the structure).

There are two types of silicone paint coatings: high temperature and water repellent in water or solvent. They exhibit excellent resistance to sunlight and weathering but poor resistance to acids and alkalies, with good resistance to water.

The aluminum formulation has a temperature resistance of 1200°F (699°C). These high-temperature types require baking for a good cure and are not chemically resistant.

They are primarily used for high-temperature service for exhaust stacks, ovens, and space heaters. In such applications, carbon-based coatings would oxidize.

Water solvent formulations are used on limestone, cement, and nonsilaceous materials; solvent formulations are used on bricks and noncalcareous masonry. They have a temperature limitation of 572°F (300°C), and can also be used at cryogenic temperatures.

Typically, the silicon atoms have one or more side groups attached to them, generally phenol (C_6H_5–), methyl (CH_3–), or vinyl (CH_2=CH–) units. These groups impart properties such as solvent resistance, lubricity, and reactivity with organic chemicals and polymers. Because these side groups affect the corrosion resistance of the resin, it is necessary to check with the supplier as to the properties of the resin being supplied.

CORROSION RESISTANCE COMPARISONS

The compatibilities of the more common paint systems are shown in the following charts with selected corrodents. In the charts, compatibility is indicated by an R, incompatibility by an X, indication of a coating's ability to resist splashing is shown by an S, and ability to be immersed is shown by a W.

All chemicals are in the pure state or are saturated solutions, unless otherwise indicated.

Acetic Acid

Acrylics (dilute)	R, S	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	R
Chlorinated rubber	R, W	Urethanes:	
Coal tar		Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich (dilute)	R
Polyamine	X		

Acetone

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	R
Long oil	X	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone (methyl)	R
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine		Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Ammonium Bicarbonate

Acrylics		Phenolic	
Alkyds:		Polyesters	
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt		Silicone	
Chlorinated rubber		Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy	R, W	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	
Polyamide	R	Zinc rich (dilute)	R
Polyamine	R		

Ammonium Chloride

Acrylics	R	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt, up to 30%	R	Silicone (methyl)	R
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	
Coal tar epoxy (dry)	R, W	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich (dilute)	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Ammonium Hydroxide

Acrylics (dilute)	R, S	Phenolic	X
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	R
Short oil	X	Polyvinyl formal	R
Asphalt		Silicone	X
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	X	Zinc rich (dilute)	R
Polyamine	R		

Benzene

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil	R	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone	X
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Butyl Alcohol

Acrylics	R	Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt		Silicone (methyl)	R
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine		Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	R		

Calcium Chloride

Acrylics (dilute)	R, S	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt, up to 30%	R	Silicone (methyl)	R
Chlorinated rubber	R	Urethanes:	
Coal tar	R	Aliphatic	R
Coal tar epoxy	R	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	X
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Calcium Hydroxide

Acrylics (dilute)	R, S	Phenolic	X
Alkyds:		Polyesters	R
Long oil	X	Polyvinyl butyral	R
Short oil	X	Polyvinyl formal	R
Asphalt (dilute)	R	Silicone (methyl)	R
Chlorinated rubber	R	Urethanes:	
Coal tar (dilute)	R	Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	X
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich (dilute)	R
Polyamine	R		

Carbon Dioxide, Dry

Acrylics	R	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy		Aromatic	R
Epoxies:		Vinyls	R
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Carbon Tetrachloride

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	X
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	R		

Chromic Acid, 10%

Acrylics (dilute)	R, S	Phenolic	X
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	
Asphalt (dilute)	R	Silicone	X
Chlorinated rubber	R	Urethanes:	
Coal tar (dilute)	R, W	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Chromic Acid, 50%

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt	X	Silicone	X
Chlorinated rubber	R	Urethanes:	
Coal tar	X	Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	X
Polyamine	X		

Citric Acid

Acrylics (dilute)	R, S	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt		Silicone	X
Chlorinated rubber	R	Urethanes:	
Coal tar (dilute)	R	Aliphatic	
Coal tar epoxy	R, W	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich (dilute)	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Detergents

Acrylics	R, S	Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt		Silicone	
Chlorinated rubber	R	Urethanes:	
Coal tar	R	Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

Ethyl Alcohol

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil	R	Polyvinyl butyral	
Short oil	R	Polyvinyl formal	
Asphalt		Silicone	R
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Ethyl Acetate

Acrylics	X	Phenolic	
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone	
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	R
Polyamine	X		

Ethylene Glycol

Acrylics	R	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil	X	Polyvinyl butyral	X
Short oil	R	Polyvinyl formal	X
Asphalt	R	Silicone (methyl)	R
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Fatty Acids

Acrylics	R	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone	X
Chlorinated rubber	X	Urethanes:	
Coal tar		Aliphatic	
Coal tar epoxy		Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine		Vinyl ester	R
Polyamide		Zinc rich	R
Polyamine	R		

Formic Acid, 10–85%

Acrylics (dilute)	R, S	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber	R	Urethanes:	
Coal tar		Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich (dilute)	R
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Gasoline, Unleaded

Acrylics	R	Phenolic	R
Alkyds:		Polyesters	R
Long oil	X	Polyvinyl butyral	X
Short oil	R	Polyvinyl formal	
Asphalt	X	Silicone	X
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

Glycerine

Acrylics	R	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	X
Short oil		Polyvinyl formal	
Asphalt		Silicone	R
Chlorinated rubber	X	Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Heptane

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil	R	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone	
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

Hydrobromic Acid, Dilute

Acrylics	R, S	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	X
Chlorinated rubber	R	Urethanes:	
Coal tar		Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich (dilute)	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Hydrobromic Acid, 30%

Acrylics	X	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber	R	Urethanes:	
Coal tar	X	Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	X	Zinc rich	X
Polyamine	X		

Hydrochloric Acid, Dilute

Acrylics	R, S	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	X
Short oil		Polyvinyl formal	
Asphalt	R	Silicone (methyl)	R
Chlorinated rubber	R, W	Urethanes:	
Coal tar	R, W	Aliphatic	X
Coal tar epoxy	R, W	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Hydrochloric Acid, 38%

Acrylics	X	Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	X
Polyamine	R		

Hydrofluoric Acid

Acrylics	R	Phenolic	X
Alkyds:		Polyesters	X
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich (dilute)	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Hydrogen Chloride (Gas, Moist)

Acrylics		Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	
Coal tar epoxy		Aromatic	
Epoxies:		Vinyls	R
Aliphatic polyamine		Vinyl ester	R
Polyamide		Zinc rich	
Polyamine (dry)	R		

Isopropyl Alcohol

Acrylics		Phenolic	R
Alkyds:		Polyesters	R
Long oil	X	Polyvinyl butyral	
Short oil	R	Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	X
Coal tar epoxy	R, W	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Methyl Acetate

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone	
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	R
Polyamine	X		

Methyl Alcohol

Acrylics		Phenolic	R, S
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	R
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Methyl Ethyl Ketone

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	R
Polyamine	R		

Methyl Isobutyl Ketone

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil	X	Polyvinyl butyral	X
Short oil	X	Polyvinyl formal	X
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Nitric Acid, Dilute

Acrylics	R, S	Phenolic	X
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone (methyl)	R
Chlorinated rubber	R, W	Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	X		

Nitric Acid, Conc

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	X
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	X
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Oil, Vegetable

Acrylics		Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	R
Asphalt	X	Silicone	
Chlorinated rubber	X	Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy	R, W	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine		Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

Oleum

Acrylics	X	Phenolic	
Alkyds:		Polyesters	X
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	X
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	X
Polyamine			

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Oxalic Acid, Conc

Acrylics	X	Phenolic (dry)	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber	R, W	Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy	R	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	R	Zinc rich	X
Polyamine	X		

Phenol

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	X
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	X
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Phosphoric Acid, 5%

Acrylics	R, S	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber	R, W	Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	R		

Phosphoric Acid, 50%

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	X
Chlorinated rubber	R, W	Urethanes:	
Coal tar		Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	X	Vinyl ester	R
Polyamide	X	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Potassium Chloride, 30%

Acrylics (dilute)	R, S	Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt (dilute)	R	Silicone	
Chlorinated rubber		Urethanes:	
Coal tar	R	Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	X
Polyamine	R		

Potassium Hydroxide, Dilute

Acrylics	R, S	Phenolic	R
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	
Short oil	X	Polyvinyl formal	
Asphalt	R	Silicone	X
Chlorinated rubber	R, W	Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy	R	Aromatic	
Epoxies:		Vinyls	X
Aliphatic polyamine	R	Vinyl ester	X
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Potassium Hydroxide, conc.

Acrylics	X	Phenolic	
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	
Short oil	X	Polyvinyl formal	
Asphalt	X	Silicone	
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	X
Polyamine	X		

Propyl Alcohol

Acrylics		Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	R
Chlorinated rubber		Urethanes:	
Coal tar		Aliphatic	
Coal tar epoxy		Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide		Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed

S = Will resist splashing; a blank indicates data unavailable.

Propylene Glycol

Acrylics		Phenolic	R, W
Alkyds:		Polyesters	R, W
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber	X	Urethanes:	
Coal tar		Aliphatic	
Coal tar epoxy	R, W	Aromatic	
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R, W
Polyamide	R, W	Zinc rich	R
Polyamine	R		

Sodium Chloride

Acrylics	R	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone, 10% (methyl)	R
Chlorinated rubber	R	Urethanes:	
Coal tar	R	Aliphatic	R
Coal tar epoxy	R	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	X
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed

S = Will resist splashing; a blank indicates data unavailable.

Sodium Hydroxide, 10%

Acrylics	R	Phenolic	R
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	
Short oil	X	Polyvinyl formal	
Asphalt (dilute)	R	Silicone (methyl)	R
Chlorinated rubber	R, W	Urethanes:	
Coal tar (dilute)	R	Aliphatic	R
Coal tar epoxy	R	Aromatic	R
Epoxies:		Vinyls	X
Aliphatic polyamine	R	Vinyl ester	X
Polyamide	R	Zinc rich	R
Polyamine	R		

Sodium Hydroxide, 70%

Acrylics	R	Phenolic	X
Alkyds:		Polyesters	X
Long oil	X	Polyvinyl butyral	
Short oil	X	Polyvinyl formal	
Asphalt	X	Silicone (methyl)	R
Chlorinated rubber	R, W	Urethanes:	
Coal tar	X	Aliphatic	
Coal tar epoxy	X	Aromatic	
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	X
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Sulfuric Acid, 10%

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	X
Chlorinated rubber	R, W	Urethanes:	
Coal tar	R	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	X	Zinc rich	X
Polyamine	R		

Sulfuric Acid, 98%

Acrylics	X	Phenolic	X
Alkyds:		Polyesters	X
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	X	Silicone (methyl)	X
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	X
Polyamide	X	Zinc rich	X
Polyamine	X		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

UV Light

Acrylics	R	Phenolic	
Alkyds:		Polyesters	
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	R	Silicone	R
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	
Aliphatic polyamine	X	Vinyl ester	
Polyamide	X	Zinc rich	
Polyamine	X		

Water, Potable

Acrylics		Phenolic	
Alkyds:		Polyesters	R
Long oil	R	Polyvinyl butyral	R
Short oil	R	Polyvinyl formal	
Asphalt	R	Silicone (methyl)	R, W
Chlorinated rubber	R, W	Urethanes:	
Coal tar	R	Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine		Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Water, Sea

Acrylics		Phenolic	R, S
Alkyds:		Polyesters	R, W
Long oil		Polyvinyl butyral	R
Short oil		Polyvinyl formal	
Asphalt		Silicone (methyl)	R, W
Chlorinated rubber	R, W	Urethanes:	
Coal tar	R, W	Aliphatic	R
Coal tar epoxy	R, W	Aromatic	R
Epoxies:		Vinyls	R, W
Aliphatic polyamine	R	Vinyl ester	R, W
Polyamide	R, W	Zinc rich	R, W
Polyamine	R, W		

Weathering

Acrylics	R	Phenolic	
Alkyds:		Polyesters	R
Long oil	R	Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	R	Silicone	R
Chlorinated rubber		Urethanes:	
Coal tar	X	Aliphatic	R
Coal tar epoxy	X	Aromatic	R
Epoxies:		Vinyls	R
Aliphatic polyamine	R	Vinyl ester	
Polyamide		Zinc rich	R
Polyamine			

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

White Liquor

Acrylics	X	Phenolic	R
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt		Silicone	
Chlorinated rubber		Urethanes:	
Coal tar	R	Aliphatic	X
Coal tar epoxy	R	Aromatic	X
Epoxies:		Vinyls	R
Aliphatic polyamine		Vinyl ester	R
Polyamide	R, W	Zinc rich	X
Polyamine	R, W		

Wines

Acrylics	X	Phenolic	
Alkyds:		Polyesters	R
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	R, S	Silicone	R
Chlorinated rubber	R	Urethanes:	
Coal tar		Aliphatic	X
Coal tar epoxy	R	Aromatic	X
Epoxies:		Vinyls	R
Aliphatic polyamine	R	Vinyl ester	R
Polyamide	R	Zinc rich	R
Polyamine	R, S		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable

Xylene

Acrylics	X	Phenolic	R, W
Alkyds:		Polyesters	R, W
Long oil		Polyvinyl butyral	
Short oil	X	Polyvinyl formal	
Asphalt	X	Silicone	X
Chlorinated rubber	X	Urethanes:	
Coal tar	X	Aliphatic	X
Coal tar epoxy	X	Aromatic	X
Epoxies:		Vinyls	X
Aliphatic polyamine	X	Vinyl ester	R, W
Polyamide	X	Zinc rich	R, W
Polyamine	X		

Zinc Chloride

Acrylics	R	Phenolic	R, W
Alkyds:		Polyesters	R, W
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	R	Silicone	R
Chlorinated rubber	R	Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy		Aromatic	
Epoxies:		Vinyls	R
Aliphatic polyamine, 40%	R, S	Vinyl ester	R
Polyamide		Zinc rich	
Polyamine	R, S		

R = Recommended; X = Unsuitable; W = Can be immersed;

S = Will resist splashing; a blank indicates data unavailable.

Zinc Nitrate

Acrylics		Phenolic	
Alkyds:		Polyesters	
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	R	Silicone	
Chlorinated rubber		Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy		Aromatic	
Epoxies:		Vinyls	R
Aliphatic polyamine		Vinyl ester	R
Polyamide		Zinc rich	
Polyamine	R		

Zinc Sulfate

Acrylics		Phenolic	R, W
Alkyds:		Polyesters	R, W
Long oil		Polyvinyl butyral	
Short oil		Polyvinyl formal	
Asphalt	R	Silicone	R, W
Chlorinated rubber		Urethanes:	
Coal tar	R	Aliphatic	
Coal tar epoxy		Aromatic	
Epoxies:		Vinyls	R
Aliphatic polyamine		Vinyl ester	R
Polyamide		Zinc rich	
Polyamine	R, W		

7 Selecting a Paint System

INTRODUCTION

There are many factors that must be considered in selecting a coating system for corrosion protection. This chapter discusses each factor. Keep in mind that the importance — and therefore the weight — of any single factor will vary from application to application; but in most cases, the factors are listed in decreasing importance.

SERVICE ENVIRONMENT

The first step in selecting a paint system for corrosion protection is to determine the environment around the structure to be painted. Is the environment predominantly a weathering environment subject to heat, cold, daily or seasonal temperature changes, precipitation, wind (flexing), exposure to sunlight, or detrimental solar rays? If the structure or item is located outdoors, are there chemical plants located nearby, or pulp or paper mills, or other industrial facilities that are apt to discharge airborne pollutants? Are color, gloss, and the overall pleasing effect more important than corrosion protection, or are the normal grays, whites, and pastels of the more corrosion-resistant paints satisfactory? If located in a chemical facility, what chemicals are used nearby? Is there any chance of a chemical spill on the painted surface?

Because surface preparation is an important factor in selecting a paint system, the suitability or availability of the surface for specific preparation techniques must be known. In some instances, certain types of surface preparation may not be permitted or practical. For example, many companies do not permit open blast cleaning where there is a preponderance of electric motors or hydraulic equipment. Refineries in general do not permit open blast cleaning, or any other method of surface preparation that might result in the possibility of a spark, static electricity build-up, or an explosion hazard.

If a new facility is being constructed, it is possible that during erection many areas may become enclosed or covered, or so positioned that access is difficult or impossible. These structures must be painted prior to installation.

When all of this information has been collected, the appropriate paint system can be selected. In most instances, it will not be practical or possible to select one single coating system for the entire plant. There will be areas requiring systems to provide protection from aggressive chemicals; whole other areas may require coating systems simply for aesthetics. If an area is a combination of mild

and aggressive conditions, a coating system should be selected that will be resistant to the most aggressive condition.

Several typical industrial environmental areas have been illustrated to which coating systems can be exposed with recommendations for paint systems to be used in these areas. The paint systems are shown in Tables 7.1 through 7.6 along with the appropriate surface preparation. Each coating system shown in a particular

TABLE 7.1
Multilayer Paint Systems Requiring Commercial Blast (SSPC-SP-6) for Surface Preparation

System A: Inorganic Zinc/Epoxy Mastic

Paint layers:
One coat inorganic zinc: 2–3 mils dft (50–75 μm)
One coat epoxy mastic: 4–6 mils dft (100–150 μm)
Properties:
Zinc primer provides outstanding corrosion resistance and undercutting resistance. A barrier protection for the zinc primer is provided by the finish coat of epoxy, which also provides a color coat for appearance. Suitable for use on carbon steel only.
Limitations:
A relatively high level of applicator competence required for the primer.

System B: Inorganic Zinc/Epoxy Primer/Polyurethane Finish

Paint layers:
One coat inorganic zinc: 2–3 mil dft (50–75 μm)
One coat epoxy primer: 4–6 mil dft (100–150 μm)
One coat polyurethane finish: 2–4 mil dft (50–100 μm)
Properties:
Zinc primer provides outstanding corrosion resistance and undercutting resistance. The zinc primer is protected by a barrier coating of epoxy primer, while the finish coat of polyurethane provides color and gloss retention. This is a premium industrial finish for steel surfaces. Can only be used on carbon steel.
Limitations:
A relatively high level of applicator competence required for the primer.

System C: Inorganic Zinc/Acrylic Finish

Paint layers:
One coat inorganic zinc: 2–3 mil dft (50–75 μm)
One coat acrylic finish: 2–3 mil dft (50–75 μm)
Properties:
Zinc primer provides outstanding corrosion resistance and undercutting resistance. Water-based, single-package finish has excellent weathering and semigloss appearance.
Limitations:
A relatively high level of applicator competence required for the primer. The finish coat has low-temperature curing restrictions.

TABLE 7.1
Multilayer Paint Systems Requiring Commercial Blast (SSPC-SP-6) for Surface Preparation (Continued)

System D: Aluminum Epoxy Mastic/Epoxy Finish

Paint layers:

One coat aluminum epoxy mastic: 4–6 mil dft (100–150 μm)

One coat epoxy finish: 4–6 mil dft (100–150 μm)

Properties:

Can be used on light rust and marginally prepared surface. The epoxy finish coat is available in a variety of colors and has good overall chemical resistance. Can be used on carbon steel or concrete. Concrete must be clean, rough, and cured for at least 28 days. Hand or power tool cleaning, including water blasting, can be used for surface preparation.

System E: Aluminum Epoxy Mastic/Acrylic Finish

Paint layers:

One coat aluminum epoxy mastic: 4–6 mil dft (100–150 μm)

One coat acrylic finish: 2–3 mil dft (50–75 μm)

Properties:

Can be used on light rust and marginally prepared surfaces. The acrylic finish coat is available in a variety of colors and has good overall chemical resistance. This is an excellent maintenance system. Normally used on carbon steel and concrete.

System F: Epoxy Mastic/Epoxy Mastic

Paint layers:

One coat epoxy mastic: 4–6 mil dft (100–150 μm)

One coat epoxy mastic: 4–6 mil dft (100–150 μm)

Properties:

Can be used on light rust and marginally prepared surfaces. The substrate is protected by the formation of a tight barrier that stops moisture from reaching the surface. Normally used on steel or concrete. Concrete must be clean, rough, and cured at least 28 days. If necessary, hand or power tools can be used for cleaning.

System G: Epoxy Primer/Epoxy Finish

Paint layers:

One coat epoxy primer: 4–6 mil dft (100–150 μm)

One coat epoxy finish: 4–6 mil dft (100–150 μm)

Properties:

An easily applied, two-coat, high-build barrier protection is provided with ease of application. Used on carbon steel or concrete.

Limitations:

Because these are two-component materials, they must be mixed just prior to application. They require additional equipment and more expertise to apply than a single-packaged product. Most epoxy finish coats will chalk, fade, and yellow when exposed to sunlight.

(*continued*)

TABLE 7.1
Multilayer Paint Systems Requiring Commercial Blast (SSPC-SP-6) for Surface Preparation (Continued)

System H: Epoxy Primer

Paint layers:

One coat epoxy primer: 4–6 mil dft (100–150 μm)

Properties:

Normally applied to carbon steel or concrete in protected areas such as the interiors of structures, behind walls and ceilings, or for temporary protection during construction.

Limitations:

This is a two-component material requiring mixing just prior to application.

System I: Epoxy Novalac/Epoxy Novalac

Paint layers:

One coat epoxy novalac: 6–8 mil dft (150–200 μm)

One coat epoxy novalac: 6–8 mil dft (150–200 μm)

Properties:

An exceptional industrial coating for a wide range of chemical resistance and physical abuse resistance uses. Has a higher temperature resistance than standard epoxy. Can be used to protect insulated piping or for secondary containment. Normally used on carbon steel and concrete surfaces.

TABLE 7.2
Multilayer Paint Systems Requiring Surface to Be Abrasive Blasted in Accordance with SSPC-SP-10 near White Blast

System A: Aluminum-Epoxy Mastic/Aluminum–Epoxy Mastic

Paint layers:

Once coat aluminum-epoxy mastic: 4–6 mil dft (100–150 μm)

One coat aluminum-epoxy mastic: 4–6 mil dft (100–150 μm)

Properties:

Tolerates poorly prepared surfaces and provides excellent barrier protection. A third coat can be added for additional protection. Can be used on carbon steel and concrete. Concrete must be clean, rough, and cured at least 28 days. If necessary, this system can be applied to surfaces that are pitted or cannot be blasted. However, the service life will be reduced.

System B: Epoxy Phenolic Primer/Epoxy Phenolic Finish/Epoxy Phenolic Finish

Paint layers:

One coat epoxy phenolic primer: 8 mil dft (200 μm)

One coat epoxy phenolic finish: 8 mil dft (200 μm)

One coat epoxy phenolic finish: 8 mil dft (200 μm)

Properties:

Because of this system's outstanding chemical resistance, it is often used in areas subject to frequent chemical spills. The finish coats are available in a limited number of colors. Normally used on carbon steel and concrete. Concrete must be clean, rough, and cured at least 28 days.

TABLE 7.2
Multilayer Paint Systems Requiring Surface to Be Abrasive Blasted in Accordance with SSPC-SP-10 near White Blast

System C: Epoxy Phenolic Primer/Epoxy Phenolic Lining/Epoxy Phenolic Lining

Paint layers:

One coat epoxy phenolic primer: 8 mil dft (200 μm)

One coat epoxy phenolic lining: 8 mil dft (200 μm)

One coat epoxy phenolic lining: 8 mil dft (200 μm)

Properties:

Because of the system's outstanding overall chemical resistance, it is suitable for lining areas subject to flowing or constant immersion in a variety of chemicals. Normally used on carbons steel and concrete. When used on concrete, the surface must be clean, rough, and cured at least 28 days.

System D: Epoxy/Epoxy

Paint layers:

One coat epoxy: 4–6 mil dft (100–150 μm)

One coat epoxy: 4–6 mil dft (100–150 μm)

Properties:

Two coats of the same product are applied, providing a high-build protection. Can be used in immersion service without the addition of corrosion inhibitors. When used in potable water systems, the product must meet Federal Standard 61. A third coat can be added for additional protection. Normally used on carbon steel and concrete.

System E: Coal Tar Epoxy/Coal Tar Epoxy

Paint layers:

One coat coal tar epoxy: 8 mil dft (200 μm)

One coat coal tar epoxy: 8 mil dft (200 μm)

Properties:

Provides excellent barrier protection and is the most economical of the water lining systems or for water immersion. Normally used on carbon steel and concrete.

System F: Solventless Elastomeric Polyurethane

Paint layers:

One coat elastomeric polyurethane: 20–250 mil dft (500–6250 μm)

Properties:

Excellent barrier protection. Normally used on carbon steel and concrete.

Limitations:

Must be applied by a knowledgeable contractor.

System G: Aluminum Epoxy Mastic/Polyurethane Finish

Paint layers:

One coat aluminum epoxy mastic: 4–6 mil dft (100–150 μm)

One coat polyurethane finish: 2–4 mil dft (50–150 μm)

Properties:

Excellent over light rust. Tolerant of minimally prepared steel. Can be applied to a wide range of surfaces, but normally used on carbon steel and concrete. This is a premium system to use when cleaning must be minimal.

Limitations:

To cure properly, temperature must be above 50°F (10°C). For lower temperature requirements, other aluminum epoxy/urethane mastics can be substituted.

TABLE 7.3
Multilayer Paint Systems Requiring Surface to Be Clean, Dry, and Free of Loose Dirt, Oil, and Chemical Contamination

System A. Aluminum Epoxy Mastic/Polyurethane Finish

Paint layers:
One coat aluminum epoxy mastic: 4–6 mils dft (100–150 μm)
One coat polyurethane finish: 2–4 mils dft (50–100 μm)
Properties:
Excellent over tight rust. Tolerant of minimally prepared steel. May be applied to a wide range of surfaces, but normally used on carbon steel and concrete. This is a premium system to use when cleaning must be minimal.
Limitations:
In order to cure properly, temperature must be above 50°F/10°C. For lower temperature requirements other aluminum epoxy/urethane mastics may be substituted.

table requires the same surface preparation. It is essential that the specified surface preparation be employed for the paint system to be effective.

Area 1: Mild Exposure

This is an area where structural steel is embedded in concrete, encased in masonry, or protected by noncorrosive-type fireproofing. In many instances, no coating will be applied to the steel. However, it is a good idea to coat the steel substrate with a protective coating to protect it during construction and in case it ends up being exposed either intentionally or accidentally.

A good practice would be to apply a general-use epoxy primer, 3 to 5 mil, dry film thickness (dft) (75 to 125 μm). If the surface cannot be abrasive blasted, a surface-tolerant epoxy mastic can be used. Recommended systems are found in Table 7.4 systems A and C.

Area 2: Temporary Protection; Normally Dry Interiors

This area consists of office space or dry storage areas (warehouses) or other locations exposed to generally mild conditions, or areas where oil-based paints presently last for 10 or more years. If located in an industrial environment, there is the possibility of exposure to occasional fumes, splashing, or spillage of corrosive materials. Because of this, it is suggested that an industrial-grade acrylic coating system or a single coat of epoxy be applied.

This recommendation is not suitable for interior surfaces that are frequently cleaned or exposed to steam cleaning. Refer to Area 4. Recommended for this area are systems A and C in Table 7.4.

TABLE 7.4
Multilayer Paint Systems for New Clean Surfaces, Free of Chemical Contamination

System A: Epoxy Mastic

Paint layers:
One coat epoxy mastic: 3–5 mil dft (75–125 μm)
Properties:
Good color selection, excellent chemical resistance, good physical characteristics, ease of maintenance. Used on carbon steel, concrete masonry units, masonry block (a filler is recommended), sheet rock (a sealer is required), wood, polyvinyl chloride, galvanized steel, and other surfaces.
Limitations:
This is a two-component material that is mixed just prior to application. Additional equipment is required and more expertise to apply than a single packaged product. Epoxy solvents may be objectionable to some people.

System B: Acrylic Primer/Acrylic Intermediate/Acrylic Finish

Paint layers:
One coat acrylic primer: 2–3 mil dft (50–75 μm)
One cost acrylic intermediate: 2–3 mil dft (50–75 μm)
One coat acrylic finish: 2–3 mil dft (50–75 μm)
Properties:
This is a single-package, water-based, low-odor, semigloss paint. It possesses excellent weathering and acid resistance. Can be used on most surfaces, including carbon steel, concrete, concrete masonry units, masonry block (a block filler is recommended), sheet rock (a sealer is required), wood, polyvinyl chloride, galvanized steel, stainless steel, copper, and fabric. Can be applied over existing coatings of any type, including inorganic zinc.
Limitations:
Must be protected from freezing during shipping and storage. For application, temperature must be above 60° (16°C) and will remain so for 2 to 3 hr after application.

System C: Acrylic Primer/Acrylic Finish

Paint layers:
One coat acrylic primer: 2–3 mil dft (50–75 μm)
One coat acrylic finish: 2–3 mil dft (50–75 μm)
Properties:
Excellent weathering and acidic chemical resistance, with good color selection.
Limitations:
For best performance, metallic surfaces should be abrasive blasted. For mild conditions, hand or power cleaning may be sufficient. Paint must be applied when temperature exceeds 60°F (16°C).

Area 3: Normally Dry Exteriors

This includes such locations as parking lots, water storage tanks, exterior storage sheds, and lighting and power line poles, which are exposed to sunlight in a

TABLE 7.5
Multilayer Paint Systems Requiring an Abrasive Blast to the Substrate Surface

System A: Epoxy Primer/Polyurethane Finish

Paint layers:
One coat epoxy primer: 3–5 mil dft (75–125 μm)
One coat polyurethane finish: 2–3 mil dft (50–75 μm)
Properties:
Two coat protection is provided with excellent high gloss finish and long-term color gloss retention. Normally applied to carbon steel and concrete.
Limitation:
Because these are two-component materials, they must be mixed just prior to application and require additional equipment and more expertise to apply.

relatively dry location. Under these conditions, oil-based paints should last 6 or more years. Materials resistant to UV rays and normally rated for exterior use include acrylics, alkyds, silicones, and polyurethanes.

Epoxies will lose gloss, normally chalk, and fade rapidly when exposed to UV rays. Recommended systems include A in Table 7.3, C in Table 7.4, A in Table 7.5, and A in Table 7.6.

Area 4: Freshwater Exposure

In this category the surface to be protected is frequently wetted by fresh water from condensation, splash, or spray. Included are interior and exterior areas that are frequently exposed to cleaning or washing, including steam cleaning.

TABLE 7.6
Multilayer Paint Systems for Previously Painted Surfaces That Have Had Loose Paint and Rust Removed by Hand Cleaning

System A: Oleoresin

Paint layers:
One coat oleoresin: 2–4 mil dft (50–100 μm)
Properties:
This very slow-drying material penetrates and protects existing surfaces that cannot be cleaned properly with a single coat. Provides long-term protection without peeling, cracking, and other such problems. Easy to apply by spray, brush, roller, or glove. Normally used on carbon steel and weathering galvanized steel.
Limitations:
This material is designed to protect steel that will not see physical abuse. It also stays soft for an extended period of time.

The systems used for these surfaces make use of inorganic zinc as a primer. Inorganic zinc is the best coating that can be applied to steel because it provides the longest-term protection. In some situations, it may be necessary to substitute an organic zinc (an organic binder such as epoxy or polyurethane with zinc added) for the inorganic zinc.

Recommended systems are B, C, and E in Table 7.1 and A in Table 7.3.

Area 5: Saltwater Exposure

This area includes interior or exterior locations on or near a seacoast, or industrial environments handling brine or other salts. Under these conditions, the surfaces are frequently wet from salt water, to include condensation, splash, or spray.

Conditions in this area are essentially the same as for fresh water and the comments for Area 4 apply here. Because of the more severe conditions, it is recommended that two coats of primer be applied for system E of Table 7.1 and system A of Table 7.3.

Recommended systems are B, C, and E in Table 7.1 and system A in Table 7.3.

Area 6: Freshwater Immersion

Wastewaters are also part of this area. Included are all areas that remain underwater for periods longer than a few hours at a time. Potable and industrial waste liquids are all included.

If the systems recommended will be used as a tank lining material, it is important that the application be performed by experienced workers. In addition, if the coating that will be applied is to come into contact with potable water, it is important that the material selected meets the necessary standards and is approved for use by the local health department. Two coats of epoxy (system D in Table 7.2) are frequently used for this service.

Recommended systems are F in Table 7.1 and systems A, D, E, and F in Table 7.2.

Area 7: Saltwater Immersion

Areas that remain underwater in a coastal or industrial area, or that are constantly subjected to flowing salt- or brine-laden water are included in this category. Because of the increased rate of corrosion, a third coat may be added to system F in Table 7.2 and systems A and E in Table 7.1 as additional protection against this more severe corrosion.

System D in Table 7.1 and systems A, E, and F in Table 7.2 are recommended for this service.

Area 8: Acidic Chemical Exposure (pH 2.0–5.0)

In chemical process industries, this is one of the most severe environments encountered. When repainting, it is important that all surfaces are clean of any

chemical residue. Inorganic zinc and zinc-filled coatings are not recommended for application in this area.

The system selected will depend on the quality of surface preparation, length of chemical exposure, and housekeeping procedures. Decreased clean-up and longer exposure times require a more chemical-resistant coating system such as system I in Table 7.1.

Other recommendations for this area include systems D, G, and I in Table 7.1 and system B in Table 7.4.

Area 9: Neutral Chemical Exposure (pH 5.0–10.0)

This is an area that is not subject to direct chemical attack but may be subject to fumes, spillage, or splash. Under these conditions, more protection is required than that supplied by a standard painting system. This would include such locations as clean rooms, packaging areas, hallways, enclosed process areas, instrument rooms, electrical load centers, and similar locations.

A list of potential chemicals that come in contact with the coating aids in the coating selection. Knowledge of clean-up procedures will also prove helpful. It may be possible to use systems requiring less surface preparation, such as system D in Table 7.1, system A in Table 7.3, system A in Table 7.4, and system A in Table 7.5.

Recommendations for area 9 are systems A and D in Table 7.1, system A in Table 7.3, systems A and C in Table 7.4, and system A in Table 7.5.

Area 10: Exposure to Mild Solvents

This is intended for locations subject to intermittent contact with aliphatic hydrocarbons such as mineral spirits, lower alcohols, glycols, etc. Such contact can be the result of splash, spillage, or fumes.

Cross-linked materials, such as epoxies, are best for this service because solvents will dissolve single-package coatings. A single coat of organic zinc is an excellent choice for immersion service solvents or for severe splashes and spills.

The gloss of a coating system is often reduced as a result of solvent splashes or spills. However, this is a surface effect that usually does not affect the overall protective properties of the coating.

Recommended systems for use in this location are A, D, and G in Table 7.1.

Area 11: Extreme pH Exposure

This covers locations that are exposed to strong solvents, extreme pH values, oxidizing chemicals, or combinations thereof with high temperatures. The usual choices for coating these areas are epoxy novalacs, epoxy phenolics, and high-build polyurethanes. Other special coatings such as the polyesters and vinyl esters can also be considered. However, these systems require special application considerations.

Regardless of which coating system is selected, surface preparation is important. An abrasive blast, even on concrete, is required. In addition, all surface contaminants must be removed. When coating concrete, a thicker film is required. System F in Table 7.2 is recommended for optimum protection.

Recommended for this location are system I in Table 7.1 and systems B, C, and F in Table 7.2.

Summary

The foregoing have been generalizations as to what environmental conditions can be encountered, along with suggested systems to protect the substrate. Data presented will act as a guide in helping the reader select the proper coating system. As mentioned, these tables are general in nature. Regardless of which areas the reader is concerned with, it is important to know specifically which acid, solvent, alkali, or chemical will be encountered in order to select the proper coating system. Keep in mind that surface preparation is critical and should not be skimped on.

EXPECTED LONGEVITY

The duration of corrosion protection afforded by the coating system is of major importance. Most commonly, once a decision has been made to coat, it is desirable to have the coating last as long as reasonably possible. On the other hand, if protection longevity is not of utmost concern, less expensive systems can be chosen. The automotive industry has long been accused of planned obsolescence — and auto body rust-through and corrosion deterioration are said to be factors in this. Some automobile manufacturers are now advertising their use of more corrosion-resistant paints and materials; but, for the most part, automobile finishes do not last more than a few years. Similarly, porch and lawn furniture and original equipment manufactured (OEM) items, such as motor housing, pipe, conduit, and electrical boxes, are painted to look good at the time of sale. However, if long-term corrosion protection is needed, a special painting order must be placed far in advance, or additional painting for protection must be done by the purchaser. Many industrial organizations and nuclear power facilities purchase unpainted or OEM painted items and then routinely repaint with a more protective coating system before placing the item in service.

COST

Cost is always a consideration on any project. Many factors must be taken into account when estimating the cost of applying paint for corrosion protection.

Most painting operations can be performed more economically in a fabricating shop or commercial coating facility. Surface preparation can be done by

chemical cleaning in shop facilities. Automated facilities and controlled environments are available for chemical and shop blast cleaning. By the same token, during the application of the coating and during the cure period, conditions can be relatively controlled. The result is a superior coating job at a reduced cost.

In almost every case, painting in a shop or commercial facility is less expensive than painting at the job site. The painting of structural steel is almost always cheaper when done on the ground rather than in the air.

As a rule of thumb, surface preparation of a material to be used in a corrosive environment costs as much as 50% or more of the total painting cost. In many cases, specifiers are "penny wise and pound foolish" when they specify a good commercial or near-white metal blast cleaning followed by the application of an oil-based paint. These paints oxidize and age in the atmosphere and, because of their oil, have good wetting and penetrating properties (enabling their application to poorly prepared surfaces). A more suitable choice of paint to apply over a thoroughly blast-cleaned surface would be a synthetic resin coating, or zinc-rich primer, which in most cases can be applied at approximately the same cost but provides far superior corrosion protection.

Table 7.7 illustrates a cost comparison using expensive and cheap paints. The initial savings using the cheap paint usually cannot be justified for corrosion protection. The cost of paint is only a minor cost in the cost of a total coating job.

TABLE 7.7
Cost of Painting: Cheap vs. Expensive Paint

	Cheap Paint	Expensive Paint
Prime		
Cost per gallon	$10.50	$20.00
Coverage per gallon	200 ft^2	250 ft^2
Thickness per coat	1 mil	1 mil
Body		
Cost per gallon	$10.50	$16.00
Coverage per gallon	200 ft^2	175 ft^2
Thickness per coat	1 mil	2 mil
Material cost/coat for prime	—	5.6 cents
Material cost/coat for body	5.25 cents	9.0 cents
Number of coats for 5 mil	5	3
Paint thickness obtained	5 mil	5 mil
Cost/ft^2	26.25 cents	23.6 cents
Material		
Surface preparation	40.0 cents	40.0 cents
Application labor	35.5 cents	20.5 cents
Scaffolding, misc.	6.0 cents	6.0 cents
Total direct applied cost	107.75	90.1

ENVIRONMENTAL COMPLIANCE

Legislation is a force that limits the use of potentially harmful or toxic coating materials and regulates surface preparation and coating application techniques. Restrictions on the VOC (volatile organic compound) content of coatings have been legislated by many air pollution control districts. Such legislation prohibits the manufacture, sale, or use of designated industrial maintenance primers and topcoats if the VOC content exceeds certain limits (commonly 420 g/L; 3.5 lb/gal for most paints). It has been determined that almost all volatilizing solvents react under the influence of UV light and degrade to form smog and deplete the ozone layer. As a result of such legislation, many coating manufacturers are formulating water-based paints, or high-solids (low solvent) coating materials to comply with these environmental regulations. In addition, new VOC-compliant paints are being formulated without the use of lead, chromate, or other toxic pigments.

Other regulations deal with the removal of old lead-containing paints. Of concern are the many industrial facilities and highway bridges from which these paints must be removed prior to repainting. Legislation requires the disposal of removed paints (and spent abrasive) in hazardous waste disposal sites if the leakage after acid digestion (pH 5) contains more than 5 ppm lead or chromate and 2 ppm mercury. The costs of such a disposal, not including collection costs, are estimated by painting contractors to be from 6 to 10 times as much as disposal costs in a normal sanitary landfill. The cost of containing the spent abrasive and paint, as opposed to letting the spent abrasive fall to the ground during blast cleaning, may in itself double or triple the cost of the paint job.

When removing coatings by blast cleaning, non-free-silica-containing abrasives should be used, and care must be taken to minimize worker exposure to inhalation or ingestion of toxic pigments and to prevent environmental contamination from the cleaning and paint operations. These considerations will have an influence on the selection of a coating system and the prerequisite surface preparation and choice of application requirements. New VOC-compliant paints are being formulated without the use of lead, chromate, and other toxic pigments.

SAFETY

At times it may be necessary to anticipate safety considerations other than the normal requirements of ventilation, removal of solvents from a coating application area, suitable and safe access to the work area, etc. For example, most steelworkers on high steel, such as bridges or tall buildings, dislike walking on painted steel because of its slickness, and depending on the paint color, the concealment of puddled water or surface ice. This concern tends to eliminate most “barrier”-type coatings, but would permit most zinc-rich coatings. Some coatings (notably zinc-rich coatings) are formulated and applied as preconstruction primers — to allow flame cutting without detrimental fumes or weld quality deficiencies.

EASE OF MAINTENANCE AND REPAIR

Thermosetting and zinc-rich coatings, although providing good long-term protection, are more difficult to touch up or repair in the event of physical damage or localized failure. Coatings applied to older-aged epoxy, urethane, or other catalyzed coatings often result in poor adhesion, which results in peeling.

Thermoplastic coatings do not normally suffer this disadvantage because solvents in the freshly applied coating soften and allow for intermolecular mixing of the new and old coatings, resulting in good intercoat adhesion.

Heavily pigmented coatings (such as zinc-rich) require agitated pots to keep the pigment in suspension during application; consequently, touch-up and repair of large areas must be done by spray using an agitated pot.

Oil-based coatings (alkyds, epoxy esters, and modifications thereof) have a greater tolerance for poor surface preparation and an ability to wet, penetrate, and adhere to poorly prepared surfaces or old coatings. As a result, these coatings are often specified although they offer less long-term environmental protection.

DECORATION/AESTHETICS

From a corrosion-protection viewpoint, this factor is probably of least importance. The more corrosion-resistant paints are available in grays, whites, and some pastel colors. However, aliphatic urethanes, which are relatively expensive, offer good chemical and environmental resistance. They offer superior tinting ability, color, and gloss retention over other coatings. These properties have been responsible for their use on railroad cars, water and fuel oil storage tanks close to public thoroughfares, aircraft, and many structures for which public visibility is high and appearance is important.

Certain other coatings can be modified with acrylics, silicones, and other resins at increased cost to improve their aesthetic appeal.

8 Organic Coatings for Immersion

On many occasions, lining, coating, and paint terminologies are used interchangeably. Technically, linings and paints are both coatings. Usually, a coating is referred to as a lining when subjected to immersion, such as the interior of a vessel; and paints refer to applications of protective materials used to guard against atmospheric corrosion. This chapter deals with coatings that are used to protect the interior of a vessel and will be subject to immersion.

Of the various coating applications, the most critical is that of a tank lining application. Liquid applied linings are coatings that can be spray applied or troweled. The material must be resistant to the corrodent and be free of pinholes through which corrosives might penetrate and reach the substrate. The severe attack that many corrosives have on the bare tank emphasizes the importance of using the correct material and the correct procedure in lining a tank to obtain a perfect coating. It is also essential that the tank be designed and constructed in the proper manner to permit a perfect lining to be applied.

In a tank lining there are usually four areas of contact with the stored product that may lead to different types of corrosion. These areas are the vapor phase (the area above the liquid level), the interphase (the area where the vapor phase meets the liquid phase), the area always immersed, and the bottom of the tank (where moisture and other contaminants of greater density may settle). Each of these areas can, at one time or another, be more severely attacked than the rest, depending on the type of material contained, the impurities present, and the amounts of oxygen and water present. In view of this, it is necessary to understand the corrosion resistance of the coating material under each condition, and not only the immersed condition.

Other factors that have an effect on the performance of the coating material are vessel design, vessel preparation prior to coating, application techniques of the coating material, curing of the coating, inspection, operating instructions, and temperature limitations. In general, the criteria for tank linings are given in Table 8.1.

DESIGN OF THE VESSEL

All vessels to be coated internally (lined) should be of welded construction. Riveted tanks will expand or contract, thus damaging the lining and causing leakage. Butt welding is preferred, but lap welding can be used, providing a fillet weld is used and all sharp edges are ground smooth (see Figure 8.1). Butt welds need not be ground flush but they must be ground to a smooth

TABLE 8.1
Criteria for Tank Linings

1. Design of the vessel
2. Lining selection
3. Shell construction
4. Shell preparation
5. Lining application
6. Cure of the lining material
7. Inspection of the lining
8. Safety
9. Causes of failure
10. Operating instructions

rounded contour. A good way to judge a weld is to run your finger over it. Sharp edges can be detected easily. All weld spatter must be removed (see Figure 8.2).

Any sharp prominence may result in a spot where the film thickness will be inadequate and noncontinuous, thus causing premature failure.

If possible, avoid the use of bolted joints. Should it be necessary to use a bolted joint, it should be made of corrosion-resistant materials and sealed shut. The mating surface of steel surfaces should be gasketted. The coating material should be applied prior to bolting.

Do not use construction that will result in the creation of pockets or crevices that will not drain or that cannot be properly sandblasted and coated (see Figure 8.3).

All joints must be continuous and solid welded. All welds must be smooth with no porosity, holes, high spots, lumps, or pockets (see Figure 8.4).

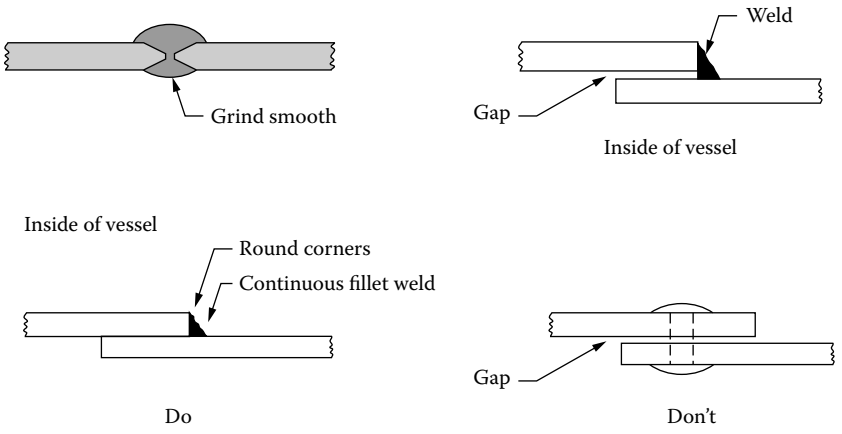


FIGURE 8.1 Butt welding is preferred rather than lap welding or riveted construction.

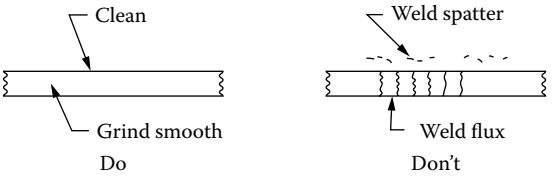


FIGURE 8.2 Remove all weld spatter and grind smooth.

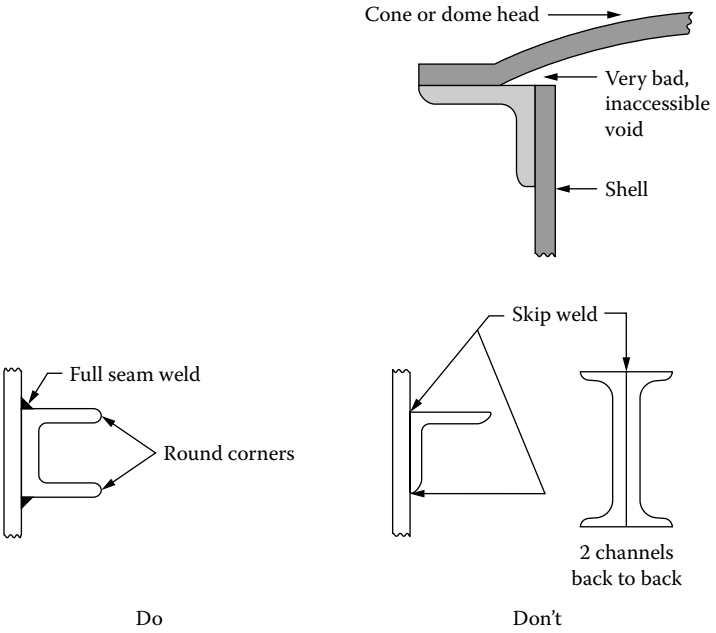


FIGURE 8.3 Avoid all pockets or crevices that cannot be properly sandblasted and lined.

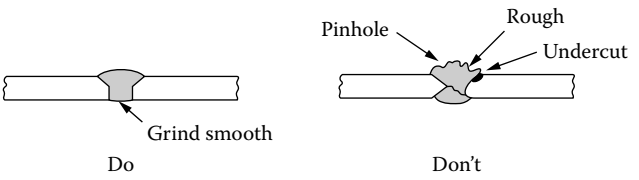


FIGURE 8.4 All joints must be continuous solid welded and ground smooth.

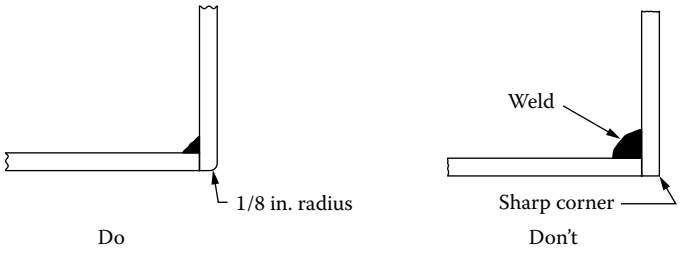


FIGURE 8.5 Grind all sharp edges to a minimum 1/8-in. radius.

All sharp edges must be ground to a minimum 1/8-in. radius (Figure 8.5).

Outlets must be of the flanged or pad type rather than threaded. If pressure requirements permit, use slip-on flanges because the inside diameter of the attaching weld is readily available for radiusing and grinding. If pressure dictates the use of weld neck flanges, the inside diameter of the attach-weld is in the throat of the nozzle. It is therefore more difficult to repair surface irregularities, such as weld under-cutting, by grinding (see Figure 8.6).

Stiffening members should be placed on the outside of the vessel rather than on the inside (Figure 8.7).

Tanks larger than 25 ft in diameter may require three manways for working entrances. Usually, two are located at the bottom (180° apart) and one at the top. The minimum opening is 20 in., but 30-in. openings are preferred.

On occasion, an alloy is used to replace the steel bottom of the vessel. Under these conditions, galvanic corrosion will take place. If a coating is applied to the steel and for several inches (usually 6 to 8 in.) onto the alloy, any discontinuity in the lining will become anodic. Once corrosion starts, it progresses rapidly because of the bare alloy cathodic area. Without the coating, galvanic corrosion would cause the steel to corrode at the weld area, but at a much lower rate. The recommended practice therefore is to line the alloy completely as well as the steel, thereby eliminating the possible occurrence of a large cathode-to-small anode area (see Figure 8.8).

It is important that processing liquor is not directed against the side of the tank, but rather toward the center. Other appurtenances inside the tank must be located for accessibility of coating. Heating elements should be placed with a minimum clearance of 6 in. Baffles, agitator base plates, pipes, ladders, and other items can either be coated in place, or detached and coated before installation. The use of complex shapes such as angles, channels, and I beams should be avoided. Sharp edges should be ground smooth and should be fully welded. Spot welding or intermittent welding should not be permitted. Gouges, hackles, deep scratches, slivered steel, or other surface flaws should be ground smooth.

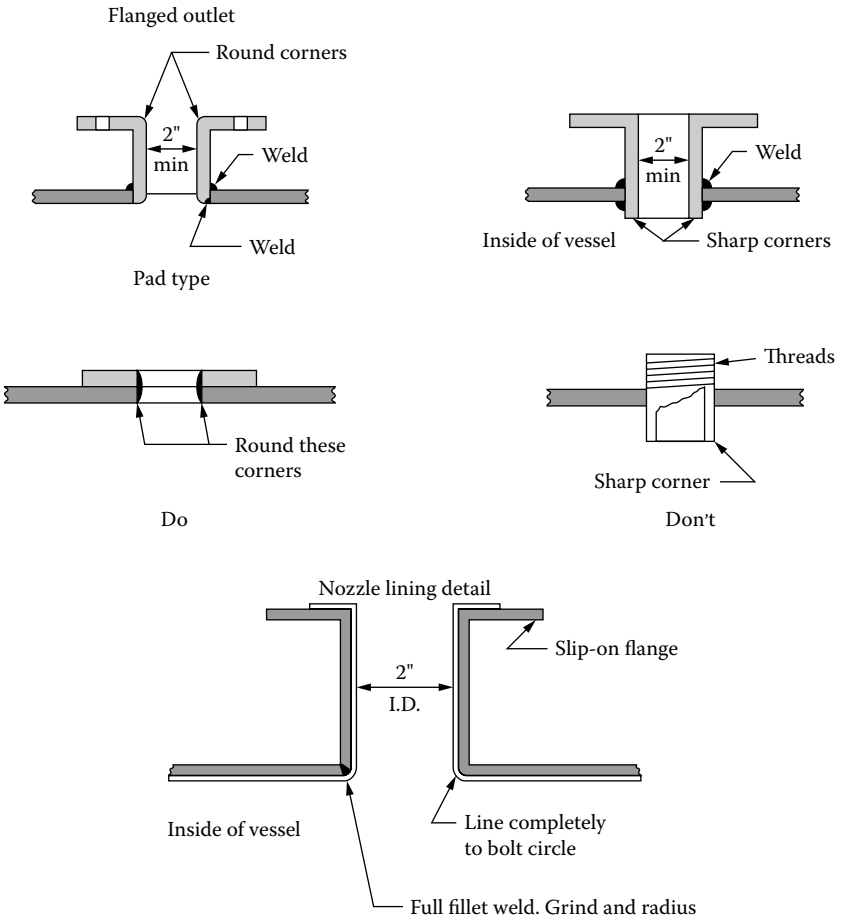


FIGURE 8.6 Typical vessel outlets.

Concrete tanks should be located above the water table. They require special coating systems. Unless absolutely necessary, expansion joints should be avoided. Small tanks do not normally require expansion joints. Larger tanks can make use of a chemical-resistant joint such as polyvinyl chloride (PVC). Any concrete curing compound must be compatible with the coating material or removed before application. Form joints must be as smooth as possible. Adequate steel reinforcement must be used in a strong, dense, concrete mix to reduce movement and cracking. The coating manufacturer should be consulted for special instructions. Concrete tanks should be coated only by a licensed applicator.

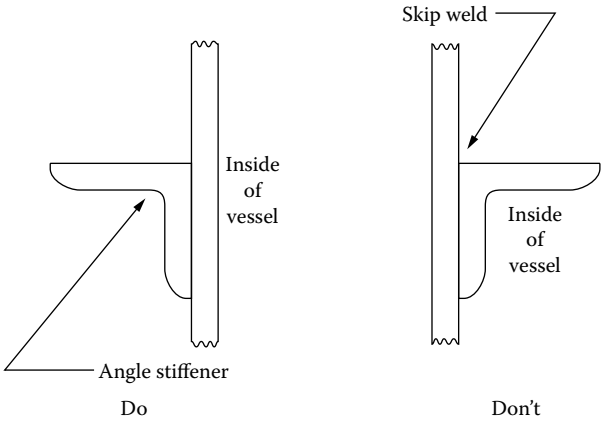


FIGURE 8.7 Stiffening members should be on the outside of the vessel.

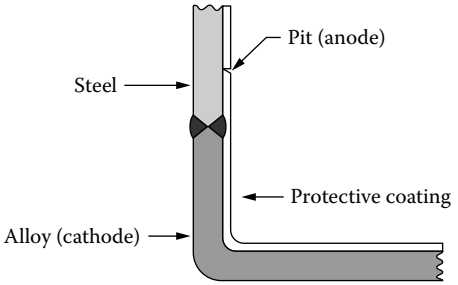


FIGURE 8.8 Potential galvanic action.

COATING SELECTION

The primary function of a coating system is to protect the substrate. An equally important consideration is product purity protection. The purity of the liquid must not be contaminated with by-products of corrosion or leachate from the coating system itself. Selection of a coating material for a stationary storage tank dedicated to holding one product at more or less constant times and temperature conditions is relatively easy because such tanks present predictable conditions for coating selection. Conversely, tanks that see intermittent storage of a variety of chemicals for solvents, such as product carriers, present a more difficult problem because the parameters of operation vary. Consideration must be given to the effect of cumulative cargoes. In addition, abrasion resistance must be considered if the product in the tank is changed regularly, with complete cleaning required between loadings. Workers and equipment will abrade the coating.

When selecting a coating system, it is necessary to determine all the conditions to which the coating will be subjected. The conditions to be considered fall into two general categories:

1. Chemicals to which the coating will be exposed
2. Conditions of operation

As a result, it is necessary to verify that the chemical resistance and physical/mechanical properties of the coating are suitable for the application.

To specify a coating material, it is necessary to know specifically what is being handled and under what conditions. The following information must be known about the material being handled:

1. What are the primary chemicals being handled, and at what concentrations?
2. Are there any secondary chemicals and, if so, at what concentrations?
3. Are there any trace impurities or chemicals present? This is extremely important because concentrations in the ppm range can cause serious problems.
4. Are there any solids present and, if so, what are the particle sizes and concentrations?
5. Will there be any agitation?
6. What are the fluid purity requirements?
7. What will be present in the vapor phase above the liquor?

The answers to these questions will narrow the selection to those coatings that are compatible. Table 8.2 provides a list of typical lining materials and their general areas of application.

Answers to the next set of questions will narrow the selection to those materials that are compatible, as well as to those coating systems that have the required physical and/or mechanical properties.

1. What is the normal operation temperature and temperature range?
2. What peak temperatures can be reached during shutdown, start-up, process upset, etc.?
3. Will any mixing areas exist where exothermic heat of mixing temperatures may develop?
4. What is the normal operating pressure?
5. What vacuum conditions and range are possible during operation, start-up, shutdown, and upset conditions?

The size of the vessel must also be considered in the coating selection. If the vessel is too large, it may not fit in a particular vendor's oven for curing of the coating. Also, nozzle diameters 4 in. and less are too small to spray-apply a liquid coating. When a coating is to be used for corrosion protection,

TABLE 8.2
Typical Lining Materials

Lining Material	Applications
High-bake phenolic	Excellent resistance to acids, solvents, food products, beverages and water. Most widely used lining material, but has poor flexibility compared with other lining materials.
Modified air-dry phenolics (catalyst required)	Nearly equal in resistance to high-bake phenolics. May be formulated for excellent resistance to alkalies, solvents, salt water, deionized water, fresh water, and mild acids. Excellent for dry products.
Modified PVC polyvinyl chloroacetals, air-cured	Excellent resistance to strong mineral acids and water. Most popular lining for water storage tanks; used in water immersion service (potable and marine) and beverage processing.
PVC plastisols	Acid resistant; must be heat cured.
Hypalon	Chemical salts.
Epoxy (amine catalyst)	Good alkali resistance. Fair to good resistance to solvents, mild acids, and dry food products. Finds application in covered hopper-car linings and nuclear containment facilities.
Epoxy polyamide	Good resistance to water and brines. Used in storage tanks and nuclear containment facilities. Poor acid resistance and fair alkali resistance.
Epoxy polyester	Good abrasion resistance. Used for covered hopper-car linings. Poor solvent resistance.
Epoxy coal tar	Excellent resistance to mild acids, mild alkalies, salt water, and fresh water. Poor solvent resistance. Used for crude oil storage tanks, sewage disposal plants, and water works.
Coal tar	Excellent water resistance. Used for water tanks.
Asphalts	Good acid and water resistance.
Neoprene	Good acid and flame resistance. Used for chemical processing equipment.
Polysulfide	Good water and solvent resistance.
Butyl rubber	Good water resistance.
Styrene-butadiene polymers	Finds application in food and beverage processing and in the lining of concrete tanks.
Rubber latex	Excellent alkali resistance. Finds application in caustic tanks (50–73%) at 180°F (82°C) to 250°F (121°C).
Urethanes	Superior abrasion resistance. Excellent resistance to strong mineral acids and alkalies. Fair solvent resistance. Used to line dishwashers and washing machines.
Vinyl ester	Excellent resistance to strong acids and better resistance up to 350°F (193°C) to 400°F (204°C), depending upon thickness.
Vinyl urethanes	Finds application in food processing, hopper cars, and wood tanks.
Fluoropolymers	High chemical resistance and fire resistance. Used in SO_2 scrubber service.

TABLE 8.2 (Continued)
Typical Lining Materials

Lining Material	Applications
Vinylidene chloride latex	Excellent fuel oil resistance.
Alkyds, epoxy esters, oleoresinous primers	Water immersion applications and as primers for other top coats.
Inorganic zinc, water-based postcure, and water-based self-cure	Jet fuel storage tanks and petroleum products.
Inorganic zinc, solvent-based self-curing	Excellent resistance to most organic solvents (aromatics, ketones, and hydrocarbons), excellent water resistance. Difficult to clean. May be sensitive to decomposition products of materials stored in tanks.
Furan	Most acid resistant organic polymer. Used for stack linings and chemical treatment tanks.

it is necessary to review the corrosion rate of the immersion environment on the bare substrate. Assuming that the substrate is carbon steel with a corrosion rate of less than 10 mil per year (mpy) at the operating temperature, pressure, and concentration of corrodent, then a thin film lining of less than 20 mil can be used. For general corrosion, this corrosion rate is not considered severe. However, if a pinhole should be present through the lining, a concentration of the corrosion current density occurs as a result of the large ratio of cathode to anode area. The pitting corrosion rate will rapidly increase above the 20-mpy rate and through-wall penetration can occur in months.

When the substrate exhibits a corrosion rate in excess of 10 to 20 mpy, a thick film coating exceeding 20 mil in thickness is used. These thicknesses are less susceptible to pinholes.

Thin linings are used for overall corrosion protection as well as for combating localized corrosion such as pitting and stress cracking of the substrate. Thin fluoropolymer coatings are used to protect product purity and to provide nonstick surfaces for easy cleaning.

Among the materials available for thin coatings are those based on epoxy and phenolic resins that are 0.15 to 0.30 mm (0.006 to 0.12 in.) thick. They are either chemically cured or heat baked. Baked phenolic coatings are used to protect railroad tank cars transporting sulfonic acid. Tanks used to store caustic soda (sodium hydroxide) have a polyamide cured epoxy coating.

Thin coatings of sprayed and baked FEP, PFA, and ETFE are also widely used. They are applied to primed surfaces as sprayed water-borne suspensions or electrostatically charged powders sprayed on a hot surface.

Each coat is baked before the next is applied. Other fluoropolymers can also be applied as thin coatings. These coatings can be susceptible to delamination in applications where temperatures cycle frequently between ambient and steam. Table 8.3 presents details about these coatings. Fluoropolymer thin coatings can also be applied as thick coatings.

When the corrosion rate of the substrate exceeds 10 mpy, thick coatings exceeding 2.5 mil (0.025 in.) are recommended. One such coating is vinyl ester reinforced with glass cloth or woven roving. Coatings greater than 125 mil (0.125 in.) thick can be sprayed or troweled. Maximum service temperature is 170°F (73°C). These coatings can be applied in the field and are used in service with acids and some organics.

Another thick coating material for service with many acids and bases is plasticized PVC. This has a maximum operating temperature of 150°F (66°C).

Sprayed and baked electrostatic powder coatings of fluoropolymers, described under thin coatings, can also be applied as thick coatings. One such coating is PVDF and glass or carbon fabric.

Manufacturers and/or other corrosion engineers should be consulted for case histories of identical applications. Included in the case history should be the name of the applicator who applied the coating, application conditions, type of equipment used, degree of application difficulty, and other special procedures required. A coating with superior chemical resistance will fail rapidly if it cannot be properly applied, so it is advantageous to learn from the experience of others.

To maximize sales, coating manufacturers formulate their products to meet as broad a range as possible of chemical and solvent environments. Consequently, a tank coating may be listed as suitable for in excess of 100 products with varying degrees of compatibility. However, there is a potential for failure if the list is viewed only from the standpoint of the products approved for service.

If more than one of these materials listed as being compatible with the coating is to be used, consideration must be given to the sequence of use in which the chemicals or solvents will be stored or carried in the tank. This is particularly critical when the cargo is water miscible (for example, methanol or cellosolve) and is followed by a water ballast. A sequence such as this creates excessive softening of the film and makes recovery of the lining film more difficult, and thus prone to early failure.

Certain tank coating systems may have excellent resistance to specific chemicals for a given period of time, after which they must be cleaned and allowed to recover for a designated period of time in order to return to their original resistance level. Thirty days is a common period of time for this process between chemicals such as acrylonitrile and solvents such as methanol.

In some cases, the density of cure can be increased by loading a hot, mildly aggressive solvent at a later date. Ketamine epoxy is such an example. There have been cases where three or four consecutive hot mild cargoes have increased the density of the lining to such an extent that the ketamine epoxy lining was resistant to methanol. Under normal circumstances ketamine is not compatible with methanol.

TABLE 8.3
Fluoropolymer Lining Systems

Lining System	Thickness, in. (mm)	Maximum Size	Design Limits	Installation	Repair Considerations
			Sprayed Dispersions		
FEP	0.04 (1.0)				
PFA	0.01–0.04 (0.25–1.0)				
PVDF	0.025–0.03 (0.06–0.76)				
PFA with mesh and carbon	0.08 (2.0)				
PVDF with mesh and carbon	0.04–0.09 (1.0–2.30)	8ft (2.4 m) dia. 40 ft (12.2 m) length	Pressure allowed. Vacuum rating undetermined.	Primer and multiple coats with combination 2 psig equipment. Each coat is baked.	Hot patching is possible, but testing is recommended.
			Electrostatic Spray Powders		
ETFE	Up to 0.09 (2.3)	8 ft (2.4 m) dia. 40 ft (12.2 m) length	Pressure allowed. Vacuum rating undetermined.	Primer and multiple coats applied with electrostatic spraying equipment. Each coat is baked.	Hot patching is possible, but testing is recommended.
FEP	0.01–(0.28)				
PFA	0.01 (0.28)				
ECTFE	0.06–0.07 (1.5–1.8)				
PVDF	0.025 (0.64)				

When case histories are unavailable, or manufacturers are unable to make a recommendation, it will be necessary to conduct tests. This can occur in the case of a proprietary material being handled or if a solution might contain unknown chemicals. Sample panels of several coating systems should be tested for a minimum of 90 days, with a 6-month test being preferable. Because of normal time requirements, 90 days is standard.

The test must be conducted at the maximum operating temperature to which the coating will be subjected and should simulate actual operating conditions, including washing cycles, cold wall, and the effects of insulation.

Other factors to consider in coating selection include service life, maintenance cycles, operating cycles, and the reliability of the coating. Different protective coatings provide different degrees of protection for different periods of time at a variety of costs. Allowable downtime of the facility for inspection and maintenance must also be considered, in terms of frequency and length of time.

Once the coating system has been selected, recommendations from the manufacturer as to a competent applicator should be requested and contact made with previous customers.

SHELL CONSTRUCTION

In the design section, several features of construction were discussed. It is important that the finished vessel shell be thoroughly inspected to ensure that the vessel has been fabricated and finished in accordance with the specifications. Such items as sharp corners and rough welds may have been overlooked by the fabricator.

On occasion, it may be necessary that certain parts of the tank, such as the bottom plate for a center post, need to be dismantled and coated separately. This particular section would then be reassembled after the tank is blast cleaned and lined.

SHELL PREPARATION

For the coating material to obtain maximum adhesion to the substrate, it is essential that the surface be absolutely clean. All steel surfaces to be coated must be abrasive blasted to a white metal in accordance with SSPC Specification SPS-63 or NACE Specification 1. A white metal blast is defined as removing all rust, scales, paints, etc. to a clean white metal that has a uniform gray-white appearance. No streaks or stains of rust or any other contaminants are permitted on the surface. At times, a near-white blast-cleaned surface equal to SSPC-SP 10 can be used. Because this is less expensive, it should be used, providing the coating manufacturer permits it.

All dust and spent abrasive must be removed from the surface by vacuum cleaning or brushing. After blasting, all workers coming into contact with the clean surface should wear clean, protective gloves and clothing to prevent contamination of the cleaned surface. Any contamination may cause premature failure by osmotic blistering or adhesion loss. The first coat must be applied before the surface starts to rust. If the blasted surface changes color, or rust bloom begins to form, the surface must be reblasted. Dehumidifiers and temperature controls are helpful.

It is important that no moisture or oil passes through the compressor and onto the blasted surface. Use a white rag to determine the quality. A black light can also be used to determine oil contamination. One hundred percent oil-free air can be supplied by rotary screw, two-stage lubrication-oil-free compressors.

Concrete surfaces must be clean, dry, and properly cured before applying the coating. All protrusions and form joints must be removed. All surfaces must be roughened by sandblasting to remove all loose, weak, or protruding concrete to open all voids and provide the necessary profile for mechanical adhesion of the coating. All dust must be removed by brushing or vacuuming. The coating manufacturer should be contacted for special priming and caulking methods.

COATING APPLICATION

The primary concern in applying a coating to a vessel is to deposit a void-free film of the specified thickness on the surface. Any area that is considerably less than the specified thickness may leave a noncontinuous film. Additionally, pinholes in the coating may cause premature failure.

Films that exceed the specified thickness always pose the danger of entrapping solvents, which can lead to poor adhesion, excessive brittleness, improper cure, and subsequent poor performance. Avoid dry-spraying of the coating material, as this causes the coating to be porous. If thinner, other than those recommended by the manufacturer are used, poor film formation may result. Do not permit application to take place below the temperature recommended by the manufacturer.

When selecting an applicator for the coating, it is important that the applicator selected be very familiar with and experienced in applying the coating to be used. Too often, the lowest bidder is selected without adequately considering the quality of workmanship, with the result of a tank coating failure. For a tank coating to be effective, a nearly perfect application is required. In view of this, a conscientious and knowledgeable applicator is needed.

When evaluating the qualifications of a tank coating contractor, ask what job he has done using the specified coating material and check his references. If possible, visit his facilities and inspect his workmanship before placing him on the bidder list. Precautions taken at this point will be repaid by assuring total performance.

CURING OF THE APPLIED COATING

Proper curing is essential if the coating is to provide the corrosion protection for which it was intended. Each coat must be cured using proper air circulation techniques. To obtain proper air circulation, it is necessary that the tank has at least two openings, one at the top and one at the bottom.

Because most solvents used in coating materials are heavier than air, the fresh air intake will be at the top of the vessel and the exhaust at the bottom. The temperature of the fresh air intake should be over 50°F (10°C) with a relative humidity of less than 89%. If possible, the fresh air intake should be fed by forced air fans.

A faster and more positive cure will be accomplished using warm forced air cure between coats and as a final cure. This will produce a dense film and tighter cross-linking, which provides superior resistance to solvents and moisture permeability.

Before placing the vessel in service, the coating should be washed down with water to remove any loose overspray. For coatings in contact with food products, a final warm, forced air cure and water wash are essential.

It is important that sufficient time is allowed to permit the coating to obtain a full cure. This usually requires 3 to 7 days. Do not skimp on this time.

When a tank is placed in service, operating instructions should be prepared and should include the maximum temperature to be used. The outside of the tank should be labeled "Do Not Exceed X°F (X°C). This tank has been coated with Y. It is to be used only for Z service."

INSPECTION OF THE LINING

Having a qualified inspector available throughout the project is highly recommended to guarantee a satisfactory coating application. The inspector should be involved with the job from the beginning. He should have an understanding of the design criteria of the vessel and the reasons for the specific design configurations. The inspector should participate in the following function:

1. Pre-work meetings
2. Selection of the contractor for fabrication and coating application
3. Surface preparation inspection
4. Coating application inspection
5. Daily inspection reports
6. Final acceptance report

The inspector should be involved with the selection of the fabricator and applicator of the coating. Again, the lowest bidder is not necessarily the best choice. The inspector should evaluate the fabricator and applicator before awarding the contract. In general, it is better to have the vessel fabricated and coated by the same contractor if possible. Evaluation should be made as to the experience the contractor has in applying the selected coating. His facility should be visited

and qualifications verified by checking on previous coating jobs he has done with the specified coating material.

Before application, the surface must be properly prepared to receive the coating, as detailed in the sections on shell construction and shell preparation. In addition, the surface profile should be checked. An adequate "key" must be provided to furnish a proper anchor pattern. Too little anchor pattern will result in too smooth a surface and therefore poor adhesion. Too deep a profile will require additional coating material. In general, the profile depth should be approximately 25% of the total lining thickness. On the basis of a 6-mil coating thickness, the profile depth should be 1.5 mil.

The type of abrasive employed will determine the profile depth. Profile depth in the field can be determined in one of many ways.

The Keane-Tator Profile Comparator contains a metal disk with nominal surface profiles of 0.5, 1, 2, 3, and 4 mil. This flashlight magnifier is used as a handy pocket-type comparator to check on the sandblasted cleaned surfaces. Metal disks for comparisons of anchor patterns prepared with grit or shot blast are also available.

A Testex Tape has been developed that is pressed into the profile, then removed, and the profile that remains on the tape is measured with a micrometer, subtracting the thickness of the tape.

Clemtex offers a series of four steel coupons with profile gauges ranging from 1 to 4 mil.

Once the surface has been prepared, the inspector must work quickly so that the application of the coating to the surface is not delayed. Normally, the steel can stand unprotected for a few hours before beginning the application without any detrimental effects.

Inspections should be made during and after each coating application. The coating should be checked for porosities and pinholing on the first visual inspection. After repairs of the visible defects, inspection may be done using low-voltage (75 V or less) holiday detectors that ring, buzz, or light up to show electrical contact through a porosity within the coating to the metal or concrete surfaces. By checking the coating in this manner during the first and second coats, such defects can be touched up and made free of porosities before applying the final topcoat.

Visual inspections are performed with either the unaided eye or by using a magnifying glass. In some cases, the use of telescopic observation or low-power magnification may be required. A pike magnifier is one of several types that can be used.

The inspector is able to identify missed areas, damaged areas, or thin areas by employing these visual techniques. Using instruments provides the inspector with a means to make an accurate appraisal of what dimensional requirements have been met by the applicator.

During and after each coating, the inspector should prepare an inspection report on the applicable items, as shown in Table 8.4.

After the final coat has been applied and the coating has been properly cured, the following tests should be conducted to verify that the lining has been properly cured.

TABLE 8.4
Inspection Report for Liquid Applied Linings

Item	Tank Lining	Concrete Surfacer	Concrete Topcoats
Pinholes	x	x	x
Blisters	x	x	x
Color and gloss uniformity			x
Bubbling	x	x	x
Fish eyes	x	x	x
Orange peel	x	x	x
Mud cracking	x	x	
Curing properties	x	x	x
Runs and sags	x	x	x
Film thickness, dry	x		
Film thickness, wet		x	x
Holidays, missed areas	x	x	x
Dry spray	x	x	x
Foreign contaminents	x	x	x
Mechanical damage	x	x	x
Uniformity	x	x	x
Adhesion	x	x	x

Sandpaper Test

When not properly cured, some coating materials will remain tacky. When abraded with fine sandpaper, no material should be seen on the face of the sandpaper. It should be removed as a fine powdery residue.

Hardness Test

Using your fingernail is a satisfactory way of determining hardness. If desired, a Barcol impressor, or a pencil hardness test, can be employed.

Adhesion

A pocketknife is the best instrument to use to test adhesion. Cut a "V" in the film and pick off the coating at the vertex. The coating should be very difficult to remove, indicating good adhesion.

Film Thickness

Dry film thicknesses on steel surfaces are determined by magnetic and eddy current nondestructive test instruments. The most popular instruments employ

the magnet principle measuring magnetic attraction, which is inversely proportional to the coating thickness. Examples are the BSA-Tinsley thickness gauge and the Elcometer 157 pulloff gauge.

The pulloff gauge is a rough guide to determine if the protective coating is within the thickness specification. The manufacturer's stated accuracy is 15%, provided the gauge is used within a true vertical plane. The accuracy is reduced when the gauge is used in a horizontal or overhead position. The pulloff gauge has other limitations in addition to accuracy:

1. The eye must record the coating thickness as the magnet breaks away from the coating.
2. Erroneous readings will result if the magnet is allowed to slide over the coating before breakaway or pulloff.

The type 7000 Tinsley gauge contains a dial-like scale with a balanced pointer that is not affected by angular positions. A direct readout from a locked-in zero reset is given with an accuracy of ±10%.

The "banana"-type thickness gauge is a more sophisticated version of the magnetic pulloff principle. A permanent magnet is mounted at one end of a balanced, pivoted arm assembly, and a coil spring is attached to the pivot and to a calibrated dial. The rotatable dial is moved forward until the magnet sticks to the lining. This unknown force is determined by rotating the dial backward, applying tension to the spring. When the spring tension exceeds the unknown magnetic attraction force, the magnet breaks contact with the coated surface. An audible click will be heard and the coating thickness will be shown on the calibrated dial.

There are several gauges that make use of the guided or controlled magnetic pulloff principle. These include Inspector thickness gauge Model 111 1E manufactured by Elcometer Instruments Ltd., the Mikrotest thickness gauge Model 102/FIM, and Mikrotest 11 FM manufactured by Elktro Physik, Cologne, West Germany.

These gauges will measure coating thickness in any position without recalibrating because the pivot arm is balanced. The Inspector gauge has an external calibration adjustment making use of a screwdriver slot located below the nameplate.

The Elcometric thickness gauge makes use of a magnetic reluctance technique. Reluctance is the characteristic of a material to resist the creation of a magnetic flux in that material (e.g., iron has less reluctance than air).

In this gauge, a permanent magnet is located between two soft iron poles resembling a horseshoe magnet. The magnet is adjustable to produce an air gap. In the center of this horseshoe is a meter-pointer assembly with a soft iron vane that creates a magnetic circuit with an indicating device that requires no power supply or battery.

When the Elcometer is placed on a dry coating applied to the steel, the magnetic flux will change in strength across the air gap in the magnetic circuit,

causing the meter pointer to move across a calibrated scale, indicating the coating thickness in either micrometers or mils.

When using the Elcometer, it is essential that the gauge be held at right angles to the surface being measured because tilting it will give erroneous measurements. The gauge must be recalibrated when changing from a vertical position to a horizontal or overhead position.

A small zero knob is located on the side of the instrument to permit external calibration. To take readings, it is necessary to depress a small button. This gauge is very sensitive to residual magnetism in the substrate, surface roughness, edge effect, and tilt of the head. Blind hole measurements cannot be made with this gauge.

Film thickness measurements should not be made close to the edge of a steel surface; the magnetic properties of the steel influence the reading, causing distorted results. It is recommended the measurements be made at least 1 in. away from the edge. Distorted readings can also result from angles, corners, welds, crevices, and joints. Always measure a clean surface, never an oily or dirty one.

Electronic gauges are also available that are more accurate than the mechanical units previously discussed. These include the Model 158 minitector thickness gauge and Model 102/F100 minitest gauge. The minitector gauge is portable and uses standard transistor radio batteries. It is manufactured by Elcometer Instruments Ltd. The minitest gauge is battery operated and comes with an automatic battery power-off switch to extend battery life. It is manufactured by Elektic Physik.

General Electric produces a model B thickness gauge that requires a 115-V power source and is not portable for field use.

SAFETY DURING APPLICATION

Many coating formulations contain solvents, making it necessary to take certain safety precautions. It is necessary that all coating materials and thinners be kept away from any source of open flame. This means that welding in adjacent areas must be discontinued during application and "no smoking" must be the rule during application.

A power air supply and ventilation must be provided during the application of the coating. The vapor concentration inside the vessel should be checked on a regular basis to ensure that the maximum allowable vapor concentration is not reached. For most solvents, a vapor concentration of between 2 and 12% in the air is sufficient to cause an explosion. As long as the vapor concentration is kept below the lower level, no explosion will take place. All electrical equipment must be grounded.

Because flammable solvents are being exhausted from the tank, precautions must be taken on the exterior of the tank. These flammable vapors will travel a considerable distance along the ground. No flames, sparks, or ungrounded equipment can be nearby.

Those applying the coating should wear fresh airline respirators and protective cream on exposed parts of the body. Water should be available for flushing accidental spills from the skin. Never allow one worker in the tank alone.

OSHA issues a form called the Material Safety Data Sheet. The manufacturers supply this form by listing all toxicants or hazardous materials and provide a list of the solvents used. Also included are the threshold limit values (TLVs) for each substance. Explosive hazards, flash points, and temperature limits are established for safe application of each coating material. These Material Safety Data Sheets should be kept on file in the job superintendent's office and at the first aid station.

CAUSES OF COATING FAILURE

Most types of failure are the result of the misuse of the tank coating, which results in blistering, cracking, hardening or softening, peeling, staining, burning, and undercutting. A frequent cause of failure is overheating during operation. When a heavily pigmented surface, or thick film, beings to shrink, stresses are formed on the surface that result in cracks. These cracks do not always expose the substrate and may not penetrate. Under these conditions, the best practice is to remove these areas and recoat according to standard repair procedures.

Aging or poor resistance to the corrosive can result in hardening or softening. As the coating ages, particularly epoxy and phenolic amines, it becomes brittle and may chip from the surface. Peeling can result from improperly cured surfaces, poor surface preparation, or a wet or dirty surface. Staining results when there is a reaction of the corrosive on the surface of the coating or slight staining from impurities in the corrosive. The true cause must be determined by scraping or detergent-washing the coating. If the stain is removed and softening of the film is not apparent, failure has not occurred.

Any of the above defects can result in undercutting. After the corrosive penetrates to the substrate, corrosion will proceed to extend under the film areas that have not been penetrated or failed. Some coatings are more resistant than others to undercutting or underfilm corrosion. Usually, if the coating exhibits good adhesive properties, and if the primer coat is chemically resistant to the corrosive environment, underfilm corrosion will be greatly retarded.

In addition, a tank coating must not impart any impurities to the material contained within it. The application is a failure if any color, taste, smell, or other contamination is imparted to the product, even if the coating is intact. Such contamination can be caused by the extraction of impurities from the coating, leading to blistering between coats or to metal.

If the coating is unsuited for the service, complete failure may occur by softening, dissolution, and finally complete disintegration of the coating. This type of problem is prevalent between the interphase and bottom of the tank. At the bottom of the tank and throughout the liquid phase, penetration is of great concern.

The vapor phase of the tank is subject to corrosion from concentrated vapors mixed with any oxygen present and can cause extensive corrosion.

OPERATING INSTRUCTIONS

When the tank is placed into service, specific instructions should be given as to what the tank is to be used for, temperature limitations, cleaning instructions, and information on the coating material.

The outside of the tank should be labeled "Do Not Exceed X°F (X°C). This tank has been lined with Y. It is to be used only for Z service."

SPECIFIC LIQUID COATINGS

Most liquid applied coating (lining) materials are capable of being formulated to meet requirements for specific applications. Corrosion data referring to the suitability of a coating material for a specific corrodent indicates that a formulation is available to meet these conditions. Because all formulations may not be suitable, the manufacturer must be checked as to the suitability of his formulation. The more common coatings are discussed.

PHENOLICS

Synthetic phenolic resins were developed and commercialized in the early 1900s by Leo Bakeland.[2] The reduction of phenol and formaldehyde produces a product that forms a highly cross-linked, three-dimensional polymer when cured. The resins have found use in various applications in the coating industry because of their excellent heat resistance, chemical resistance, and electrical properties. They also offer good adhesion to many substrates and have good compatibility with other polymers.

Phenolic resins have two basic classifications: resoles and novalaks. Resoles, or heat-reactive resins, are made using an excess of formaldehyde and a base catalyst. The polymer that is produced has reactive methylol groups that form a thermoset structure when heat is applied.

Novalaks are made using an excess of phenol and an acid catalyst. Reaction occurs by the protonation of the formaldehyde,[3] and the intermediate is characterized by methylene linkages rather than methylol groups. These products are not heat reactive and they require additional cross-linking agents such as hexamethylenetetramine to become thermosetting.

Both polymerization reactions evolve water during cure. This condensation reaction serves to limit film thicknesses to approximately 3 mil because the volatiles will cause blistering while curing takes place.

The outstanding phenolic systems are those that are baked at approximately 450°F (230°C) to provide a 3 to 5 mil (75 to 130 μm) coating of high chemical resistance.

Phenolic coatings have a wet temperature resistance to 200°F (93°C). They are odorless, tasteless, nontoxic, and suitable for food use. They must be baked at a metal temperature ranging from 350 to 450°F (175 to 230°C). The coating must be applied in a thin film (approximately 1 mil [0.03 mm]) and partially baked between coats. Multiple thin coats are necessary to allow removal of water

from the condensation reaction. The cured coating is difficult to patch due to extreme solvent resistance.

A brown color results upon baking, which can be used to indicate the degree of cross-linking. It can be modified with epoxies and other resins to enhance water, chemical, and heat resistance.

Phenolic resins exhibit excellent resistance to most organic solvents, especially aromatics and chlorinated solvents. Organic polar solvents capable of hydrogen bonding, such as alcohols and ketones, can attack phenolics. Although the phenolics have an aromatic character, the phenolic hydroxyls provide sites for hydrogen bonding and attack by caustics.

Phenolics are not suitable for use in strong alkaline environments. Strong mineral acids also attack the phenolics, and acids such as nitric, chromic, and hydrochloric cause severe degradation. Sulfuric and phosphoric acids may be suitable under some conditions. There is some loss of properties when phenolics are in contact with organic acids such as acetic, formic, and oxalic.

Although attacked by oxidants and by even dilute alkalies, the phenolics provide both corrosion and contamination protection in a wide variety of chemical and petroleum services. Refer to Table 8.5 for the compatibility of phenolics with selected corrodents.

Applications include coating of tanks used for alcohol storage and fermentation and other food products, as well as for hot water immersion services.

Modified air-dried phenolics are nearly equivalent to high bake phenolics with a dry heat resistance of 150°F (65°C). They can be formulated for excellent resistance to alkalies, solvents, fresh water, salt water, deionized water, and mild acid resistance.

Epoxy

Epoxy resins can be formulated with a wide range of properties.[4] These medium- to high-priced resins are noted for their adhesion. Epoxy linings provide excellent chemical and corrosion resistance. They exhibit good resistance to alkalies, nonoxidizing acids, and many solvents. Typically, epoxies are compatible with the following materials at 200°F (93°C) unless otherwise noted:

- Acids
  - Acetic acid, 10%, to 150°F (66°C)
  - Benzoic acid
  - Butyric acid
  - Fatty acids
  - Hydrochloric acid, 10%
  - Oxalic acid
  - Rayon spin bath
  - Sulfuric acid, 20%, to 180ºF (82°C)
- Bases
  - Sodium hydroxide, 50%, to 180°F (82°C)
  - Sodium sulfide, 10%

TABLE 8.5
Compatibility of Phenolics with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetic acid, 10%	212	100	Cresol	300	149
Acetic acid, glacial	70	21	Ethylene glycol	70	21
Acetic anhydride	70	21	Ferric chloride, 50% in water	300	149
Acetone	x	x			
Aluminum chloride, aqueous	90	32	Hydrobromic acid, dilute	200	93
			Hydrobromic acid, 20%	200	93
Aluminum sulfate	300	149	Hydrobromic acid, 50%	200	93
Ammonia gas	90	32	Hydrochloric acid, 20%	300	149
Ammonium carbonate	90	32	Hydrochloric acid, 38%	300	149
Ammonium chloride, 10%	80	27	Hydrofluoric acid, 30%	x	x
Ammonium chloride, 50%	80	27	Hydrofluoric acid, 60%	x	x
Ammonium chloride, sat.	80	27	Hydrofluoric acid, 100%	x	x
Ammonium hydroxide, 25%	x	x	Lactic acid, 25%	160	71
Ammonium hydroxide, sat.	x	x	Methyl ethyl ketone	160	71
Ammonium nitrate	160	71	Methyl isobutyl ketone	x	x
Ammonium sulfate, 10–40%	300	149	Muriatic acid	160	71
Aniline	x	x	Nitric acid, 5%	300	149
Benzaldehyde	70	21	Nitric acid, 20%	x	x
Benzene	160	21	Nitric acid 70%	x	x
Benzenesulfonic acid, 10%	70	21	Nitric acid, anhydrous	x	x
Benzoic acid			Nitrous acid, conc.	x	x
Benzyl alcohol	70	21	Phosphoric acid, 50–80%	x	x
Butadiene	x	x	Picric acid	212	100
Butyl phthalate	160	71	Sodium hydroxide, 10%	300	149
Calcium chlorate	300	149	Sodium hydroxide, 50%	x	x
Calcium hypochlorite, 10%	x	x	Sodium hydroxide, conc.	x	x
Carbon dioxide, dry	300	149	Sodium hypochlorite, 15%	x	x
Carbon dioxide, wet	300	149	Sodium hypochlorite, conc.	x	x
Carbon tetrachloride	200	93			
Carbonic acid	200	93	Sulfuric acid, 10%	250	121
Chlorine gas, wet	x	x	Sulfuric acid, 50%	250	121
Chlorine, liquid	x	x	Sulfuric acid, 70%	200	93
Chlorobenzene	260	127	Sulfuric acid, 90%	70	21
Chloroform	160	71	Sulfuric acid, 98%	x	x
Chromic acid, 50%	x	x	Sulfuric acid, 100%	x	x
Chromyl chloride	x	x	Sulfurous acid	80	27
Citric acid, conc.	160	71	Thionyl chloride	200	93
Copper acetate	160	71	Zinc chloride	300	149

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that data is unavailable.

Source: Ref. 1.

    - Trisodium phosphate
    - Magnesium hydroxide
- Salts, Metallic Salts
    - Aluminum
    - Calcium
    - Iron
    - Magnesium
    - Potassium
    - Sodium
    - Most ammonium salts
- Alcohols, Solvents
    - Methyl
    - Ethyl acetate, to 150°F (66°C)
    - Ethyl
    - Naphtha
    - Isopropyl, to 150°F (66°C)
    - Toluene
    - Benzene, to 150°F (66°C)
    - Xylene
- Miscellaneous
    - Distilled water
    - Seawater
    - Jet fuel
    - Gasoline
    - White liquor
    - Diesel fuel
    - Sour crude oil
    - Black liquor

Epoxies are not satisfactory for use with:

- Bromine water
- Chromic acid
- Bleaches
- Fluorine
- Methylene chloride
- Hydrogen peroxide
- Sulfuric acid, above 70%
- Wet chlorine gas
- Wet sulfur dioxide

Refer to Table 8.6 for the compatibility of epoxy with selected corrodents, and Ref. 1 for a more comprehensive listing.

Epoxy resins must be cured with cross-linking agents (hardeners) or catalysts to develop the desired properties. Cross-linking takes place at the epoxy and

TABLE 8.6
Compatibility of Epoxy with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	150	66	Barium sulfide	300	149
Acetamide	90	32	Benzaldehyde	x	x
Acetic acid, 10%	190	88	Benzene	160	71
Acetic acid, 50%	110	43	Benzenesulfonic acid, 10%	160	71
Acetic acid, 80%	110	43	Benzoic acid	200	93
Acetic anhydride	x	x	Benzyl alcohol	x	x
Acetone	110	43	Benzyl chloride	60	16
Acetyl chloride	x	x	Borax	250	121
Acrylic acid	x	x	Boric acid, 4%	200	93
Acrylonitrile	90	32	Bromine gas, dry	x	x
Adipic acid	250	121	Bromine gas, moist	x	x
Allyl alcohol	x	x	Bromine, liquid	x	x
Allyl chloride	140	60	Butadiene	100	38
Alum	300	149	Butyl acetate	170	77
Aluminum chloride, aq. 1%	300	149	Butyl alcohol	140	60
Aluminum chloride, dry	90	32	n-Butylamine	x	x
Aluminum fluoride	180	82	Butyric acid	210	99
Aluminum hydroxide	180	82	Calcium bisulfide		
Aluminum nitrate	250	121	Calcium bisulfite	200	93
Aluminum sulfate	300	149	Calcium carbonate	300	149
Ammonia gas, dry	210	99	Calcium chlorate	200	93
Ammonium bifluoride	90	32	Calcium chloride, 37.5%	190	88
Ammonium carbonate	140	60	Calcium hydroxide, sat.	180	82
Ammonium chloride, sat.	180	82	Calcium hypochlorite, 70%	150	66
Ammonium fluoride, 25%	150	66	Calcium nitrate	250	121
Ammonium hydroxide, 25%	140	60	Calcium sulfate	250	121
Ammonium hydroxide, sat.	150	66	Caprylic acid	x	x
Ammonium nitrate, 25%	250	121	Carbon bisulfide	100	38
Ammonium persulfate	250	121	Carbon dioxide, dry	200	93
Ammonium phosphate	140	60	Carbon disulfide	100	38
Ammonium sulfate, 10–40%	300	149	Carbon monoxide	80	27
Ammonium sulfite	100	38	Carbon tetrachloride	170	77
Amyl acetate	80	27	Carbonic acid	200	93
Amyl alcohol	140	60	Cellosolve	140	60
Amyl chloride	80	27	Chloroacetic acid, 92% water	150	66
Aniline	150	66	Chloroacetic acid	x	x
Antimony trichloride	180	82	Chlorine gas, dry	150	66
Aqua regia, 3:1	x	x	Chlorine gas, wet	x	x
Barium carbonate	240	116	Chlorobenzene	150	66

TABLE 8.6 (Continued)
Compatibility of Epoxy with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Barium chloride	250	121	Chloroform	110	43
Barium hydroxide, 10%	200	93	Chlorosulfonic acid	x	x
Barium sulfate	250	121	Chromic acid, 10%	110	43
Chromic acid, 50%	x	x	Methyl ethyl ketone	90	32
Citric acid, 15%	190	88	Methyl isobutyl ketone	140	60
Citric acid, 32%	190	88	Muriatic acid	140	60
Copper acetate	200	93	Nitric acid, 5%	160	71
Copper carbonate	150	66	Nitric acid, 20%	100	38
Copper chloride	250	121	Nitric acid, 70%	x	x
Copper cyanide	150	66	Nitric acid, anhydrous	x	x
Copper sulfate, 17%	210	99	Nitrous acid, conc.	x	x
Cresol	100	38	Oleum	x	x
Cupric chloride, 5%	80	27	Perchloric acid, 10%	90	32
Cupric chloride, 50%	80	27	Perchloric acid, 70%	80	27
Cyclohexane	90	32	Phenol	x	x
Cyclohexanol	80	27	Phosphoric aci, 50–80%	110	43
Dichloroacetic acid	x	x	Picric acid	80	27
Dichloroethane (ethylene dichloride)	x	x	Potassium bromide, 30%	200	93
			Salicylic acid	140	60
Ethylene glycol	300	149	Sodium carbonate	300	149
Ferric chloride	300	149	Sodium chloride	210	99
Ferric chloride, 50% in water	250	121	Sodium hydroxide, 10%	190	88
			Sodium hydroxide, 50%	200	93
Ferric nitrate, 10–50%	250	121	Sodium hypochlorite, 20%	x	x
Ferrous chloride	250	121	Sodium hypochlorite, conc.	x	x
Ferrous nitrate					
Fluorine gas, dry	90	32	Sodium sulfide, to 10%	250	121
Hydrobromic acid, dilute	180	82	Stannic chloride	200	93
Hydrobromic acid, 20%	180	82	Stannous chloride	160	71
Hydrobromic acid, 50%	110	43	Sulfuric acid, 10%	140	60
Hydrochloric acid, 20%	200	93	Sulfuric acid, 50%	110	43
Hydrochloric acid, 38%	140	60	Sulfuric acid, 70%	110	43
Hydrocyanic acid, 10%	160	71	Sulfuric acid, 90%	x	x
Hydrofluoric acid, 30%	x	x	Sulfuric acid, 98%	x	x
Hydrofluoric acid, 70%	x	x	Sulfuric acid, 100%	x	x
Hydrofluoric acid, 100%	x	x	Sulfuric acid, fuming	x	x
Hypochlorous acid	200	93	Sulfurous acid, 20%	240	116
Ketones, general	x	x	Thionyl chloride	x	x

(*continued*)

TABLE 8.6 (Continued)
Compatibility of Epoxy with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Lactic acid, 25%	220	104	Toluene	150	66
Lactic acid, conc.	200	93	Trichloroacetic acid	x	x
Magnesium chloride	190	88	White liquor	90	32
Methyl chloride	x	x	Zinc chloride	250	121

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

hydroxyl groups, which are the reaction sites. The primary types of curing agents used for coatings are aliphatic amines and catalytic curing agents.

Epoxies (amine, catalyst) are widely used because curing of the epoxies takes place at room temperature. High exothermic temperatures develop during the curing reaction, which limits the mass of material that can be cured. Amine-cured coatings exhibit good resistance to alkalies, and fair to good resistance to mild acids, solvents, and dry food products. They are widely used for hopper car coatings and nuclear containment facilities. The maximum allowable temperature is 275°F (135°C).

Catalytic curing agents require a temperature of 200°F (93°C) or higher to react. These baked epoxies exhibit excellent resistance to acids, alkalies, solvents, inorganic salts, and water. The maximum operating temperature is 325°F (163°C), somewhat higher than that of the amine-cured epoxies.

Furans

Furan polymers are derivatives of furfuryl alcohol and furfural.[4] Using an acid catalyst, polymerization occurs by the condensation route, which generates heat and by-product water.

All furan coatings must be postcured to drive out the reaction "condensate" in order to achieve optimum properties.

Furan polymers are noted for their excellent resistance to solvents and they exhibit excellent resistance to strong concentrated mineral acids, caustics, and combinations of solvents with acids and bases. These furans are subject to many different formulations, making them suitable for specific applications. Consequently, the manufacturer should be consulted for the correct formulation for a specific application.

In general, furan formulations are compatible with the following:

- Solvents
  - Acetone
  - Benzene
  - Carbon disulfide
  - Chlorobenzene
  - Ethanol
  - Ethyl acetate
  - Methanol
  - Methyl ethyl ketone
  - Perchlorethylene
  - Styrene
  - Trichlorethylene
  - Toluene
  - Xylene
- Acids
  - Acetic acid
  - Hydrochloric acid
  - Nitric acid, 5%
  - Phosphoric acid
  - Sulfuric acid, 60%, to 150°F (66°C)
- Bases
  - Diethylamine
  - Sodium carbonate
  - Sodium hydroxide, 50%
  - Sodium sulfide
- Water
  - Demineralized
  - Distilled
- Others
  - Pulp mill liquor

The furan resins are not satisfactory for use with oxidizing media, such as chromic or nitric acids, peroxides, hypochlorites, chlorine, phenol, and concentrated sulfuric acid. Refer to Table 8.7 for the compatibility of furan resins with selected corrodents and to Ref. 1 for a more complete listing.

Vinyl Esters

The vinyl ester class of resins was developed during the late 1950s and early 1960s. Vinyl esters were first used as dental fillings. They had improved toughness and bonding ability over the acrylic materials that were being used at the time. Over the next several years, changes in the molecular structure of the vinyl esters produced resins that found extensive use in corrosion-resistant equipment.

TABLE 8.7
Compatibility of Furans with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Benzenesulfonic acid, 10%	160	71
Acetic acid, 10%	212	100	Benzoic acid	260	127
Acetic acid, 50%	160	71	Benzyl alcohol	80	27
Acetic acid, 80%	80	27	Benzyl chloride	140	60
Acetic acid, glacial	80	27	Borax	140	60
Acetic anhydride	80	27	Boric acid	300	149
Acetone	80	27	Bromine gas, dry	x	x
Acetyl chloride	200	93	Bromine gas, moist	x	x
Acrylic acid	80	27	Bromine, liquid, 3% max.	300	149
Acrylonitrile	80	27	Butadiene		
Adipic acid, 25%	280	138	Butyl acetate	260	127
Allyl alcohol	300	149	Butyl alcohol	212	100
Allyl chloride	300	149	n-Butylamine	x	x
Alum, 5%	140	60	Butyric acid	260	127
Aluminum chloride, aq.	300	149	Calcium bisulfite	260	127
Aluminum chloride, dry	300	149	Calcium chloride	160	71
Aluminum fluoride	280	138	Calcium hydroxide, sat.	260	127
Aluminum hydroxide	260	127	Calcium hypochlorite	x	x
Aluminum sulfate	160	71	Calcium nitrate	260	127
Ammonium carbonate	240	116	Calcium oxide		
Ammonium hydroxide, 25%	250	121	Calcium sulfate	260	127
Ammonium hydroxide, sat.	200	93	Caprylic acid	250	121
Ammonium nitrate	250	121	Carbon bisulfide	160	71
Ammonium persulfate	260	127	Carbon dioxide, dry	90	32
Ammonium phosphate	260	127	Carbon dioxide, wet	80	27
Ammonium sulfate, 10–40%	260	127	Carbon disulfide	260	127
Ammonium sulfide	260	127	Carbon tetrachloride	212	100
Ammonium sulfite	240	116	Cellosolve	240	116
Amyl acetate	260	127	Chlorine gas, dry	260	127
Amyl alcohol	278	137	Chlorine gas, wet	260	127
Amyl chloride	x	x	Chlorine, liquid	x	x
Aniline	80	27	Chloroacetic acid	240	116
Antimony trichloride	250	121	Chloroacetic acid, 50% water	100	38
Aqua regia, 3:1	x	x	Chlorobenzene	260	127
Barium carbonate	240	116	Chloroform	x	x
Barium chloride	260	127	Chlorosulfonic acid	260	127
Barium hydroxide	260	127	Chromic acid, 10%	x	x
Barium sulfide	260	127	Chromic acid, 50%	x	x
Benzaldehyde	80	27	Chromyl chloride	250	121
Benzene	160	71	Citric acid, 15%	250	121

TABLE 8.7 (Continued)
Compatibility of Furans with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Citric acid, conc.	250	121	Manganese chloride	200	93
Copper acetate	260	127	Methyl chloride	120	49
Copper carbonate			Methyl ethyl ketone	80	27
Copper chloride	260	127	Methyl isobutyl ketone	160	71
Copper cyanide	240	116	Muriatic acid	80	27
Copper sulfate	300	149	Nitric acid, 5%	x	x
Cresol	260	127	Nitric acid, 20%	x	x
Cupric chloride, 5%	300	149	Nitric acid, 70%	x	x
Cupric chloride, 50%	300	149	Nitric acid, anhydrous	x	x
Cyclohexane	140	60	Nitrous acid, conc.	x	x
Cyclohexanol			Oleum	190	88
Dichloroacetic acid	x	x	Perchloric acid, 10%	x	x
Dichloroethane (ethylene dichloride)	250	121	Perchloric acid, 70%	260	127
			Phenol	x	x
Ethylene glycol	160	71	Phosphoric acid, 50%	212	100
Ferric chloride	260	127	Picric acid		
Ferric chloride, 50% in water	160	71	Potassium bromide, 30%	260	127
Ferric nitrate, 10–50%	160	71	Salicylic acid	260	127
Ferrous chloride	160	71	Silver bromide, 10%		
Ferrous nitrate			Sodium carbonate	212	100
Fluorine gas, dry	x	x	Sodium chloride	260	127
Fluorine gas, moist	x	x	Sodium hydroxide, 10%	x	x
Hydrobromic acid, 20%	212	100	Sodium hydroxide, 50%	x	x
Hydrobromic acid, 50%	212	100	Sodium hydroxide, conc.	x	x
Hydrobromic acid, dilute	212	100	Sodium hypochlorite, 15%	x	x
Hydrochloric acid, 20%	212	100	Sodium hypochlorite, conc.	x	x
Hydrochloric acid, 38%	80	27	Sodium sulfide, to 10%	260	127
Hydrocyanic acid, 10%	160	71	Stannic chloride	260	127
Hydrofluoric acid, 30%	230	110	Stannous chloride	250	121
Hydrofluoric acid, 70%	140	60	Sulfuric acid, 10%	160	71
Hydrofluoric acid, 100%	140	60	Sulfuric acid, 100%	x	x
Hypochlorous acid	x	x	Sulfuric acid, 50%	80	27
Iodine solution, 10%	x	x	Sulfuric acid, 70%	80	27
Ketones, general	100	38	Sulfuric acid, 90%	x	x
Lactic acid, 25%	212	100	Sulfuric acid, 98%	x	x
Lactic acid, conc.	160	71	Sulfuric acid, fuming	x	x
Magnesium chloride	260	127	Sulfurous acid	160	71
Malic acid, 10%	260	127	Thionyl chloride	x	x

(*continued*)

TABLE 8.7 (Continued)
Compatibility of Furans with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Toluene	212	100	White liquor	140	60
Trichloroacetic acid, 30%	80	27	Zinc chloride	160	71

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Present-day vinyl esters possess several advantages over unsaturated polyesters. They provide toughness in the cured polymer while maintaining good thermal stability and physical properties at elevated temperatures.

Vinyl esters are available in various formulations. Halogenated modifications are available where fire resistance and ignition resistance are major concerns. The vinyl esters are resistant up to 400°F (204°C).

Vinyl esters can be used to handle most hot, highly chlorinated and acid mixtures at elevated temperatures. They also provide excellent resistance to strong mineral acids and bleaching solutions. Vinyl esters excel in alkaline and bleach environments and are used extensively in the very corrosive conditions found in the pulp and paper industry.

The family of vinyl esters includes a wide variety of formulations. As a result, there can be difference in the compatibility of formulations among manufacturers. When one checks compatibility in a table, one must keep in mind that all formulations will not act as shown. An indication that a vinyl ester is compatible generally means that at least one formulation is compatible. This is the case in Table 8.8, which shows the compatibility of vinyl ester with selected corrodents. The resin manufacturer must be consulted to verify the resistance.

Epoxy Polyamide

Polyamide resins (nylons) can react with epoxies to form durable protective coatings with a temperature resistance of 225°F (107°C) dry and 150°F (60°C) wet. The chemical resistance of epoxy polyamides is inferior to that of amine-cured epoxies. They are partially resistant to acids, acid salts, alkaline and organic solvents, and are resistant to moisture. Refer to Table 8.9 for the compatibility of epoxy polyamides with selected corrodents and to Ref. 1 for a more comprehensive listing.

Applications include storage tanks and nuclear containment facilities.

TABLE 8.8
Compatibility of Vinyl Ester with Selected Corrodent

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Amyl acetate	110	38
Acetamide			Amyl alcohol	210	99
Acetic acid, 10%	200	93	Amyl chloride	120	49
Acetic acid, 50%	180	82	Aniline	x	x
Acetic acid, 80%	150	66	Antimony trichloride	160	71
Acetic acid, glacial	150	66	Aqua regia, 3:1	x	x
Acetic anhydride	100	38	Barium carbonate	260	127
Acetone	x	x	Barium chloride	200	93
Acetyl chloride	x	x	Barium hydroxide	150	66
Acrylic acid	100	38	Barium sulfate	200	93
Acrylonitrile	x	x	Barium sulfide	180	82
Adipic acid	182	82	Benzaldehyde	x	x
Allyl alcohol	90	32	Benzene	x	x
Allyl chloride	90	32	Benzenesulfonic acid, 10%	200	93
Alum	240	116	Benzoic acid	180	82
Aluminum acetate	210	99	Benzyl alcohol	100	38
Aluminum chloride, aqueous	260	127	Benzyl chloride	90	32
Aluminum chloride, dry	140	60	Borax	210	99
Aluminum fluoride	100	38	Boric acid	200	93
Aluminum hydroxide	200	93	Bromine gas, dry	100	38
Aluminum nitrate	200	93	Bromine gas, moist	100	38
Aluminum sulfate	250	121	Bromine, liquid	x	x
Ammonia gas	100	38	Butadiene		
Ammonium bifluoride	150	66	n-Butylamine	x	x
Ammonium carbonate	150	66	Butyl acetate	80	27
Ammonium chloride, 10%	200	93	Butyl alcohol	120	49
Ammonium chloride, 50%	200	93	Butyric acid	130	54
Ammonium chloride, sat.	200	93	Calcium bisulfide		
Ammonium fluoride, 10%	140	60	Calcium bisulfite	180	82
Ammonium fluoride, 25%	140	60	Calcium carbonate	180	82
Ammonium hydroxide, 25%	100	38	Calcium chlorate	260	127
Ammonium hydroxide, sat.	130	54	Calcium chloride	180	82
Ammonium nitrate	250	121	Calcium hydroxide, 10%	180	82
Ammonium oxychloride			Calcium hydroxide, sat.	180	82
Ammonium persulfate	180	82	Calcium hypochlorite	180	82
Ammonium phosphate	200	93	Calcium nitrate	210	99
Ammonium sulfate, 10–40%	220	104	Calcium oxide	160	71
Ammonium sulfide	120	49	Calcium sulfate	250	116
Ammonium sulfite	220	104	Caprylic acid	220	104

(*continued*)

TABLE 8.8 (Continued)
Compatibility of Vinyl Ester with Selected Corrodent

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Carbon bisulfide	x	x	Ferrous nitrate	200	93
Carbon dioxide, dry	200	93	Fluorine gas, dry	x	x
Carbon dioxide, wet	220	104	Fluorine gas, moist	x	x
Carbon disulfide	x	x	Hydrobromic acid, 20%	180	82
Carbon monoxide	350	177	Hydrobromic acid, 50%	200	93
Carbon tetrachloride	180	82	Hydrobromic acid, dilute	180	82
Carbonic acid	120	49	Hydrochloric acid, 20%	220	104
Cellosolve	140	60	Hydrochloric acid, 38%	180	82
Chlorine gas, dry	250	121	Hydrocyanic acid, 10%	160	71
Chlorine gas, wet	250	121	Hydrofluoric acid, 30%	x	x
Chlorine, liquid	x	x	Hydrofluoric acid, 70%	x	x
Chloroacetic acid	200	93	Hydrofluoric acid, 100%	x	x
Chloroacetic acid, 50% water	150	66	Hypochlorous acid	150	66
			Iodine solution, 10%	150	66
Chlorobenzene	110	43	Ketones, general	x	x
Chloroform	x	x	Lactic acid, 25%	210	99
Chlorosulfonic acid	x	x	Lactic acid, conc.	200	93
Chromic acid, 10%	150	66	Magnesium chloride	260	127
Chromic acid, 50%	x	x	Malic acid, 10%	140	60
Chromyl chloride	210	99	Manganese chloride	210	99
Citric acid, 15%	210	99	Methyl chloride		
Citric acid, conc.	210	99	Methyl ethyl ketone	x	x
Copper acetate	210	99	Methyl isobutyl ketone	x	x
Copper carbonate			Muriatic acid	180	82
Copper chloride	220	104	Nitric acid, 20%	150	66
Copper cyanide	210	99	Nitric acid, 5%	180	82
Copper sulfate	240	116	Nitric acid, 70%	x	x
Cresol	x	x	Nitrous acid, 10%	150	66
Cupric chloride, 5%	260	127	Nitrous acid, anhydrous	x	x
Cupric chloride, 50%	220	104	Oleum	x	x
Cyclohexane	150	66	Perchloric acid, 10%	150	66
Cyclohexanol	150	66	Perchloric acid, 70%	x	x
Dibutyl phthalate	200	93	Phenol	x	x
Dichloroacetic acid	100	38	Phosphoric acid, 50–80%	210	99
Dichloroethane (ethylene dichloride)	110	43	Picric acid	200	93
			Potassium bromide, 30%	160	71
Ethylene glycol	210	99	Salicylic acid	150	66
Ferric chloride	210	99	Silver bromide, 10%		
Ferric chloride, 50% in water	210	99	Sodium carbonate	180	82
Ferric nitrate, 10–50%	200	93	Sodium chloride	180	82
Ferrous chloride	200	93	Sodium hydroxide, 10%	170	77

(*continued*)

TABLE 8.8 (Continued)
Compatibility of Vinyl Ester with Selected Corrodent

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sodium hydroxide, 50%	220	104	Sulfuric acid, 70%	180	82
Sodium hydroxide, conc.			Sulfuric acid, 90%	x	x
Sodium hypochlorite, 20%	180	82	Sulfuric acid, 98%	x	x
Sodium hypochlorite, conc.	100	38	Sulfuric acid, fuming	x	x
Sodium sulfide, to 50%	220	104	Sulfurous acid, 10%	120	49
Stannic chloride	210	99	Thionyl chloride	x	x
Stannous chloride	200	93	Toluene	120	49
Sulfuric acid, 10%	200	93	Trichloroacetic acid, 50%	210	99
Sulfuric acid, 100%	x	x	White liquor	180	82
Sulfuric acid, 50%	210	99	Zinc chloride	180	82

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Coal Tar Epoxy

Coal tar epoxies can be applied to bare steel or concrete without a primer. They will not cure below 50°F (10°C) and have a temperature resistance of 225°F (105°C) dry or 150°F (65°C) wet. They have a low cost per unit coverage.

Coal tar epoxy combines the moisture resistance of coal tar with the chemical resistance of epoxy. It possesses excellent resistance to saltwater, freshwater, mild acids, and mild alkalies, but has poor solvent resistance. Refer to Table 8.10 for the compatibility of epoxy coal tar with selected corrodents. Ref. 1 has a more comprehensive listing.

Coal tar epoxy finds application as a coating for crude oil storage tanks, and in sewage disposal plants and water works.

Coal Tar

Unless cross-linked with another resin, coal tar is thermoplastic and will flow at temperatures of 100°F (38°C) or less. It hardens and embrittles in cold weather.

Coal tar exhibits excellent water resistance, good resistance to acids, alkalies, and minerals, animal and vegetable oils, and salts. Table 8.11 provides the compatibility of coal tar with selected corrodents. Ref. 1 provides a more extensive listing.

TABLE 8.9
Compatibility of Epoxy Polyamides with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Lard oil	x	x
Acetic acid, all conc.	x	x	Lauric acid	x	x
Acetic acid vapors	x	x	Linseed oil	100	38
Acetone	x	x	Magnesium chloride, 50%	100	38
Aluminum chloride, dry	100	38	Mercuric chloride	100	38
Aluminum fluoride	x	x	Mercuric nitrate	100	38
Ammonium chloride, all	100	38	Methyl alcohol	100	38
Ammonium hydroxide, 25%	100	38	Methyl sulfate	x	x
Aqua regia, 3:1	x	x	Methylene chloride	x	x
Benzene	x	x	Mineral oil	100	38
Boric acid	140	60	Nitric acid	x	x
Bromine gas, dry	x	x	Oil, vegetable	100	38
Bromine gas, moist	x	x	Oleum	x	x
Calcium chloride	110	43	Oxalic acid, all conc.	100	38
Calcium hydroxide, all	140	60	Perchloric acid	x	x
Citric acid, all conc.	100	38	Petroleum oils, sour	100	38
Diesel fuels	100	38	Phenol	x	x
Ethanol	100	38	Phosphoric acid	x	x
Ferric chloride	100	38	Potassium chloride, 30%	100	38
Formaldehyde, to 50%	100	38	Potassium hydroxide, 50%	100	38
Formic acid	x	x	Propylene glycol	100	38
Glucose	100	38	Sodium chloride	110	43
Green liquor	100	38	Sodium hydroxide, to 50%	100	38
Hydrobromic acid	x	x	Sulfur dioxide wet	100	38
Hydrochloric acid, dilute	100	38	Sulfuric acid	x	x
Hydrochloric acid, 20%	x	x	Water demineralized	110	43
Hydrofluoric acid, dilute	100	38	Water, distilled	130	54
Hydrofluoric acid, 30%	x	x	Water, salt	130	54
Hydrofluoric acid, vapors	100	38	Water, sea	110	43
Hydrogen sulfide, dry	100	38	Water, sewage	100	38
Hydrogen sulfide, wet	100	38	White liquor	150	66
Iodine	x	x	Wines	100	38
Lactic acid	x	x	Xylene	x	x

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

TABLE 8.10
Compatibility of Coal Tar Epoxy with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Lard oil	x	x
Acetic acid, to 20%	100	38	Lauric acid	x	x
Acetic acid, vapors	100	38	Linseed oil	100	38
Acetone	x	x	Magnesium chloride, 50%	90	32
Aluminum chloride, dry	100	38	Mercuric chloride	100	38
Aluminum fluoride	120	49	Mercuric nitrate	100	38
Ammonium chloride, dry	100	88	Methyl alcohol	100	38
Ammonium hydroxide, 25%	110	43	Methyl sulfate	x	x
Aqua regia, 3:1	x	x	Methylene chloride	x	x
Benzene	x	x	Mineral oil	100	38
Boric acid	100	38	Nitric acid	x	x
Bromine gas, dry	100	38	Oil vegetable	100	38
Bromine gas, moist	x	x	Oleum	x	x
Calcium chloride	100	38	Oxalic acid, all conc.	100	38
Calcium hydroxide, all	100	38	Perchloric acid	x	x
Citric acid, all conc.	100	38	Petroleum oils, sour	100	38
Diesel fuels	100	38	Phenol	x	x
Ethanol	100	38	Phosphoric acid	x	x
Ferric chloride	100	38	Potassium chloride, 30%	100	38
Formaldehyde, to 50%	100	38	Potassium hydroxide, 50%	100	38
Formic acid	x	x	Propylene glycol	100	38
Glucose	100	38	Sodium chloride	110	43
Green liquor	100	38	Sodium hydroxide, to 50%	100	38
Hydrobromic acid	x	x	Sulfur dioxide wet	100	38
Hydrochloric acid, dilute	100	38	Sulfuric acid	x	x
Hydrochloric acid, 20%	x	x	Water, demineralized	100	38
Hydrofluoric acid, dilute	100	38	Water, distilled	100	38
Hydrofluoric acid, 30%	x	x	Water, salt	130	54
Hydrofluoric acid, vapors	110	43	Water, sea	90	32
Hydrogen sulfide, dry	100	38	Water sewage	100	38
Hydrogen sulfide, wet	100	38	White liquor	100	38
Iodine	x	x	Wines	100	38
Lactic acid	x	x	Xylene	x	x

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

TABLE 8.11
Compatibility of Coal Tar with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Lard oil	x	x
Acetic acid, all conc.			Lauric acid	x	x
Acetic acid vapors			Linseed oil		
Acetone	x	x	Magnesium chloride, 50%		
Aluminum chloride, dry			Mercuric chloride		
Aluminum fluoride			Mercuric nitrate		
Ammonium chloride, all			Methyl alcohol		
Ammonium hydroxide, 25%			Methyl sulfate		
Aqua regia, 3:1	x	x	Methylene chloride	x	x
Benzene	x	x	Mineral oil		
Boric acid			Nitric acid	x	x
Bromine gas, dry	x	x	Oil vegetable		
Bromine gas, moist	x	x	Oleum	x	x
Calcium chloride			Oxalic acid, all conc.		
Calcium hydroxide, all conc.			Perchloric acid	x	x
Citric acid, all conc.			Petroleum oils, sour		
Diesel fuels			Phenol	x	x
Ethanol			Phosphoric acid	x	x
Ferric chloride			Potassium chloride, 30%		
Formaldehyde, to 50%	x	x	Potassium hydroxide, 50%		
Formic acid	x	x	Propylene glycol		
Glucose			Sodium chloride		
Green liquor	x	x	Sodium hydroxide, to 50%		
Hydrobromic acid	x	x	Sulfur dioxide, wet		
Hydrochloric acid, dilute	x	x	Sulfuric acid	x	x
Hydrochloric acid, 20%	x	x	Water, demineralized	90	32
Hydrofluoric acid, dilute	x	x	Water, distilled		
Hydrofluoric acid, 30%	x	x	Water, salt		
Hydrofluoric acid, vapors			Water, sea	90	32
Hydrogen sulfide, dry			Water, sewage	90	32
Hydrogen sulfide, wet			White liquor		
Iodine	x	x	Wines		
Lactic acid	x	x	Xylene	x	x

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Coal tar finds application as a coating both for the interior and exterior of underground pipelines.

Urethanes

Polyurethane-resin-based coatings are extremely versatile. They are higher priced than alkyds but lower priced than epoxies. Polyurethane resins are available as oil modified, moisture curing, bleached, two component, and lacquers. Because of the versatility of the isocyanate reaction, wide diversity exists in specific coating properties. Exposure to the isocyanate should be minimized to avoid sensitivity that may result in an asthmatic-like breathing condition. Continued exposure to humidity may result in gassing or bubbling of the coating in humid conditions.

The urethane coatings have a maximum operating temperature of 250°F (121°C) dry and 150°F (66°C) wet. These coatings are resistant to most mineral and vegetable oils, greases, fuels, and to aliphatic and chlorinated hydrocarbons. Aromatic hydrocarbons, polar solvents, esters, ethers, and ketones will attack urethane and alcohols will soften urethane.

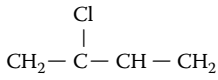
Urethane finds limited service in weak acid solutions and cannot be used in concentrated acids. Urethanes are not resistant to steam or caustics, but they are resistant to the deteriorating effects of being immersed in water. Refer to Table 8.12 for the compatibility of urethane with selected corrodents and Ref. 1 for a more comprehensive listing.

It is possible to apply uniform coatings or films of urethane to a variety of substrate materials, including metal, glass, wood, fabric, and paper. Urethane coatings are often applied to the interior of pipes and tanks.

Filtration units, clarifiers, holding tanks, and treatment sumps constructed of reinforced concrete are widely used in the treatment of municipal, industrial, and thermal generating station wastewater. In many cases, particularly in anaerobic, industrial, and thermal generating systems, urethane coatings are used to protect the concrete from severe chemical attack and prevent seepage into the concrete of chemicals that can attack the reinforcing steel. These coatings provide protection against abrasion and erosion, and act as a waterproofing system to combat leakage of the equipment resulting from concrete movement and shrinkage.

Neoprene

Neoprene is one of the oldest and most versatile of the synthetic rubbers. Chemically, it is polychloroprene. Its basic unit is a chlorinated butadiene whose formula is:



The raw material is acetylene, which makes this product more expensive than some of the other elastomeric materials.

TABLE 8.12
Compatibility of Urethanes with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Lard oil	90	32
Acetic acid, all conc.	90	32	Lauric acid		
Acetic acid, vapors	90	32	Linseed oil	90	32
Acetone	90	32	Magnesium chloride, 50%	90	32
Aluminum chloride, dry			Mercuric chloride		
Aluminum fluoride			Mercuric nitrate		
Ammonium chloride, all	90	32	Methyl alcohol	90	32
Ammonium hydroxide, 25%	90	32	Methyl sulfate		
Aqua regia, 3:1	x	x	Methylene chloride	x	x
Benzene	x	x	Mineral oil	90	32
Boric acid	90	32	Nitric acid	x	x
Bromine gas, dry			Oil vegetable		
Bromine gas, moist			Oleum	x	x
Calcium chloride	80	27	Oxalic acid, all conc.		
Calcium hydroxide, all	90	32	Perchloric acid	x	x
Citric acid, all conc.			Petroleum oils, sour		
Diesel fuels			Phenol	x	x
Ethanol	90	32	Phosphoric acid		
Ferric chloride	90	32	Potassium chloride, 30%	90	32
Formaldehyde, to 50%			Potassium hydroxide, 50%	90	32
Formic acid	x	x	Propylene glycol		
Glucose	x	x	Sodium chloride	80	27
Green liquor			Sodium hydroxide, to 50%	90	32
Hydrobromic acid			Sulfur dioxide, wet		
Hydrochloric acid, dilute	x	x	Sulfuric acid, 10%	90	32
Hydrochloric acid, 20%	x	x	Water, demineralized		
Hydrofluoric acid, dilute			Water, distilled	90	32
Hydrofluoric acid, 30%			Water, salt	x	x
Hydrofluoric acid vapors			Water, sea	80	27
Hydrogen sulfide, dry			Water, sewage		
Hydrogen sulfide, wet			White liquor		
Iodine			Wines	x	x
Lactic acid			Xylene	x	x

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

As with other coating materials, neoprene is available in a variety of formulations. Depending on the compounding procedure, material can be produced to impart specific properties to meet application needs.

Neoprene is also available in a variety of forms. In addition to a neoprene latex that is similar to natural rubber latex, neoprene is produced in "fluid" form as either a compounded latex dispersion or solvent solution. Once these materials have solidified or cured, they have the same physical and mechanical properties as the solid or cellular forms of neoprene.

Neoprene solvent solutions are prepared by dissolving neoprene in standard rubber solvents. These solutions can be formulated in a range of viscosities suitable for application by brush, spray, or roller. Major areas of application include coatings for storage tanks, industrial equipment, and chemical processing equipment. These coatings protect the vessels from corrosion by acids, oils, alkalies, and most hydrocarbons.

Neoprene possesses excellent resistance to attack from solvents, waxes, fats, oils, greases, and many other petroleum-based products. It also exhibits excellent service when in contact with aliphatic compounds (methyl and ethyl alcohols, ethylene glycols, etc.) and aliphatic hydrocarbons. It is also resistant to dilute mineral acids, inorganic salt solutions, and alkalies.

Chlorinated and aromatic hydrocarbons, organic esters, aromatic hydroxy compounds, and certain ketones will attack neoprene. Refer to Table 8.13 for the compatibility of neoprene with selected corrodents and Ref. 1 for a more comprehensive listing.

Polysulfide Rubber

Polysulfide rubbers are manufactured by combining ethylene ($CH_2{=}CH_2$) with an alkaline polysulfide. Morton Thiokol Inc. markets a series of liquid polysulfides that can be oxidized to rubbers.

The polysulfide rubbers possess outstanding resistance to solvents. They exhibit excellent resistance to oils, gasoline, and aliphatic and aromatic hydrocarbon solvents, very good water resistance, good alkali resistance, and fair acid resistance. Contact with strong concentrated inorganic acids, such as sulfuric, nitric, or hydrochloric, should be avoided. Refer to Table 8.14 for the compatibility of polysulfides with selected corrodents and Ref. 1 for a more comprehensive listing.

Hypalon

Chlorosulfonated polyethylene synthetic rubber is manufactured by DuPont under the trade name Hypalon. In many respects, it is similar to neoprene but it does possess some advantages over neoprene in certain types of service. It has better heat and ozone resistance and better chemical resistance.

Hypalon has a broad range of service temperatures with excellent thermal properties. General-purpose compounds can operate continuously at temperatures

TABLE 8.13
Compatibility of Neoprene with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	200	93	Ammonium sulfite		
Acetamide	200	93	Amyl acetate	x	x
Acetic acid, 10%	160	71	Amyl alcohol	200	93
Acetic acid, 50%	160	71	Amyl chloride	x	x
Acetic acid, 80%	160	71	Aniline	x	x
Acetic acid, glacial	x	x	Antimony trichloride	140	60
Acetic anhydride	x	x	Aqua regia, 3:1	x	x
Acetone	x	x	Barium carbonate	150	66
Acetyl chloride	x	x	Barium chloride	150	66
Acrylic acid	x	x	Barium hydroxide	230	110
Acrylonitrile	140	60	Barium sulfate	200	93
Adipic acid	160	71	Barium sulfide	200	93
Allyl alcohol	120	49	Benzaldehyde	x	x
Allyl chloride	x	x	Benzene	x	x
Alum	200	93	Benzene sulfonic acid, 10%	100	38
Aluminum acetate					
Aluminum chloride, aq.	150	66	Benzoic acid	150	66
Aluminum chloride, dry			Benzyl alcohol	x	x
Aluminum fluoride	200	93	Benzyl chloride	x	x
Aluminum hydroxide	180	82	Borax	200	93
Aluminum nitrate	200	93	Boric acid	150	66
Aluminum sulfate	200	93	Bromine gas, dry	x	x
Ammonia gas	140	60	Bromine gas, moist	x	x
Ammonium bifluoride	x	x	Bromine, liquid	x	x
Ammonium carbonate	200	93	Butadiene	140	60
Ammonium chloride, 10%	150	66	Butyl acetate	60	16
Ammonium chloride, 50%	150	66	Butyl alcohol	200	93
Ammonium chloride, sat.	150	66	Butyl phthalate		
Ammonium fluoride, 10%	200	93	n-Butylamine		
Ammonium fluoride, 25%	200	93	Butyric acid	x	x
Ammonium hydroxide, 25%	200	93	Calcium bisulfide		
Ammonium hydroxide, sat.	200	93	Calcium bisulfite	x	x
Ammonium nitrate	200	93	Calcium carbonate	200	93
Ammonium oxychloride			Calcium chlorate	200	93
Ammonium persulfate	200	93	Calcium chloride	150	66
Ammonium phosphate	150	66	Calcium hydroxide, 10%	230	110
Ammonium sulfate, 10–40%	150	66	Calcium hydroxide, sat.	230	110
Ammonium sulfide	160	71	Calcium hypochlorite	x	x

TABLE 8.13 (Continued)
Compatibility of Neoprene with Selected Corrodents

Chemical	Maximum Temp °F	Maximum Temp °C	Chemical	Maximum Temp °F	Maximum Temp °C
Calcium nitrate	150	66	Dichloroethane (ethylene dichloride)	x	x
Calcium oxide	200	93	Ethylene glycol	100	38
Calcium sulfate	150	66	Ferric chloride	160	71
Caprylic acid			Ferric chloride, 50% in water	160	71
Carbon bisulfide	x	x	Ferric nitrate, 10–50%	200	93
Carbon dioxide, dry	200	93	Ferrous chloride	90	32
Carbon dioxide, wet	200	93	Ferrous nitrate	200	93
Carbon disulfide	x	x	Fluorine gas, dry	x	x
Carbon monoxide	x	x	Fluorine gas, moist	x	x
Carbon tetrachloride	x	x	Hydrobromic acid, 20%	x	x
Carbonic acid	150	66	Hydrobromic acid, 50%	x	x
Cellosolve	x	x	Hydrobromic acid, dilute	x	x
Chlorine gas, dry	x	x	Hydrochloric acid, 20%	x	x
Chlorine gas, wet	x	x	Hydrochloric acid, 38%	x	x
Chlorine, liquid	x	x	Hydrocyanic acid, 10%	x	x
Chloroacetic acid	x	x	Hydrofluoric acid, 30%	x	x
Chloroacetic acid, 50% water	x	x	Hydrofluoric acid, 70%	x	x
Chlorobenzene	x	x	Hydrofluoric acid, 100%	x	x
Chloroform	x	x	Hypochlorous acid	x	x
Chlorosulfonic acid	x	x	Iodine solution, 10%	80	27
Chromic acid, 10%	140	60	Ketones, general	x	x
Chromic acid, 50%	100	38	Lactic acid, 25%	140	60
Chromyl chloride			Lactic acid, conc.	90	32
Citric acid, 15%	150	66	Magnesium chloride	200	93
Citric acid, conc.	150	66	Malic acid		
Copper acetate	160	71	Manganese chloride	200	93
Copper carbonate			Methyl chloride	x	x
Copper chloride	200	93	Methyl ethyl ketone	x	x
Copper cyanide	160	71	Methyl isobutyl ketone	x	x
Copper sulfate	200	93	Muriatic acid	x	x
Cresol	x	x	Nitric acid, 5%	x	x
Cupric chloride, 5%	200	93	Nitric acid, 20%	x	x
Cupric chloride, 50%	160	71	Nitric acid, 70%	x	x
Cyclohexane	x	x	Nitric acid, anhydrous	x	x
Cyclohexanol	x	x	Nitrous acid, conc.	x	x
Dichloroacetic acid	x	x	Oleum	x	x

(*continued*)

TABLE 8.13 (Continued)
Compatibility of Neoprene with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Perchloric acid, 10%			Sodium sulfide, to 50%	200	93
Perchloric acid, 70%	x	x	Stannic chloride	200	93
Phenol	x	x	Stannous chloride	x	x
Phosphoric acid, 50–80%	150	66	Sulfuric acid, 10%	150	66
Picric acid	200	93	Sulfuric acid, 50%	100	38
Potassium bromide, 30%	160	71	Sulfuric acid, 70%	x	x
Salicylic acid			Sulfuric acid, 90%	x	x
Silver bromide, 10%			Sulfuric acid, 98%	x	x
Sodium carbonate	200	93	Sulfuric acid, 100%	x	x
Sodium chloride	200	93	Sulfuric acid, fuming	x	x
Sodium hydroxide, 10%	230	110	Sulfurous acid	100	38
Sodium hydroxide, 50%	230	110	Thionyl chloride	x	x
Sodium hydroxide, conc.	230	110	Toluene	x	x
Sodium hypochlorite, 20%	x	x	Trichloroacetic acid	x	x
Sodium hypochlorite, conc.	x	x	White liquor	140	60
			Zinc chloride	160	71

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

of 248 to 275°F (120 to 135°C). Special compounds can be formulated that can be used intermittently up to 302°F (150°C). On the low temperature side, conventional compounds can be used continuously down to 0 to –20°F (–18 to –28°C).

When properly compounded, Hypalon is resistant to attack by hydrocarbon oils and fuels, even at elevated temperatures. It is also resistant to such oxidizing chemicals as sodium hypochlorite, sodium peroxide, ferric chlorides, and sulfuric, chromic, and hydrofluoric acids. Concentrated hydrochloric acid (37%) at elevated temperatures (above 158°F [70°C]) will attack Hypalon, but can be handled with no adverse effects at all concentrations below that temperature. Nitric acid up to 60% concentration at room temperature can also be handled without adverse effect.

Hypalon is also resistant to salt solutions, alcohols, and both weak and concentrated alkalies. Long-term contact with water has little effect on Hypalon.

TABLE 8.14
Compatibility of Polysulfides with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde			Lard oil		
Acetic acid, all conc.	80	27	Lauric acid		
Acetic acid vapors	90	32	Linseed oil	150	66
Acetone	80	27	Magnesium chloride, 50%		
Aluminum chloride, dry			Mercuric chloride		
Aluminum fluoride			Mercuric nitrate		
Ammonium chloride, all	140	66	Methyl alcohol	80	27
Ammonium hydroxide, 25%	x	x	Methyl sulfate		
Aqua regia, 3:1			Methylene chloride		
Benzene	x	x	Mineral oil	80	27
Boric acid			Nitric acid	x	x
Bromine gas dry			Oil vegetable	x	x
Bromine gas moist			Oleum	x	x
Calcium chloride	150	66	Oxalic acid, all conc.	x	x
Calcium hydroxide, all	x	x	Perchloric acid		
Citric acid, all conc.	x	x	Petroleum oils, sour		
Diesel fuels	80	27	Phenol	x	x
Ethanol	150	66	Phosphoric acid	x	x
Ferric chloride			Potassium chloride, 30%		
Formaldehyde, to 50%	80	27	Potassium hydroxide, 50%	80	27
Formic acid			Propylene glycol		
Glucose			Sodium chloride	80	27
Green liquor			Sodium hydroxide, to 50%	x	x
Hydrobromic acid			Sulfur dioxide, wet		
Hydrochloric acid, dilute	x	x	Sulfuric acid	x	x
Hydrochloric acid, 20%	x	x	Water, demineralized	80	27
Hydrofluoric acid, dilute	x	x	Water, distilled	80	27
Hydrofluoric acid, 30%	x	x	Water salt	80	27
Hydrofluoric acid, vapors			Water, sea	80	27
Hydrogen sulfide, dry			Water, sewage	80	27
Hydrogen sulfide, wet			White liquor		
Iodine			Wines	x	x
Lactic acid	x	x	Xylene	80	27

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Hypalon has poor resistance to aliphatic, aromatic, and chlorinated hydrocarbons, aldehydes, and ketones. Refer to Table 8.15 for the compatibility of Hypalon with selected corrodents and Ref. 1 for a more complete listing.

Hypalon finds useful applications in many industries and many fields. Because of its outstanding resistance to oxidizing acids, it is used to line (coat) railroad tank cars and other tanks containing oxidizing chemicals and acids.

Plastisols

PVC plastisols are liquid dispersions of polyvinyl chloride and/or PVC copolymer resins in compatible plasticizers. The liquids vary in viscosity from thin, milk-like fluids to heavy pastes having the consistency of molasses. The lowest viscosity products are generally used for spray coating. PVC powders have essentially the same properties as liquids. Polyvinylchloride plastisol and powder coatings have limited adhesion and require primers. These coatings must be heat cured.

The viscosity of plastisol is controlled by formulator techniques, and is often kept low via the addition of inactive diluents such as odorless mineral spirits. If more than minor amounts of diluents are used, the product is often referred to as an organosol.

These products share a common compounding technology. The primary components are the dispersion-grade resin, plasticizers, PVC stabilizers (which are common to all PVC), and assorted fillers, pigments, and a wide variety of additives to control properties of the product in storage, during processing, and in the finished state.

Plasticizers are liquids that provide mobility to the plastisol system. They are of primary significance, and they are selected first when formulating. Plasticizers differ in the permanence characteristics they impart to the finished product. The blend of plasticizers will also assist in the control of viscosity and its stability, and in the fusion characteristics of the finished plastisol. The plasticizers are the same as used in dry (pellet or dry blend) compounding. The finished compounds are the same with regard to performance, weathering, and chemical properties.

Because plasticized PVC is compounded of a polyvinyl chloride dispersion of high-molecular-weight vinyl chloride polymers in a suitable liquid plasticizer, formulations can be made for special applications. By selective compounding, both physical and corrosion-resistant properties can be modified. For certain applications, this feature can be advantageous.

Two types of PVC resin are produced: normal impact (type 1) and high impact (type 2). Type 1 is an unplasticized PVC having normal impact and optimum chemical resistance. Type 2 is a plasticized PVC and has optimum impact strength and reduced chemical resistance. Plastisol PVC is the latter type.

Type 1 PVC (unplasticized) resists attack by most acids and strong alkalies, gasoline, kerosene, aliphatic alcohols, and hydrocarbons. It is particularly useful in the handling of hydrochloric acid. The chemical resistance of type 2 PVC (plastisol) to oxidizing and highly alkaline chemicals is reduced.

TABLE 8.15
Compatibility of Hypalon with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	60	16	Barium sulfate	200	93
Acetamide	x	x	Barium sulfide	200	93
Acetic acid, 10%	200	93	Benzaldehyde	x	x
Acetic acid, 50%	200	93	Benzene	x	x
Acetic acid, 80%	200	93	Benzene sulfonic acid, 10%	x	x
Acetic acid, glacial	x	x	Benzoic acid	200	93
Acetic anhydride	200	93	Benzyl alcohol	140	60
Acetone	x	x	Benzyl chloride	x	x
Acetyl chloride	x	x	Borax	200	93
Acrylonitrile	140	60	Boric acid	200	93
Adipic acid	140	60	Bromine gas, dry	60	16
Allyl alcohol	200	93	Bromine gas, moist	60	16
Aluminum fluoride	200	93	Bromine liquid	60	16
Aluminum hydroxide	200	93	Butadiene	x	x
Aluminum nitrate	200	93	Butyl acetate	60	16
Aluminum sulfate	180	82	Butyl alcohol	200	93
Ammonia carbonate	140	60	Butyric acid	x	x
Ammonia gas	90	32	Calcium bisulfite	200	93
Ammonium chloride, 10%	190	88	Calcium carbonate	90	32
Ammonium chloride, 10%	200	93	Calcium chlorate	90	32
Ammonium chloride, 50%	190	88	Calcium chloride	200	93
Ammonium fluoride, sat.	190	88	Calcium hydroxide, 10%	200	93
Ammonium hydroxide, 25%	200	93	Calcium hydroxide, sat.	200	93
Ammonium hydroxide, sat.	200	93	Calcium hypochlorite	200	93
Ammonium nitrate	200	93	Calcium nitrate	100	38
Ammonium persulfate	80	27	Calcium oxide	200	93
Ammonium phosphate	140	60	Calcium sulfate	200	93
Ammonium sulfate, 10–40%	200	93	Caprylic acid	x	x
Ammonium sulfide	200	93	Carbon dioxide, dry	200	93
Amyl acetate	60	16	Carbon dioxide, wet	200	93
Amyl alcohol	200	93	Carbon disulfide	200	93
Amyl chloride	x	x	Carbon monoxide	x	x
Aniline	140	60	Carbon tetrachloride	200	93
Antimony trichloride	140	60	Carbonic acid	x	x
Barium carbonate	200	93	Chloracetic acid	x	x
Barium chloride	200	93	Chlorine gas, dry	x	x
Barium hydroxide	200	93	Chlorine gas, wet	90	32

(*continued*)

TABLE 8.15 (Continued)
Compatibility of Hypalon with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Chlorobenzene	x	x	Ketones, general	x	x
Chloroform	x	x	Lactic acid, 25%	140	60
Chlorosulfonic acid	x	x	Lactic acid, conc.	80	27
Chromic acid, 10%	150	66	Magnesium chloride	200	93
Chromic acid, 50%	150	66	Manganese chloride	180	82
Chromyl chloride			Methyl chloride	x	x
Citric acid, 15%	200	93	Methyl ethyl ketone	x	x
Citric acid, conc.	200	93	Methyl isobutyl ketone	x	x
Copper acetate	x	x	Muriatic acid	140	60
Copper chloride	200	93	Nitric acid, 5%	100	38
Copper cyanide	200	93	Nitric acid, 20%	100	38
Copper sulfate	200	93	Nitric acid, 70%	x	x
Cresol	x	x	Nitric acid, anhydrous	x	x
Cupric chloride, 5%	200	93	Oleum	x	x
Cupric chloride, 50%	200	93	Perchloric acid, 10%	100	38
Cyclohexane	x	x	Perchloric acid, 70%	90	32
Cyclohexanol	x	x	Phenol	x	x
Dichloroethane (ethylene dichloride)	x	x	Phosphoric acid, 50–80%	200	93
			Picric acid	80	27
Ethylene glycol	200	93	Potassium bromide, 30%	200	93
Ferric chloride	200	93	Sodium carbonate	200	93
Ferric chloride, 50% in water	200	93	Sodium chloride	200	93
Ferric nitrate, 10–50%	200	93	Sodium hydroxide, 10%	200	93
Ferrous chloride	200	93	Sodium hydroxide, 50%	200	93
Fluorine gas, dry	140	60	Sodium hydroxide, conc.	200	93
Hydrobromic acid, 20%	100	38	Sodium hypochlorite, 20%	200	93
Hydrobromic acid, 50%	100	38	Sodium hypochlorite, conc.		
Hydrobromic acid, dilute	90	32	Sodium sulfide, to 50%	200	93
Hydrochloric acid, 20%	160	71	Stannic chloride	90	32
Hydrochloric acid, 38%	140	60	Stannous chloride	200	93
Hydrocyanic acid, 10%	90	32	Sulfuric acid, 10%	200	93
Hydrofluoric acid, 30%	90	32	Sulfuric acid, 50%	200	93
Hydrofluoric acid, 70%	90	32	Sulfuric acid, 70%	160	71
Hydrofluoric acid, 100%	90	32	Sulfuric acid, 90%	x	x
Hypochlorous acid	x	x	Sulfuric acid, 98%	x	x

TABLE 8.15 (Continued)
Compatibility of Hypalon with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sulfuric acid, 100%	x	x	Toluene	x	x
Sulfurous acid	160	71	Zinc chloride	200	93

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x.

Source: Ref. 1.

Plastisol can be attacked by aromatics, chlorinated organic compounds, and lacquer solvents.

In addition to handling highly corrosive and abrasive chemicals, many applications have also been found in marine environments. Table 8.16 lists the compatibility of plastisol with selected corrodents and Ref. 1 provides additional listings.

Vinyl plastisol coatings are popular for use as an acid-resisting coating. Plastisol has a maximum operating temperature of 140°F (60°C).

Perfluoroalkoxy (PFA)

PFA is manufactured by DuPont. It is not degraded by systems commonly encountered in chemical processes. It is inert to strong mineral acids, inorganic bases, inorganic oxidizing agents, salt solutions, and such organic compounds as organic acids, anhydrides, aromatics, aliphatic hydrocarbons, alcohols, aldehydes, esters, ethers, chlorocarbons, fluorocarbons, and mixtures of the above. Refer to Table 8.17 for the compatibility of PFA with selected corrodents and Ref. 1 for additional listings.

PFA will be attacked by certain halogen complexes containing fluorine. These include chlorine trifluoride, bromine trifluoride, iodine pentafluoride, and fluorine itself. It is also attacked by such metals as sodium or potassium, particularly in their molten states.

Standard lining thickness is nominally 0.040 in. on interior and wetted surfaces. When abrasion is a problem, a thickness of 0.090 in. is available. Coatings applied on carbon steel or stainless steel have a continuous service temperature range of between –60°F (–51°C) and 400°F (204°C).

A primer is required prior to applying the coating. If damaged, the coating cannot be repaired. Heat is required to cure the coating.

Applications are used to provide corrosion protection, nonstick surfaces, and purity protection of chemicals being handled.

TABLE 8.16
Compatibility of Plastisols with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Antimony trichloride	140	60
Acetamide	x	x	Aqua regia, 3:1	x	x
Acetic acid, 10%	100	38	Barium carbonate	140	60
Acetic acid, 50%	90	32	Barium chloride	140	60
Acetic acid, 80%	x	x	Barium hydroxide	140	60
Acetic acid, glacial	x	x	Barium sulfate	140	60
Acetic anhydride	x	x	Barium sulfide	140	60
Acetone	x	x	Benzaldehyde	x	x
Acetyl chloride	x	x	Benzene	x	x
Acrylic acid	x	x	Benzene sulfonic acid, 10%	140	60
Acrylonitrile	x	x	Benzoic acid	140	60
Adipic acid	140	60	Benzyl alcohol	x	x
Allyl alcohol	90	32	Borax	140	60
Allyl chloride	x	x	Boric acid	140	60
Alum	140	60	Bromine gas, dry	x	x
Aluminum acetate	100	38	Bromine gas, moist	x	x
Aluminum chloride, aq.	140	60	Bromine liquid	x	x
Aluminum fluoride	140	60	Butadiene	60	16
Aluminum hydroxide	140	60	Butyl acetate	x	x
Aluminum nitrate	140	60	Butyl alcohol	x	x
Aluminum oxychloride	140	60	n-Butylamine	x	x
Aluminum sulfate	140	60	Butyric acid	x	x
Ammonia gas	140	60	Calcium bisulfide	140	60
Ammonium bifluoride	90	32	Calcium bisulfide	x	x
Ammonium carbonate	140	60	Calcium bisulfite	140	60
Ammonium chloride, 10%	140	60	Calcium carbonate	140	60
Ammonium chloride, 50%	140	60	Calcium chlorate	140	60
Ammonium chloride, sat.	140	60	Calcium chloride	140	60
Ammonium fluoride, 10%	90	32	Calcium hydroxide, 10%	140	60
Ammonium fluoride, 25%	90	32	Calcium hydroxide, sat.	140	60
Ammonium hydroxide, 25%	140	60	Calcium hypochlorite	140	60
Ammonium hydroxide, sat.	140	60	Calcium nitrate	140	60
Ammonium nitrate	140	60	Calcium oxide	140	60
Ammonium persulfate	140	60	Calcium sulfate	140	60
Ammonium phosphate	140	60	Carbon dioxide, dry	140	60
Ammonium sulfate, 10–40%	140	60	Carbon dioxide, wet	140	60
Ammonium sulfide	140	60	Carbon disulfide	x	x
Amyl acetate	x	x	Carbon monoxide	140	60
Amyl alcohol	x	x	Carbon tetrachloride	x	x
Amyl chloride	x	x	Carbonic acid	140	60
Aniline	x	x	Cellosolve	x	x

TABLE 8.16 (Continued)
Compatibility of Plastisols with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Chloracetic acid	105	40	Lactic acid, 25%	140	60
Chlorine gas, dry	140	60	Lactic acid, conc.	80	27
Chlorine gas, wet	x	x	Magnesium chloride	140	60
Chlorine, liquid	x	x	Malic acid	140	60
Chlorobenzene	x	x	Methyl chloride	x	x
Chloroform	x	x	Methyl ethyl ketone	x	x
Chlorosulfonic acid	60	16	Methyl isobutyl ketone	x	x
Chromic acid, 10%	140	60	Muriatic acid	140	60
Chromic acid, 50%	x	x	Nitric acid, 5%	100	38
Citric acid, 15%	140	60	Nitric acid, 20%	140	60
Citric acid, conc.	140	60	Nitric acid, 70%	70	23
Copper carbonate	140	60	Nitric acid, anhydrous	x	x
Copper chloride	140	60	Nitrous acid, conc.	60	16
Copper cyanide	140	60	Oleum	x	x
Copper sulfate	140	60	Perchloric acid, 10%	60	16
Cresol	x	x	Perchloric acid, 70%	60	16
Cyclohexanol	x	x	Phenol	x	x
Dichloroacetic acid	120	49	Phosphoric acid, 50–80%	140	60
Dichloroethane (ethylene dichloride)	x	x	Picric acid	x	x
			Potassium bromide, 30%	140	60
Ethylene glycol	140	60	Salicylic acid	x	x
Ferric chloride	140	60	Silver bromide, 10%	105	40
Ferric nitrate, 10–50%	140	60	Sodium carbonate	140	60
Ferrous chloride	140	60	Sodium chloride	140	60
Ferrous nitrate	140	60	Sodium hydroxide, 10%	140	60
Fluorine gas, dry	x	x	Sodium hydroxide, 50%	140	60
Fluorine gas, moist	x	x	Sodium hydroxide, conc.	140	60
Hydrobromic acid, 20%	140	60	Sodium hypochlorite, 20%	140	60
Hydrobromic acid, 50%	140	60	Sodium hypochlorite, conc.	140	60
Hydrobromic acid, dilute	140	60	Sodium sulfide, to 50%	140	60
Hydrochloric acid, 20%	140	60	Stannic chloride	140	60
Hydrochloric acid, 38%	140	60	Stannous chloride	140	60
Hydrocyanic acid, 10%	140	60	Sulfuric acid, 10%	140	60
Hydrofluoric acid, 30%	120	149	Sulfuric acid, 50%	140	60
Hydrofluoric acid, 70%	68	20	Sulfuric acid, 70%	140	60
Hypochlorous acid	140	60	Sulfuric acid, 90%	x	x
Ketones, general	x	x	Sulfuric acid, 98%	x	x

(*continued*)

TABLE 8.16 (Continued)
Compatibility of Plastisols with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sulfuric acid, 100%	x	x	Toluene	x	x
Sulfuric acid, fuming	x	x	Trichloroacetic acid	x	x
Sulfurous acid	140	60	White liquor	140	60
Thionyl chloride	x	x	Zinc chloride	140	60

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Fluorinated Ethylene Propylene (FEP)

FEP is a fluorinated thermoplast but is less expensive than PTFE (Teflon). With few exceptions, FEP exhibits the same corrosion resistance as PTFE but at a lower temperature. It is resistant to practically all chemicals, the exception being extremely potent oxidizers such as chlorine trifluoride and related compounds. Some chemicals in high concentrations will attack FEP when at or near the service temperature limit. Refer to Table 8.18 for the compatibility of FEP with selected corrodents. Ref. 1 provides additional listings.

Coating thicknesses range from 0.010 to 0.060 in., with a maximum service temperature of 390°F (199°C). Damages to these coatings cannot be repaired. The coating is a fusion from a water or solvent dispersion and requires a heat cure temperature of 500 to 600°F (260 to 315°C). Application is by spray.

Previously glass lined tanks can be refurbished with this lining.

PTFE (Teflon)

PTFE coatings are spray applied as water or solvent dispersions. They require heat curing at approximately 750°F (399°C). Their maximum service temperature is 500°F (260°C).

PTFE is chemically inert in the presence of most corrodents. There are very few chemicals that will attack teflon within normal use temperatures. These reactants are among the most violent oxidizers and reducing agents known. Elemental sodium in intimate contact with fluorocarbons removes fluorine from the polymer molecule. The other alkali metals (potassium, lithium, etc.) react in a similar manner.

Fluorine and related compounds (e.g., chlorine trifluoride) are absorbed into the PTFE resin with such intimate contact that the mixture becomes sensitive to a source of ignition such as impact.

TABLE 8.17
Compatibility of PFA with Selected Corrodents[a]

Chemical	Maximum Temp °F	Maximum Temp °C	Chemical	Maximum Temp °F	Maximum Temp °C
Acetaldehyde	450	232	Aniline[c]	450	232
Acetamide	450	232	Antimony trichloride	450	232
Acetic acid, 10%	450	232	Aqua regia, 3:1	450	232
Acetic acid, 50%	450	232	Barium carbonate	450	232
Acetic acid, 80%	450	232	Barium chloride	450	232
Acetic acid, glacial	450	232	Barium hydroxide	450	232
Acetic anhydride	450	232	Barium sulfate	450	232
Acetone	450	232	Barium sulfide	450	232
Acetyl chloride	450	232	Benzaldehyde[c]	450	232
Acrylonitrile	450	232	Benzene sulfonic acid, 10%	450	232
Adipic acid	450	232	Benzene[b]	450	232
Allyl alcohol	450	232	Benzoic acid	450	232
Allyl chloride	450	232	Benzyl alcohol[c]	450	232
Alum	450	232	Benzyl chloride[b]	450	232
Aluminum chloride, aq.	450	232	Borax	450	232
Aluminum fluoride	450	232	Boric acid	450	232
Aluminum hydroxide	450	232	Bromine gas, dry[b]	450	232
Aluminum nitrate	450	232	Bromine, liquid[b,c]	450	232
Aluminum oxychloride	450	232	Butadiene[b]	450	232
Aluminum sulfate	450	232	Butyl acetate	450	232
Ammonia gas[b]	450	232	Butyl alcohol	450	232
Ammonium bifluoride[b]	450	232	Butyl phthalate	450	232
Ammonium carbonate	450	232	n-Butylamine[c]	450	232
Ammonium chloride, 10%	450	232	Butyric acid	450	232
Ammonium chloride, 50%	450	232	Calcium bisulfide	450	232
Ammonium chloride, sat.	450	232	Calcium bisulfite	450	232
Ammonium fluoride, 10%[b]	450	232	Calcium carbonate	450	232
Ammonium fluoride, 25%[b]	450	232	Calcium chlorate	450	232
Ammonium hydroxide, 25%	450	232	Calcium chloride	450	232
Ammonium hydroxide, sat.	450	232	Calcium hydroxide, 10%	450	232
Ammonium nitrate	450	232	Calcium hydroxide, sat.	450	232
Ammonium persulfate	450	232	Calcium hypochlorite	450	232
Ammonium phosphate	450	232	Calcium nitrate	450	232
Ammonium sulfate, 10–40%	450	232	Calcium oxide	450	232
Ammonium sulfide	450	232	Calcium sulfate	450	232
Amyl acetate	450	232	Caprylic acid	450	232
Amyl alcohol	450	232	Carbon bisulfide[b]	450	232
Amyl chloride	450	232	Carbon dioxide, dry	450	232

(*continued*)

TABLE 8.17 (Continued)
Compatibility of PFA with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Carbon dioxide, wet	450	232	Hydrobromic acid, 20%[b,d]	450	232
Carbon disulfide[b]	450	232	Hydrobromic acid, 50%[b,d]	450	232
Carbon monoxide	450	232	Hydrobromic acid, dilute[b,d]	450	232
Carbon tetrachloride[b,c,d]	450	232	Hydrochloric acid, 20%[b,d]	450	232
Carbonic acid	450	232	Hydrochloric acid, 38%[b,d]	450	232
Chloracetic acid	450	232	Hydrocyanic acid, 10%	450	232
Chloracetic acid, 50% water	450	232	Hydrofluoric acid, 30%[b]	450	232
Chlorine gas, dry	x	x	Hydrofluoric acid, 70%[b]	450	232
Chlorine gas, wet[b]	450	232	Hydrofluoric acid, 100%[b]	450	232
Chlorine, liquid[c]	x	x	Hypochlorous acid	450	232
Chlorobenzene[b]	450	232	Iodine solution, 10%[b]	450	232
Chloroform[b]	450	232	Ketones, general	450	232
Chlorosulfonic acid[c]	450	232	Lactic acid, 25%	450	232
Chromic acid, 10%	450	232	Lactic acid, conc.	450	232
Chromic acid, 50%[c]	450	232	Magnesium chloride	450	232
Chromyl chloride	450	232	Malic acid	450	232
Citric acid, 15%	450	232	Methyl chloride[b]	450	232
Citric acid, conc.	450	232	Methyl ethyl ketone[b]	450	232
Copper carbonate	450	232	Methyl isobutyl ketone[b]	450	232
Copper chloride	450	232	Muriatic acid[b]	450	232
Copper cyanide	450	232	Nitric acid, 5%[b]	450	232
Copper sulfate	450	232	Nitric acid, 20%[b]	450	232
Cresol	450	232	Nitric acid, 70%[b]	450	232
Cupric chloride, 5%	450	232	Nitric acid, anhydrous[b]	450	232
Cupric chloride, 50%	450	232	Nitrous acid, 10%	450	232
Cyclohexane	450	232	Oleum	450	232
Cyclohexanol	450	232	Perchloric acid, 10%	450	232
Dichloroacetic acid	450	232	Perchloric acid, 70%	450	232
Dichloroethane (ethylene dichloride)[b]	450	232	Phenol[b]	450	232
			Phosphoric acid, 50–80%[c]	450	232
Ethylene glycol	450	232	Picric acid	450	232
Ferric chloride	450	232	Potassium bromide, 30%	450	232
Ferric chloride, 50% in water[c]	450	232	Salicylic acid	450	232
Ferric nitrate, 10–50%	450	232	Sodium carbonate	450	232
Ferrous chloride	450	232	Sodium chloride	450	232
Ferrous nitrate	450	232	Sodium hydroxide, 10%	450	232
Fluorine gas, dry	x	x	Sodium hydroxide, 50%	450	232
Fluorine gas, moist	x	x	Sodium hydroxide, conc.	450	232

TABLE 8.17 (Continued)
Compatibility of PFA with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sodium hypochlorite, 20%	450	232	Sulfuric acid, 98%	450	232
Sodium hypochlorite, conc.	450	232	Sulfuric acid, 100%	450	232
Sodium sulfide, to 50%	450	232	Sulfuric acid, fuming[b]	450	232
Stannic chloride	450	232	Sulfurous acid	450	232
Stannous chloride	450	232	Thionyl chloride[b]	450	232
Sulfuric acid, 10%	450	232	Toluene[b]	450	232
Sulfuric acid, 50%	450	232	Trichloroacetic acid	450	232
Sulfuric acid, 70%	450	232	White liquor	450	232
Sulfuric acid, 90%	450	232	Zinc chloride[c]	450	232

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

[b] Material will permeate.

[c] Material will be absorbed.

[d] Material will cause stress cracking.

Source: Ref. 1.

The handling of 80% sodium hydroxide, aluminum chloride, ammonia, and certain amines at high temperature may produce the same effect as elemental sodium. Also, slow oxidative attack can be produced by 70% nitric acid under pressure at 480°F (250°C).

Refer to Table 8.19 for the compatibility of PTFE with selected corrodents. Ref. 1 provides additional details.

Tefzel (ETFE)

Tefzel is the trademark of DuPont. Ethylene-tetrafluoroethylene is a modified, partially fluorinated copolymer of ethylene and polytetrafluoroethylene (PTFE). Because it contains more than 75% PTFE by weight, it has better resistance to abrasion and cut-through than PTFE, while retaining most of the corrosion-resistant properties.

The typical Tefzel coating thickness is nominally 0.040 in. thick on all interior surfaces and flange faces. Coating thicknesses from 0.020 to 0.090 in. are available, depending on application requirements and part geometry. For coatings or linings applied on carbon steel or stainless steel, the continuous service temperature range is from –25°F (–32°C) to 225°F (104°C).

TABLE 8.18
Compatibility of FEP with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	200	93	Amyl alcohol	400	204
Acetamide	400	204	Amyl chloride	400	204
Acetic acid, 10%	400	204	Aniline[b]	400	204
Acetic acid, 50%	400	204	Antimony trichloride	250	121
Acetic acid, 80%	400	204	Aqua regia, 3:1	400	204
Acetic acid, glacial	400	204	Barium carbonate	400	204
Acetic anhydride	400	204	Barium chloride	400	204
Acetone[b]	400	204	Barium hydroxide	400	204
Acetyl chloride	400	204	Barium sulfate	400	204
Acrylic acid	200	93	Barium sulfide	400	204
Acrylonitrile	400	204	Benzaldehyde[b]	400	204
Adipic acid	400	204	Benzene[b, c]	400	204
Allyl alcohol	400	204	Benzenesulfonic acid, 10%	400	204
Allyl chloride	400	204	Benzoic acid	400	204
Alum	400	204	Benzyl alcohol	400	204
Aluminum acetate	400	204	Benzyl chloride	400	204
Aluminum chloride, aq.	400	204	Borax	400	204
Aluminum chloride, dry	300	149	Boric acid	400	204
Aluminum fluoride[c]	400	204	Bromine gas, dry[c]	200	93
Aluminum hydroxide	400	204	Bromine gas, moist[c]	200	93
Aluminum nitrate	400	204	Bromine liquid[b, c]	400	204
Aluminum oxychloride	400	204	Butadiene[c]	400	204
Aluminum sulfate	400	204	Butyl acetate	400	204
Ammonia gas[c]	400	204	Butyl alcohol	400	204
Ammonium bifluoride[c]	400	204	n-Butylamine[b]	400	204
Ammonium carbonate	400	204	Butyl phthalate	400	204
Ammonium chloride, 10%	400	204	Butyric acid	400	204
Ammonium chloride, 50%	400	204	Calcium bisulfide	400	204
Ammonium chloride, sat.	400	204	Calcium bisulfide[c]	400	204
Ammonium fluoride, 10%[c]	400	204	Calcium bisulfite	400	204
Ammonium fluoride, 25%[c]	400	204	Calcium carbonate	400	204
Ammonium hydroxide, 25%	400	204	Calcium chlorate	400	204
Ammonium hydroxide, sat.	400	204	Calcium chloride	400	204
Ammonium nitrate	400	204	Calcium hydroxide, 10%	400	204
Ammonium persulfate	400	204	Calcium hydroxide, sat.	400	204
Ammonium phosphate	400	204	Calcium hypochlorite	400	204
Ammonium sulfate, 10–40%	400	204	Calcium nitrate	400	204
Ammonium sulfide	400	204	Calcium oxide	400	204
Ammonium sulfite	400	204	Calcium sulfate	400	204
Amyl acetate	400	204	Caprylic acid	400	204

TABLE 8.18 (Continued)
Compatibility of FEP with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Carbon dioxide, dry	400	204	Ferrous nitrate	400	204
Carbon dioxide, wet	400	204	Fluorine gas, dry	200	93
Carbon disulfide	400	204	Fluorine gas, moist	x	x
Carbon monoxide	400	204	Hydrobromic acid, 20%[c,d]	400	204
Carbon tetrachloride[b, c, d]	400	204	Hydrobromic acid, 50%[c,d]	400	204
Carbonic acid	400	204	Hydrobromic acid, dilute	400	204
Cellosolve	400	204	Hydrochloric acid, 20%[c,d]	400	204
Chloracetic acid	400	204	Hydrochloric acid, 38%[c,d]	400	204
Chloracetic acid, 50% water	400	204	Hydrocyanic acid, 10%	400	204
Chlorine gas, dry	x	x	Hydrofluoric acid, 30%[c]	400	204
Chlorine gas, wet[c]	400	204	Hydrofluoric acid, 70%[c]	400	204
Chlorine, liquid[b]	400	204	Hydrofluoric acid, 100%[c]	400	204
Chlorobenzene[c]	400	204	Hypochlorous acid	400	204
Chloroform[c]	400	204	Iodine solution, 10%[c]	400	204
Chlorosulfonic acid[b]	400	204	Ketones, general	400	204
Chromic acid, 10%	400	204	Lactic acid, 25%	400	204
Chromic acid, 50%[b]	400	204	Lactic acid, conc.	400	204
Chromyl chloride	400	204	Magnesium chloride	400	204
Citric acid, 15%	400	204	Malic acid	400	204
Citric acid, conc.	400	204	Manganese chloride	300	149
Copper acetate	400	204	Methyl chloride[c]	400	204
Copper carbonate	400	204	Methyl ethyl ketone[c]	400	204
Copper chloride	400	204	Methyl isobutyl ketone[c]	400	204
Copper cyanide	400	204	Muriatic acid[c]	400	204
Copper sulfate	400	204	Nitric acid, 5%[c]	400	204
Cresol	400	204	Nitric acid, 20%[c]	400	204
Cupric chloride, 5%	400	204	Nitric acid, 70%[c]	400	204
Cupric chloride, 50%	400	204	Nitric acid, anhydrous[c]	400	204
Cyclohexane	400	204	Nitrous acid, conc.	400	204
Cyclohexanol	400	204	Oleum	400	204
Dichloroacetic acid	400	204	Perchloric acid, 10%	400	204
Dichloroethane (ethylene dichloride)[c]	400	204	Perchloric acid, 70%	400	204
			Phenol[c]	400	204
Ethylene glycol	400	204	Phosphoric acid, 50–80%	400	204
Ferric chloride	400	204	Picric acid	400	204
Ferric chloride, 50% in water[b]	260	127	Potassium bromide, 30%	400	204
Ferric nitrate, 10–50%	260	127	Salicylic acid	400	204
Ferrous chloride	400	204	Silver bromide, 10%	400	204

(*continued*)

TABLE 8.18 (Continued)
Compatibility of FEP with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sodium carbonate	400	204	Sulfuric acid, 50%	400	204
Sodium chloride	400	204	Sulfuric acid, 70%	400	204
Sodium hydroxide, 10%[b]	400	204	Sulfuric acid, 90%	400	204
Sodium hydroxide, 50%	400	204	Sulfuric acid, 98%	400	204
Sodium hydroxide, concentrated	400	204	Sulfuric acid, 100%	400	204
			Sulfuric acid, fuming[c]	400	204
Sodium hypochlorite, 20%	400	204	Sulfurous acid	400	204
Sodium hypochlorite, conc.	400	204	Thionyl chloride[c]	400	204
Sodium sulfide, to 50%	400	204	Toluene[c]	400	204
Stannic chloride	400	204	Trichloracetic acid	400	204
Stannous chloride	400	204	White liquor	400	204
Sulfuric acid, 10%	400	204	Zinc chloride[d]	400	204

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

[b] Material will be absorbed.

[c] Material will permeate.

[d] Material will cause stress cracking.

Source: Ref. 1.

Tefzel is inert to strong mineral acids, inorganic bases, halogens, and strong metal salt solutions. Even carboxylic acids, aromatic and aliphatic hydrocarbons, alcohols, ketones, aldehydes, ethers, chlorocarbons, and classic polymer solvents have little effect on Tefzel. Very strong oxidizing acids near their boiling points, such as nitric acid at high concentrations, will affect ETFE to varying degrees. So will strong organic bases such as amines and sulfonic acids. Refer to Table 8.20 for the compatibility of ETFE with selected corrodents and Ref. 1 for additional listings.

ECTFE (Halar)

ECTFE is manufactured under the trade name of Halar by Ausimont. Ethylene-chlorotrifluoroethylene is a 1:1 alternating copolymer of ethylene and chlorotrifluoroethylene. This chemical structure gives the polymer a unique combination of properties. It possesses excellent chemical resistance and, of all the fluoropolymers, ECTFE ranks among the best for abrasion resistance.

TABLE 8.19
Compatibility of PTFE with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	450	232	Antimony trichloride	450	232
Acetamide	450	232	Aqua regia, 3:1	450	232
Acetic acid, 10%	450	232	Barium carbonate	450	232
Acetic acid, 50%	450	232	Barium chloride	450	232
Acetic acid, 80%	450	232	Barium hydroxide	450	232
Acetic acid, glacial	450	232	Barium sulfate	450	232
Acetic anhydride	450	232	Barium sulfide	450	232
Acetone	450	232	Benzaldehyde	450	232
Acetyl chloride	450	232	Benzene sulfonic acid, 10%	450	232
Acrylonitrile	450	232	Benzene[b]	450	232
Adipic acid	450	232	Benzoic acid	450	232
Allyl alcohol	450	232	Benzyl alcohol	450	232
Allyl chloride	450	232	Benzyl chloride	450	232
Alum	450	232	Borax	450	232
Aluminum chloride, aq.	450	232	Boric acid	450	232
Aluminum fluoride	450	232	Bromine gas, dry[b]	450	232
Aluminum hydroxide	450	232	Bromine liquid[b]	450	232
Aluminum nitrate	450	232	Butadiene[b]	450	232
Aluminum oxychloride	450	232	Butyl acetate	450	232
Aluminum sulfate	450	232	Butyl alcohol	450	232
Ammonia gas[b]	450	232	n-Butylamine	450	232
Ammonium bifluoride	450	232	Butyl phthalate	450	232
Ammonium carbonate	450	232	Butyric acid	450	232
Ammonium chloride, 10%	450	232	Calcium bisulfide	450	232
Ammonium chloride, 50%	450	232	Calcium bisulfite	450	232
Ammonium chloride, sat.	450	232	Calcium carbonate	450	232
Ammonium fluoride, 10%	450	232	Calcium chlorate	450	232
Ammonium fluoride, 25%	450	232	Calcium chloride	450	232
Ammonium hydroxide, 25%	450	232	Calcium hydroxide, 10%	450	232
Ammonium hydroxide, sat.	450	232	Calcium hydroxide, sat.	450	232
Ammonium nitrate	450	232	Calcium hypochlorite	450	232
Ammonium persulfate	450	232	Calcium nitrate	450	232
Ammonium phosphate	450	232	Calcium oxide	450	232
Ammonium sulfate, 10–40%	450	232	Calcium sulfate	450	232
Ammonium sulfide	450	232	Caprylic acid	450	232
Amyl acetate	450	232	Carbon dioxide, dry	450	232
Amyl alcohol	450	232	Carbon dioxide, wet	450	232
Amyl chloride	450	232	Carbon disulfide	450	232
Aniline	450	232	Carbon disulfide[b]	450	232

(*continued*)

TABLE 8.19 (Continued)
Compatibility of PTFE with Selected Corrodents[a]

Chemical	Maximum Temp °F	Maximum Temp °C	Chemical	Maximum Temp °F	Maximum Temp °C
Carbon monoxide	450	232	Hydrochloric acid, 38%[c]	450	232
Carbon tetrachloride[c]	450	232	Hydrocyanic acid, 10%[c]	450	232
Carbonic acid	450	232	Hydrofluoric acid, 30%[c]	450	232
Chloracetic acid	450	232	Hydrofluoric acid, 70%[c]	450	232
Chloracetic acid, 50% water	450	232	Hydrofluoric acid, 100%[b]	450	232
Chlorine gas, dry	x	x	Hypochlorous acid	450	232
Chlorine gas, wet[b]	450	232	Iodine solution, 10%[b]	450	232
Chlorine, liquid	x	x	Ketones, general	450	232
Chlorobenzene[b]	450	232	Lactic acid, 25%	450	232
Chloroform[b]	450	232	Lactic acid, conc.	450	232
Chlorosulfonic acid	450	232	Magnesium chloride	450	232
Chromic acid, 10%	450	232	Malic acid	450	232
Chromic acid, 50%	450	232	Methyl chloride[b]	450	232
Chromyl chloride	450	232	Methyl ethyl ketone[b]	450	232
Citric acid, 15%	450	232	Methyl isobutyl ketone[c]	450	232
Citric acid, conc.	450	232	Muriatic acid[b]	450	232
Copper carbonate	450	232	Nitric acid, 20%[b]	450	232
Copper chloride	450	232	Nitric acid, 5%[b]	450	232
Copper cyanide, 10%	450	232	Nitric acid, 70%[b]	450	232
Copper sulfate	450	232	Nitric acid, anhydrous[b]	450	232
Cresol	450	232	Nitrous acid, 10%	450	232
Cupric chloride, 5%	450	232	Oleum	450	232
Cupric chloride, 50%	450	232	Perchloric acid, 10%	450	232
Cyclohexane	450	232	Perchloric acid, 70%	450	232
Cyclohexanol	450	232	Phenol[b]	450	232
Dichloroethane (ethylene dichloride)[b]	450	232	Phosphoric acid, 50–80%	450	232
			Picric acid	450	232
Dichloroethane acid	450	232	Potassium bromide, 30%	450	232
Ethylene glycol	450	232	Salicylic acid	450	232
Ferric chloride	450	232	Sodium carbonate	450	232
Ferric chloride, 50% in water	450	232	Sodium chloride	450	232
Ferric nitrate, 10–50%	450	232	Sodium hydroxide, 10%	450	232
Ferrous chloride	450	232	Sodium hydroxide, 50%	450	232
Ferrous nitrate	450	232	Sodium hydroxide, conc.	450	232
Fluorine gas, dry	x	x	Sodium hypochlorite, 20%	450	232
Fluorine gas, moist	x	x	Sodium hypochlorite, conc.	450	232
Hydrobromic acid, 20%[c]	450	232	Sodium sulfide, to 50%	450	232
Hydrobromic acid, 50%[c]	450	232	Stannic chloride	450	232
Hydrobromic acid, dilute[bc]	450	232	Stannous chloride	450	232
Hydrochloric acid, 20%[c]	450	232	Sulfuric acid, 10%	450	232

TABLE 8.19 (Continued)
Compatibility of PTFE with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sulfuric acid, 50%	450	232	Sulfurous acid, fuming[b]	450	232
Sulfuric acid, 70%	450	232	Thionyl chloride	450	232
Sulfuric acid, 90%	450	232	Toluene[b]	450	232
Sulfuric acid, 98%	450	232	Trichloroacetic acid	450	232
Sulfuric acid, 100%	450	232	White liquor	450	232
Sulfurous acid	450	232	Zinc chloride[d]	450	232

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

[b] Material will permeate.

[c] Material will cause stress cracking.

[d] Material will be absorbed.

Source: Ref. 1.

The resistance to permeation by oxygen, carbon dioxide, chlorine gas, or hydrochloric acid is superior to that of PTFE or FEP, being 10 to 100 times better. Water absorption is less than 0.1%.

Halar exhibits outstanding chemical resistance. It is virtually unaffected by all corrosive chemicals commonly encountered in industry, including strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and essentially all organic solvents except hot amines (e.g., aniline dimethylamine). As with other fluorocarbons, Halar will be attacked by metallic sodium and potassium. Refer to Table 8.21 for the compatibility of ECTFE with selected corrodents and Ref. 1 for additional listings.

Coating thicknesses range from 0.010 to 0.040 in., with a temperature range from cryogenic to 320°F (160°C). In addition to its corrosion resistance, the material has excellent impact strength and abrasion resistance. Previously glass-lined vessels can be refurbished.

Fluoroelastomers (FKM)

Fluoroelastomers are fluorine-containing hydrocarbon polymers with a saturated structure obtained by polymerizing fluorinated monomers such as vinylidene fluoride, hexafluoropropene, and tetrafluoroethylene. They are manufactured

TABLE 8.20
Compatibility of ETFE with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	200	93	Aqua regia, 3:1	210	99
Acetamide	250	121	Barium carbonate	300	149
Acetic acid, 10%	250	121	Barium chloride	300	149
Acetic acid, 50%	250	121	Barium hydroxide	300	149
Acetic acid, 80%	230	110	Barium sulfate	300	149
Acetic acid, glacial	230	110	Barium sulfide	300	149
Acetic anhydride	300	149	Benzaldehyde	210	99
Acetone	150	66	Benzene	210	99
Acetyl chloride	150	66	Benzene sulfonic acid, 10%	210	99
Acrylonitrile	150	66	Benzoic acid	270	132
Adipic acid	280	138	Benzyl alcohol	300	149
Allyl alcohol	210	99	Benzyl chloride	300	149
Allyl chloride	190	88	Borax	300	149
Alum	300	149	Boric acid	300	149
Aluminum chloride, aq.	300	149	Bromine gas, dry	150	66
Aluminum chloride, dry	300	149	Bromine water, 10%	230	110
Aluminum fluoride	300	149	Butadiene	250	121
Aluminum hydroxide	300	149	Butyl acetate	230	110
Aluminum nitrate	300	149	Butyl alcohol	300	149
Aluminum oxychloride	300	149	Butyl phthalate	150	66
Aluminum sulfate	300	149	n-Butylamine	120	49
Ammonium bifluoride	300	149	Butyric acid	250	121
Ammonium carbonate	300	149	Calcium bisulfide	300	149
Ammonium chloride, 10%	300	149	Calcium carbonate	300	149
Ammonium chloride, 50%	290	143	Calcium chlorate	300	149
Ammonium chloride, sat.	300	149	Calcium chloride	300	149
Ammonium fluoride, 10%	300	149	Calcium hydroxide, 10%	300	149
Ammonium fluoride, 25%	300	149	Calcium hydroxide, sat.	300	149
Ammonium hydroxide, 25%	300	149	Calcium hypochlorite	300	149
Ammonium hydroxide, sat.	300	149	Calcium nitrate	300	149
Ammonium nitrate	230	110	Calcium oxide	260	127
Ammonium persulfate	300	149	Calcium sulfate	300	149
Ammonium phosphate	300	149	Caprylic acid	210	99
Ammonium sulfate, 10–40%	300	149	Carbon bisulfide	150	66
Ammonium sulfide	300	149	Carbon dioxide, dry	300	149
Amyl acetate	250	121	Carbon dioxide, wet	300	149
Amyl alcohol	300	149	Carbon disulfide	150	66
Amyl chloride	300	149	Carbon monoxide	300	149
Aniline	230	110	Carbon tetrachloride	270	132
Antimony trichloride	210	99	Carbonic acid	300	149

TABLE 8.20 (Continued)
Compatibility of ETFE with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Cellosolve	300	149	Lactic acid, conc.	250	121
Chloracetic acid, 50%	230	110	Magnesium chloride	300	149
Chloracetic acid, 50% water	230	110	Malic acid	270	132
Chlorine gas, dry	210	99	Manganese chloride	120	49
Chlorine gas, wet	250	121	Methyl chloride	300	149
Chlorine, water	100	38	Methyl ethyl ketone	230	110
Chlorobenzene	210	99	Methyl isobutyl ketone	300	149
Chloroform	230	110	Muriatic acid	300	149
Chlorosulfonic acid	80	27	Nitric acid, 5%	150	66
Chromic acid, 10%	150	66	Nitric acid, 20%	150	66
Chromic acid, 50%	150	66	Nitric acid, 70%	80	27
Chromyl chloride	210	99	Nitric acid, anhydrous	x	x
Citric acid, 15%	120	49	Nitrous acid, conc.	210	99
Copper chloride	300	149	Oleum	150	66
Copper cyanide	300	149	Perchloric acid, 10%	230	110
Copper sulfate	300	149	Perchloric acid, 70%	150	66
Cresol	270	132	Phenol	210	99
Cupric chloride, 5%	300	149	Phosphoric acid, 50–80%	270	132
Cyclohexane	300	149	Picric acid	130	54
Cyclohexanol	250	121	Potassium bromide, 30%	300	149
Dichloroacetic acid	150	66	Salicylic acid	250	121
Ethylene glycol	300	149	Sodium carbonate	300	149
Ferric chloride, 50% in water	300	149	Sodium chloride	300	149
Ferric nitrate, 10–50%	300	149	Sodium hydroxide, 10%	230	110
Ferrous chloride	300	149	Sodium hydroxide, 50%	230	110
Ferrous nitrate	300	149	Sodium hypochlorite, 20%	300	149
Fluorine gas, dry	100	38	Sodium hypochlorite,	300	149
Fluorine gas, moist	100	38	conc.		
Hydrobromic acid, 20%	300	149	Sodium sulfide, to 50%	300	149
Hydrobromic acid, 50%	300	149	Stannic chloride	300	149
Hydrobromic acid, dilute	300	149	Stannous chloride	300	149
Hydrochloric acid, 20%	300	149	Sulfuric acid, 10%	300	149
Hydrochloric acid, 38%	300	149	Sulfuric acid, 50%	300	149
Hydrocyanic acid, 10%	300	149	Sulfuric acid, 70%	300	149
Hydrofluoric acid, 30%	270	132	Sulfuric acid, 90%	300	149
Hydrofluoric acid, 70%	250	121	Sulfuric acid, 98%	300	149
Hydrofluoric acid, 100%	230	110	Sulfuric acid, 100%	300	149
Hypochlorous acid	300	149	Sulfuric acid, fuming	120	49
Lactic acid, 25%	250	121	Sulfurous acid	210	99

(*continued*)

TABLE 8.20 (Continued)
Compatibility of ETFE with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Thionyl chloride	210	99	Trichloroacetic acid	210	99
Toluene	250	121	Zinc chloride	300	149

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Material extracted from Ref. 1.

under various trade names such as Viton by DuPont, Technoflon by Ausimont, and Fluorel by 3M.

The fluoroelastomers have been approved by the U.S. Food and Drug Administration for use in repeated contact with food products. More details are available in the *Federal Register* (Vol. 33 No. 5, Tuesday, January 9, 1968), Part 121—Food Additives, Subpart F—Food Additives Resulting from Contact with Containers or Equipment and Food Additives Otherwise Affecting Food–Rubber Articles Intended for Repeated Use.

As with other rubbers, fluoroelastomers are capable of being compounded with various additives to enhance specific properties for particular applications.

FKM coatings have an allowable temperature range of –40°F (–40°C) to 400°F (206°C).

Fluoroelastomers provide excellent resistance to oils, fuels, lubricants, most mineral acids, many aliphatic and aromatic hydrocarbons (carbon tetrachloride, benzene, toluene, xylene) that act as solvents for chlorinated solvents, and pesticides. Special formulations can be produced to obtain resistance to hot mineral acids, steam, and hot water.

These elastomers are not suitable for use with low-molecular-weight esters and ethers, ketones, certain amines, or hot anhydrous hydrofluoric or chlorosulfonic acids. Their solubility in low-molecular-weight ketones is an advantage in producing solution coatings of fluoroelastomers. Refer to Table 8.22 for the compatibility of fluoroelastomers with selected corrodents and Ref. 1 for additional listings.

The chemical stability of these elastomers is an important property for their use as protective coatings. Applications include coatings for power station stacks operated with high-sulfur fuels, and tank coatings for the chemical industry.

TABLE 8.21
Compatibility of ECTFE with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetic acid, 10%	250	121	Barium carbonate	300	149
Acetic acid, 50%	250	121	Barium chloride	300	149
Acetic acid, 80%	150	66	Barium hydroxide	300	149
Acetic acid, glacial	200	93	Barium sulfate	300	149
Acetic anhydride	100	38	Barium sulfide	300	149
Acetone	150	66	Benzaldehyde	150	66
Acetyl chloride	150	66	Benzene	150	66
Acrylonitrile	150	66	Benzene sulfonic acid, 10%	150	66
Adipic acid	150	66	Benzoic acid	250	121
Allyl chloride	300	149	Benzyl alcohol	300	149
Alum	300	149	Benzyl chloride	300	149
Aluminum chloride, aq.	300	149	Borax	300	149
Aluminum chloride, dry			Boric acid	300	149
Aluminum fluoride	300	149	Bromine gas, dry	x	x
Aluminum hydroxide	300	149	Bromine liquid	150	66
Aluminum nitrate	300	149	Butadiene	250	121
Aluminum oxychloride	150	66	Butyl acetate	150	66
Aluminum sulfate	300	149	Butyl alcohol	300	149
Ammonia gas	300	149	Butyric acid	250	121
Ammonium bifluoride	300	149	Calcium bisulfide	300	149
Ammonium carbonate	300	149	Calcium bisulfite	300	149
Ammonium chloride, 10%	290	143	Calcium carbonate	300	149
Ammonium chloride, 50%	300	149	Calcium chlorate	300	149
Ammonium chloride, sat.	300	149	Calcium chloride	300	149
Ammonium fluoride, 10%[b]	300	149	Calcium hydroxide, 10%	300	149
Ammonium fluoride, 25%[b]	300	149	Calcium hydroxide, sat.	300	149
Ammonium hydroxide, 25%	300	149	Calcium hypochlorite	300	149
Ammonium hydroxide, sat.	300	149	Calcium nitrate	300	149
Ammonium nitrate	300	149	Calcium oxide	300	149
Ammonium persulfate	150	66	Calcium sulfate	300	149
Ammonium phosphate	300	149	Caprylic acid	220	104
Ammonium sulfate, 10–40%	300	149	Carbon bisulfide	80	27
Ammonium sulfide	300	149	Carbon dioxide, dry	300	149
Amyl acetate	160	71	Carbon dioxide, wet	300	149
Amyl alcohol	300	149	Carbon disulfide	80	27
Amyl chloride	300	149	Carbon monoxide	150	66
Aniline[c]	90	32	Carbon tetrachloride	300	149
Antimony trichloride	100	38	Carbonic acid	300	149
Aqua regia, 3:1	250	121	Cellosolve	300	149

(*continued*)

TABLE 8.21 (Continued)
Compatibility of ECTFE with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Chloracetic acid	250	121	Iodine solution, 10%	250	121
Chloracetic acid, 50% water	250	121	Lactic acid, 25%	150	66
Chlorine gas, dry	150	66	Lactic acid, conc.	150	66
Chlorine gas, wet	250	121	Magnesium chloride	300	149
Chlorine, liquid	250	121	Malic acid	250	121
Chlorobenzene	150	66	Methyl chloride	300	149
Chloroform	250	121	Methyl ethyl ketone	150	66
Chlorosulfonic acid	80	27	Methyl isobutyl ketone	150	66
Chromic acid, 10%	250	121	Muriatic acid	300	149
Chromic acid, 50%[c]	250	121	Nitric acid, 5%	300	149
Citric acid, 15%	300	149	Nitric acid, 20%[b]	250	121
Citric acid, conc.	300	149	Nitric acid, 70%[b]	150	66
Copper carbonate	150	66	Nitric acid, anhydrous	150	66
Copper chloride	300	149	Nitrous acid, conc.	250	121
Copper cyanide	300	149	Oleum	x	x
Copper sulfate	300	149	Perchloric acid, 10%	150	66
Cresol	300	149	Perchloric acid, 70%	150	66
Cupric chloride, 5%	300	149	Phenol	150	66
Cupric chloride, 50%	300	149	Phosphoric acid, 50–80%	250	121
Cyclohexane	300	149	Picric acid	88	27
Cyclohexanol	300	149	Potassium bromide, 30%	300	149
Ethylene glycol	300	149	Salicylic acid	250	121
Ferric chloride	300	149	Sodium carbonate	300	149
Ferric chloride, 50% in water	300	149	Sodium chloride	300	149
Ferric nitrate, 10–50%	300	149	Sodium hydroxide, 10%	300	149
Ferrous chloride	300	149	Sodium hydroxide, 50%	250	121
Ferrous nitrate	300	149	Sodium hydroxide, conc.	150	66
Fluorine gas, dry	x	x	Sodium hypochlorite, 20%	300	149
Fluorine gas, moist	80	27	Sodium hypochlorite, conc.	300	149
Hydrobromic acid, 20%	300	149	Sodium sulfide, to 50%	300	149
Hydrobromic acid, 50%	300	149	Stannic chloride	300	149
Hydrobromic acid, dilute	300	149	Stannous chloride	300	149
Hydrochloric acid, 20%	300	149	Sulfuric acid, 10%	250	121
Hydrochloric acid, 38%	300	149	Sulfuric acid, 50%	250	121
Hydrocyanic acid, 10%	300	149	Sulfuric acid, 70%	250	121
Hydrofluoric acid, 30%	250	121	Sulfuric acid, 90%	150	66
Hydrofluoric acid, 70%	240	116	Sulfuric acid, 98%	150	66
Hydrofluoric acid, 100%	240	116	Sulfuric acid, 100%	80	27
Hypochlorous acid	300	149	Sulfuric acid, fuming	300	149

TABLE 8.21 (Continued)
Compatibility of ECTFE with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sulfurous acid	250	121	Trichloroacetic acid	150	66
Thionyl chloride	150	66	White liquor	250	121
Toluene	150	66	Zinc chloride	300	149

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Polyvinylidene Fluoride (PVDF)

PVDF is a homopolymer of 1,1–difluoroethane with alternating CH_2 and CF_2 groups along the polymer chain. These groups impart a unique polarity that influences its solubility. The polymer has the characteristic stability of fluoropolymers when exposed to aggressive chemical and thermal conditions.

Polyvinylidene fluoride is manufactured under the trade name of Kynar by Elf Atochem, Solef by Solvay, Hylar by Ausimont U.S.A., and Super Pro 230 and ISO by Asahi/America.

PVDF can be used in applications intended for repeated contact with food per Title 21, Code of Federal Regulations, Chapter 1, Part 177.2520. It is also permitted for use in processing or storage areas in contact with meat or poultry food products prepared under federal inspection according to the U.S. Department of Agriculture (U.S.D.A.). Use is also permitted under "3-A Sanitary Standards for Multiple-Use Plastic Materials Used as Product Contact Surfaces for Dairy Equipment Serial No. 2000."

PVDF linings have an operating temperature range of from –4°F (–20°C) to 280°F (138°C). Coating thicknesses range from 0.010 to 0.040 in.

Polyvinylidene fluoride is resistant to most acids, alkalies, aliphatic and aromatic hydrocarbons, alcohols, and strong oxidizing agents. Highly polar solvents such as acetone and ethyl acetate may cause swelling. When used with strong alkalies, stress cracking results. Refer to Table 8.23 for the compatibility of PVDF with selected corrodents and Ref. 1 for additional listings.

Typical applications include coating vessels, agitators, pump housings, centrifuge housings, and dust collectors. Previously glass-lined tanks and accessories can be refurbished.

TABLE 8.22
Compatibility of Fluoroelastomers with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Amyl alcohol	200	93
Acetamide	210	199	Amyl chloride	190	88
Acetic acid, 10%	190	88	Aniline	230	110
Acetic acid, 50%	180	82	Antimony trichloride	190	88
Acetic acid, 80%	180	82	Aqua regia, 3:1	190	88
Acetic acid, glacial	x	x	Barium carbonate	250	121
Acetic anhydride	x	x	Barium chloride	400	204
Acetone	x	x	Barium hydroxide	400	204
Acetyl chloride	400	204	Barium sulfate	400	204
Acrylic acid	x	x	Barium sulfide	400	204
Acrylonitrile	x	x	Benzaldehyde	x	x
Adipic acid	190	82	Benzene	400	204
Allyl alcohol	190	88	Benzene sulfonic acid, 10%	190	88
Allyl chloride	100	38	Benzoic acid	400	204
Alum	190	88	Benzyl alcohol	400	204
Aluminum acetate	180	82	Benzyl chloride	400	204
Aluminum chloride, aq.	400	204	Borax	190	88
Aluminum fluoride	400	204	Boric acid	400	204
Aluminum hydroxide	190	88	Bromine gas, dry, 25%	180	82
Aluminum nitrate	400	204	Bromine gas, moist, 25%	180	82
Aluminum oxychloride	x	x	Bromine liquid	350	177
Aluminum sulfate	390	199	Butadiene	400	204
Ammonia gas	x	x	Butyl acetate	x	x
Ammonium bifluoride	140	60	Butyl alcohol	400	204
Ammonium carbonate	190	88	n-Butylamine	x	x
Ammonium chloride, 10%	400	204	Butyl phthalate	80	27
Ammonium chloride, 50%	300	149	Butyric acid	120	49
Ammonium chloride, sat.	300	149	Calcium bisulfide	400	204
Ammonium fluoride, 10%	140	60	Calcium bisulfite	400	204
Ammonium fluoride, 25%	140	60	Calcium carbonate	190	88
Ammonium hydroxide, 25%	190	88	Calcium chlorate	190	88
Ammonium hydroxide, sat.	190	88	Calcium chloride	300	149
Ammonium nitrate	x	x	Calcium hydroxide, 10%	300	149
Ammonium persulfate	140	60	Calcium hydroxide, sat.	400	204
Ammonium phosphate	180	82	Calcium hypochlorite	400	204
Ammonium sulfate, 10–40%	180	82	Calcium nitrate	400	204
Ammonium sulfide	x	x	Calcium sulfate	200	93
Amyl acetate	x	x	Carbon bisulfide	400	204

TABLE 8.22 (CONTINUED)
Compatibility of Fluoroelastomers with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Carbon dioxide, dry	80	27	Fluorine gas, dry	x	x
Carbon dioxide, wet	x	x	Fluorine gas, moist	x	x
Carbon disulfide	400	204	Hydrobromic acid, 20%	400	204
Carbon monoxide	400	204	Hydrobromic acid, 50%	400	204
Carbon tetrachloride	350	177	Hydrobromic acid, dilute	400	204
Carbonic acid	400	204	Hydrochloric acid, 20%	350	177
Cellosolve	x	x	Hydrochloric acid, 38%	350	177
Chloracetic acid	x	x	Hydrocyanic acid, 10%	400	204
Chloraceticacid, 50% water	x	x	Hydrofluoric acid, 30%	210	99
Chlorine gas, dry	190	88	Hydrofluoric acid, 70%	350	177
Chlorine gas, wet	190	88	Hydrofluoric acid, 100%	x	x
Chlorine, liquid	190	88	Hypochlorous acid	400	204
Chlorobenzene	400	204	Iodine solution, 10%	190	88
Chloroform	400	204	Ketones, general	x	x
Chlorosulfonic acid	x	x	Lactic acid, 25%	300	149
Chromic acid, 10%	350	177	Lactic acid, conc.	400	204
Chromic acid, 50%	350	177	Magnesium chloride	390	199
Citric acid, 15%	300	149	Malic acid	390	199
Citric acid, conc.	400	204	Manganese chloride	180	82
Copper acetate	x	x	Methyl chloride	190	88
Copper carbonate	190	88	Methyl ethyl ketone	x	x
Copper chloride	400	204	Methyl isobutyl ketone	x	x
Copper cyanide	400	204	Muriatic acid	350	149
Copper sulfate	400	204	Nitric acid, 5%	400	204
Cresol	x	x	Nitric acid, 20%	400	204
Cupric chloride, 5%	180	82	Nitric acid, 70%	190	88
Cupric chloride, 50%	180	82	Nitric acid, anhydrous	190	88
Cyclohexane	400	204	Nitrous acid, conc.	90	32
Cyclohexanol	400	204	Oleum	190	88
Dichloroethane (ethylene dichloride)	190	88	Perchloric acid, 10%	400	204
			Perchloric acid, 70%	400	204
Ethylene glycol	400	204	Phenol	210	99
Ferric chloride	400	204	Phosphoric acid, 50–80%	300	149
Ferric chloride, 50% in water	400	204	Picric acid	400	204
Ferric nitrate, 10–50%	400	204	Potassium bromide, 30%	190	88
Ferrous chloride	180	82	Salicylic acid	300	149
Ferrous nitrate	210	99	Sodium carbonate	190	88

(*continued*)

TABLE 8.22 (Continued)
Compatibility of Fluoroelastomers with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sodium chloride	400	204	Sulfuric acid, 70%	350	149
Sodium hydroxide, 10%	x	x	Sulfuric acid, 90%	350	149
Sodium hydroxide, 50%	x	x	Sulfuric acid, 98%	350	149
Sodium hydroxide, conc.	x	x	Sulfuric acid, 100%	180	82
Sodium hypochlorite, 20%	400	204	Sulfuric acid, fuming	200	93
Sodium hypochlorite, conc.	400	204	Sulfurous acid	400	204
Sodium sulfide, to 50%	190	88	Thionyl chloride	x	x
Stannic chloride	400	204	Toluene	400	204
Stannous chloride	400	204	Trichloroacetic acid	190	88
Sulfuric acid, 10%	350	149	White liquor	190	88
Sulfuric acid, 50%	350	149	Zinc chloride	400	204

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

Isophthalic Polyester

The isophthalic polyesters use isophthalic acid in place of phthalic anhydrides as the saturated monomer. This increases the cost of production but improves the chemical resistance.

The standard corrosion-grade isophthalic polyesters are made with a 1:1 molar ratio of isophthalic acid and maleic anhydride or fumaric acid with propylene glycol.

The isophthalic polyesters are the most common type used for chemical service applications. They have a wide range of corrosion resistance, being satisfactory for use up to 125°F (52°C) in such acids as 10% acetic, benzoic, citric, oleic, 25% phosphoric, 10 to 25% sulfuric, and fatty acids. Most inorganic salts are also compatible with isophthalic polyesters. Solvents such as amyl alcohol, ethylene glycol, formaldehyde, gasoline, kerosene, and naphtha are also compatible.

The isophthalic polyesters are not resistant to acetone, amyl acetate, benzene, carbon disulfide, solutions of alkaline salts of potassium and sodium, hot distilled water, or higher concentrations of oxidizing acids. Refer to Table 8.24 for the compatibility of isophthalic polyesters with selected corrodents and Ref. 1 for a more comprehensive listing.

TABLE 8.23
Compatibility of PVDF with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	150	66	Amyl acetate	190	88
Acetamide	90	32	Amyl alcohol	280	138
Acetic acid 10%	300	149	Amyl chloride	280	138
Acetic acid, 50%	300	149	Aniline	200	93
Acetic acid, 80%	190	88	Antimony trichloride	150	66
Acetic acid, glacial	190	88	Aqua regia, 3:1	130	54
Acetic anhydride	100	38	Barium carbonate	280	138
Acetone	x	x	Barium chloride	280	138
Acetyl chloride	120	49	Barium hydroxide	280	138
Acrylic acid	150	66	Barium sulfate	280	138
Acrylonitrile	130	54	Barium sulfide	280	138
Adipic acid	280	138	Benzaldehyde	120	49
Allyl alcohol	200	93	Benzene	150	66
Allyl chloride	200	93	Benzene sulfonic acid, 10%	100	38
Alum	180	82	Benzoic acid	250	121
Aluminum acetate	250	121	Benzyl alcohol	280	138
Aluminum chloride, aq.	300	149	Benzyl chloride	280	138
Aluminum chloride, dry	270	132	Borax	280	138
Aluminum fluoride	300	149	Boric acid	280	138
Aluminum hydroxide	260	127	Bromine gas, dry	210	99
Aluminum nitrate	300	149	Bromine gas, moist	210	99
Aluminum oxychloride	290	143	Bromine liquid	140	60
Aluminum sulfate	300	149	Butadiene	280	138
Ammonia gas	270	132	Butyl acetate	140	60
Ammonium bifluoride	250	121	Butyl alcohol	280	138
Ammonium carbonate	280	138	n-Butylamine	x	x
Ammonium chloride, 10%	280	138	Butyl phthalate	80	27
Ammonium chloride, 50%	280	138	Butyric acid	230	110
Ammonium chloride, sat.	280	138	Calcium bisulfide	280	138
Ammonium fluoride, 10%	280	138	Calcium bisulfite	280	138
Ammonium fluoride, 25%	280	138	Calcium carbonate	280	138
Ammonium hydroxide, 25%	280	138	Calcium chlorate	280	138
Ammonium hydroxide, sat.	280	138	Calcium chloride	280	138
Ammonium nitrate	280	138	Calcium hydroxide, 10%	270	132
Ammonium persulfate	280	138	Calcium hydroxide, sat.	280	138
Ammonium phosphate	280	138	Calcium hypochlorite	280	138
Ammonium sulfate, 10–40%	280	138	Calcium nitrate	280	138
Ammonium sulfide	280	138	Calcium oxide	250	121
Ammonium sulfite	280	138	Calcium sulfate	280	138

(*continued*)

TABLE 8.23 (Continued)
Compatibility of PVDF with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Caprylic acid	220	104	Ferrous nitrate, 10–50%	280	138
Carbon bisulfide	80	27	Fluorine gas, dry	80	27
Carbon dioxide, dry	280	138	Fluorine gas, moist	80	27
Carbon dioxide, wet	280	138	Hydrobromic acid, 20%	280	138
Carbon disulfide	80	27	Hydrobromic acid, 50%	280	138
Carbon monoxide	280	138	Hydrobromic acid, dilute	260	127
Carbon tetrachloride	280	138	Hydrochloric acid, 20%	280	138
Carbonic acid	280	138	Hydrochloric acid, 38%	280	138
Cellosolve	280	138	Hydrocyanic acid, 10%	280	138
Chloracetic acid	200	93	Hydrofluoric acid, 30%	260	127
Chloracetic acid, 50% water	210	99	Hydrofluoric acid, 70%	200	93
			Hydrofluoric acid, 100%	200	93
Chloride gas, dry	210	99	Hypochlorous acid	280	138
Chlorine gas, wet, 10%	210	99	Iodine solution	250	121
Chlorine, liquid	210	99	Ketones, general	110	43
Chlorobenzene	220	104	Lactic acid, 25%	130	54
Chloroform	250	121	Lactic acid, conc.	110	43
Chlorosulfonic acid	110	43	Magnesium chloride	280	138
Chromic acid, 10%	220	104	Malic acid	250	121
Chromic acid, 50%	250	121	Manganess chloride	280	138
Chromyl chloride	110	43	Methyl chloride	x	x
Citric acid, 15%	250	121	Methyl ethyl ketone	x	x
Citric acid, concentrated	250	121	Methyl isobutyl ketone	110	43
Copper acetate	250	121	Muriatic acid	280	138
Copper carbonate	250	121	Nitric acid, 20%	180	82
Copper chloride	280	138	Nitric acid, 5%	200	93
Copper cyanide	280	138	Nitric acid, 70%	120	49
Copper sulfate	280	138	Nitric acid, anhydrous	150	66
Cresol	210	99	Nitrous acid, conc.	210	99
Cupric chloride, 5%	270	132	Oleum	x	x
Cupric chloride, 50%	270	132	Perchloric acid, 10%	210	99
Cyclohexane	250	121	Perchloric acid, 70%	120	49
Cyclohexanol	210	99	Phenol	200	93
Dichlorethane (ethylene dichloride)	280	138	Phosphoric acid, 50–80%	220	104
			Picric acid	80	27
Dichloroacetic acid	120	49	Potassium bromide, 30%	280	138
Ethylene glycol	280	138	Salicylic acid	220	104
Ferric chloride	280	138	Silver bromide, 10%	250	121
Ferric chloride, 50% in water	280	138	Sodium carbonate	280	138
Ferrous chloride	280	138	Sodium chloride	280	138
Ferrous nitrate	280	138	Sodium hydroxide, 10%	230	110

TABLE 8.23 (Continued)
Compatibility of PVDF with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sodium hydroxide, 50%	220	104	Sulfuric acid, 90%	210	99
Sodium hydroxide, conc.[b]	150	66	Sulfuric acid, 98%	140	60
Sodium hypochlorite, 20%	280	138	Sulfuric acid, 100%	x	x
Sodium hypochlorite, conc.	280	138	Sulfuric acid, fuming	x	x
Sodium sulfide, to 50%	280	138	Sulfurous acid	220	104
Stannic chloride	280	138	Thionyl chloride	x	x
Stannous chloride	280	138	Toluene	x	x
Sulfuric acid, 10%	250	121	Trichloroacetic acid	130	54
Sulfuric acid, 50%	220	104	White liquor	80	27
Sulfuric acid, 70%	220	104	Zinc chloride	260	127

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

[b] Subject to stress corrosion cracking.

Source: Ref. 1.

Applications include coating of chemical storage tanks. In food contact applications, these resins withstand acids and corrosive salts encountered in foods and food handling.

Bisphenol A Fumarate Polyesters

This is a premium-grade, corrosion-resistant resin. It costs approximately one third more than an isophthalic resin.

Standard bisphenol A fumarate resins are derived from the propylene glycol or oxide diether of bisphenol A and fumaric acid. The aromatic structure contributed by the bisphenol A provides several benefits. Thermal stability is improved; and because the number of interior chain ester groups is reduced, the resistance to hydrolysis and saponification increases. Bisphenol A fumarate polyesters have the best hydrolysis resistance of any commercial unsaturated polyester.

The bisphenol polyesters are superior in their corrosion resistant properties to the isophthalic polyesters. They show good performance with moderate alkaline solutions, and excellent resistance to the various categories of bleaching agents.

TABLE 8.24
Compatibility of Isophthalic Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Aqua regia, 3:1	x	x
Acetic acid, 10%	180	82	Barium carbonate	190	88
Acetic acid, 50%	110	43	Barium chloride	140	60
Acetic acid, 80%	x	x	Barium hydroxide	x	x
Acetic acid, glacial	x	x	Barium sulfate	160	71
Acetic anhydride	x	x	Barium sulfide	90	32
Acetone	x	x	Benzaldehyde	x	x
Acetyl chloride	x	x	Benzene	x	x
Acrylic acid	x	x	Benzene sulfonic acid, 10%	180	82
Acrylonitrile	x	x	Benzoic acid	180	82
Adipic acid	220	104	Benzyl alcohol	x	x
Allyl alcohol	x	x	Benzyl chloride	x	x
Allyl chloride	x	x	Borax	140	60
Alum	250	121	Boric acid	180	82
Aluminum chloride, aq.	180	82	Bromine gas, dry	x	x
Aluminum chloride, dry	170	77	Bromine gas, moist	x	x
Aluminum fluoride, 10%	140	60	Bromine liquid	x	x
Aluminum hydroxide	160	71	Butyl acetate	x	x
Aluminum nitrate	160	71	Butyl alcohol	80	27
Aluminum sulfate	180	82	n-Butylamine	x	x
Ammonia gas	90	32	Butyric acid, 25%	129	49
Ammonium carbonate	x	x	Calcium bisulfide	160	71
Ammonium chloride, 10%	160	71	Calcium bisulfite	150	66
Ammonium chloride, 50%	160	71	Calcium carbonate	160	71
Ammonium chloride, sat.	180	82	Calcium chlorate	160	71
Ammonium fluoride, 10%	90	32	Calcium chloride	180	82
Ammonium fluoride, 25%	90	32	Calcium hydroxide, 10%	160	71
Ammonium hydroxide, 25%	x	x	Calcium hydroxide, sat.	160	71
Ammonium hydroxide, sat.	x	x	Calcium hypochlorite, 10%	120	49
Ammonium nitrate	160	71	Calcium nitrate	140	60
Ammonium persulfate	160	71	Calcium oxide	160	71
Ammonium phosphate	160	71	Calcium sulfate	160	71
Ammonium sulfate, 10%	180	82	Caprylic acid	160	71
Ammonium sulfide	x	x	Carbon bisulfide	x	x
Ammonium sulfite	x	x	Carbon dioxide, dry	160	71
Amyl acetate	x	x	Carbon dioxide, wet	160	71
Amyl alcohol	160	71	Carbon disulfide	x	x
Amyl chloride	x	x	Carbon monoxide	160	71
Aniline	x	x	Carbon tetrachloride	x	x
Antimony trichloride	160	71	Carbonic acid	160	71

TABLE 8.24 (Continued)
Compatibility of Isophthalic Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Cellosolve	x	x	Hydrofluoric acid, 30%	x	x
Chloracetic acid, 50% water	x	x	Hydrofluoric acid, 70%	x	x
Chloride gas, dry	160	71	Hydrofluoric acid, 100%	x	93
Chlorine gas, wet,	160	71	Hypochlorous acid	90	32
Chlorine, liquid	x	x	Ketones, general	x	x
Chloroacetic acid, 25%	150	66	Lactic acid, 25%	160	71
Chlorobenzene	x	x	Magnesium chloride	180	82
Chloroform	x	x	Malic acid	90	32
Chlorosulfonic acid	x	x	Methyl ethyl ketone	x	x
Chromic acid, 10%	x	x	Methyl isobutyl ketone	x	x
Chromic acid, 50%	x	x	Muriatic acid	160	71
Chromyl chloride	140	60	Nitric acid, 5%	120	49
Citric acid, 15%	160	71	Nitric acid, 20%	x	x
Citric acid, conc.	200	93	Nitric acid, 70%	x	x
Copper acetate	160	71	Nitric acid, anhydrous	x	x
Copper chloride	180	82	Nitrous acid, conc.	120	49
Copper cyanide	160	71	Oleum	x	x
Copper sulfate	200	93	Perchloric acid, 10%	x	x
Cresol	x	x	Perchloric acid, 70%	x	x
Cupric chloride, 5%	170	77	Phenol	x	x
Cupric chloride, 50%	170	77	Phosphoric acid, 50–80%	180	82
Cyclohexane	80	27	Picric acid	x	x
Dichloroacetic acid	x	x	Potassium bromide, 30%	160	71
Dichloroethane (ethylene dichloride)	x	x	Salicylic acid	100	38
			Sodium carbonate, 20%	90	32
Ethylene glycol	120	49	Sodium chloride	200	93
Ferric chloride	180	82	Sodium hydroxide, 10%	x	x
Ferric chloride, 50% in water	160	71	Sodium hydroxide, 50%	x	x
Ferric nitrate, 10–50%	180	82	Sodium hydroxide, conc.	x	x
Ferrous chloride	180	82	Sodium hypochlorite, 20%	x	x
Ferrous nitrate	160	71	Sodium hypochlorite, conc.	x	x
Fluorine gas, dry	x	x	Sodium sulfide, to 50%	x	x
Fluorine gas, moist	x	x	Stannic chloride	180	82
Hydrobormic acid, dilute	120	49	Stannous chloride	180	82
Hydrobromic acid, 20%	140	60	Sulfuric acid, 10%	160	71
Hydrobromic acid, 50%	140	60	Sulfuric acid, 50%	150	66
Hydrochloric acid, 20%	160	71	Sulfuric acid, 70%	x	x
Hydrochloric acid, 38%	160	71	Sulfuric acid, 90%	x	x
Hydrocyanic acid, 10%	90	32	Sulfuric acid, 98%	x	x

(*continued*)

TABLE 8.24 (Continued)
Compatibility of Isophthalic Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sulfuric acid, 100%	x	x	Toluene	110	43
Sulfuric acid, fuming	x	x	Trichloroacetic acid, 50%	170	77
Sulfurous acid	x	x	White liquor	x	x
Thionyl chloride	x	x	Zinc chloride	180	82

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

The bisphenol polyesters will break down in highly concentrated acids or alkalies. These resins can be used in the handling of the following materials:

1. Acids (to 200°F/93°C):
   Acetic
   Benzoic
   Boric
   Butyric
   Chloroacetic, 15%
   Chromic, 5%
   Citric
   Fatty acids
   Hydrochloric, 10%
   Lactic
   Maleic
   Oleic
   Oxalic
   Phosphoric, 80%
   Stearic
   Sulfonic, 30%
   Tannic
   Tartaric
   Trichloroacetic, 50%
   Rayon spin bath
2. Salt solutions (to 200°F/93°C):
   All aluminum salts
   Most ammonium salts
   Calcium salts
   Most plating solutions
   Copper salts
   Iron salts
   Zinc salts
3. Alkalies:
   Ammonium hydroxide, 5%, to 160°F (71°C)
   Calcium hydroxide, 25%, to 160°F (71°C)
   Calcium hypochlorite, 20%, to 200°F (93°C)
   Chlorine dioxide, 15%, to 200°F (93°C)
   Potassium hydroxide, 25%, to 160°F (71°C)
   Sodium chlorite, to 200°F (93°C)
   Sodium hydrosulfite, to 200°F (93°C)

TABLE 8.25
Compatibility of Bisphenol A Fumarate Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Antimony trichloride	220	104
Acetic acid, 10%	220	104	Aqua regia, 3:1	x	x
Acetic acid, 50%	160	171	Barium carbonate	200	93
Acetic acid, 80%	160	171	Barium chloride	220	104
Acetic acid, glacial	x	x	Barium hydroxide	150	66
Acetic anhydride	110	43	Barium sulfate	220	104
Acetone	x	x	Barium sulfide	140	60
Acetyl chloride	x	x	Benzaldehyde	x	x
Acrylic acid	100	38	Benzene	x	x
Acrylonitrile	x	x	Benzene sulfonic acid, 10%	200	93
Adipic acid	220	104	Benzoic acid	180	82
Allyl alcohol	x	x	Benzyl alcohol	x	x
Allyl chloride	x	x	Benzyl chloride	x	x
Alum	220	104	Borax	220	104
Aluminum chloride, aq.	200	93	Boric acid	220	104
Aluminum fluoride, 10%	90	32	Bromine gas, dry	90	32
Aluminum hydroxide	160	71	Bromine gas, moist	100	38
Aluminum nitrate	200	93	Bromine, liquid	x	x
Aluminum sulfate	200	93	Butyl acetate	80	27
Ammonia gas	200	93	Butyl alcohol	80	27
Ammonium carbonate	90	32	n-Butylamine	x	x
Ammonium chloride, 10%	200	93	Butyric acid	220	93
Ammonium chloride, 50%	220	104	Calcium bisulfite	180	82
Ammonium chloride, sat.	220	104	Calcium carbonate	210	99
Ammonium fluoride, 10%	180	82	Calcium chlorate	200	93
Ammonium fluoride, 25%	120	49	Calcium chloride	220	104
Ammonium hydroxide, 20%	140	60	Calcium hydroxide, 10%	180	82
Ammonium hydroxide, 25%	100	38	Calcium hydroxide, sat.	160	71
Ammonium nitrate	220	104	Calcium hypochlorite, 10%	80	27
Ammonium persulfate	180	82	Calcium nitrate	220	93
Ammonium phosphate	80	27	Calcium sulfate	220	93
Ammonium sulfate, 10–40%	220	104	Caprylic acid	160	71
Ammonium sulfide	110	43	Carbon bisulfide	x	x
Ammonium sulfite	80	27	Carbon dioxide, dry	350	177
Amyl acetate	80	27	Carbon dioxide, wet	210	99
Amyl alcohol	200	93	Carbon disulfide	x	x
Amyl chloride	x	x	Carbon monoxide	350	177
Aniline	x	x	Carbon tetrachloride	110	43

(*continued*)

TABLE 8.25 (Continued)
Compatibility of Bisphenol A Fumarate Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Carbonic acid	90	32	Hydrofluoric acid, 30%	90	32
Cellosolve	140	60	Hypochlorous acid, 20%	90	32
Chlorine gas, dry	200	93	Iodine solution, 10%	200	104
Chlorine gas, wet	200	93	Lactic acid, 5%	210	99
Chlorine, liquid	x	x	Lactic acid, conc.	220	104
Chloroacetic acid, 50% water	140	60	Magnesium chloride	220	104
			Malic acid	160	71
Chloroacetic acid, to 25%	80	27	Methyl ethyl ketone	x	x
Chlorobenzene	x	x	Methyl isobutyl ketone	x	x
Chloroform	x	x	Muriatic acid	130	54
Chlorosulfonic acid	x	x	Nitric acid, 5%	160	71
Chromic acid, 10%	x	x	Nitric acid, 20%	100	38
Chromic acid, 50%	x	x	Nitric acid 70%	x	x
Chromyl chloride	150	66	Nitric acid, anhydrous	x	x
Citric acid, 15%	220	104	Oleum	x	x
Citric acid, conc.	220	104	Phenol	x	x
Copper acetate	180	82	Phosphoric acid, 50–80%	220	104
Copper chloride	220	104	Picric acid	110	43
Copper cyanide	220	104	Potassium bromide, 30%	200	93
Copper sulfate	220	104	Salicylic acid	150	66
Cresol	x	x	Sodium carbonate	160	71
Cyclohexane	x	x	Sodium chloride	220	104
Dichloroacetic acid	100	38	Sodium hydroxide, 10%	130	54
Dichloroethane	x	x	Sodium hydroxide, 50%	220	104
(ethylene dichloride)	220	104	Sodium hydroxide, conc.	200	93
Ethylene glycol	220	104	Sodium hypochlorite, 20%	x	x
Ferric chloride	220	104	Sodium sulfide, to 50%	210	99
Ferric chloride, 50% in water	220	104	Stannic chloride	200	93
Ferric nitrate, 10–50%	220	104	Stannous chloride	220	104
Ferrous chloride	220	104	Sulfuric acid, 10%	220	104
Ferrous nitrate	220	104	Sulfuric acid, 50%	220	104
Fluorine gas, moist			Sulfuric acid, 70%	160	71
Hydrobromic acid, 20%	220	104	Sulfuric acid, 90%	x	x
Hydrobromic acid, 50%	160	71	Sulfuric acid, 98%	x	x
Hydrobromic acid, dilute	220	104	Sulfuric acid, 100%	x	x
Hydrochloric acid, 20%	190	88	Sulfuric acid, fuming	x	x
Hydrochloric acid, 38%	x	x	Sulfurous acid	110	43
Hydrocyanic acid, 10%	200	93	Thionyl chloride	x	x

TABLE 8.25 (Continued)
Compatibility of Bisphenol A Fumarate Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Toluene	x	x	White liquor	180	82
Trichloroacetic acid, 50%	180	82	Zinc chloride	250	121

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1

4. Solvents:
   Sour crude oil — Alcohols at ambient temperatures
   Glycerine — Linseed oil
5. Gases (to 200°F/93°C):
   Carbon dioxide — Sulfur dioxide, dry
   Carbon monoxide — Sulfur trioxide
   Chlorine, wet — Rayon waste gases, 150°F (65°C)

Solvents such as benzene, carbon disulfide, ether, methyl ethyl ketone, toluene, xylene, trichloroethylene, and trichloroethane will attack the resin. Sulfuric acid above 70%, sodium hydroxide, and 30% chromic acid will also attack the resin. Refer to Table 8.25 for the compatibility of bisphenol A fumarate polyester resin with selected corrodents.

Refer to Table 8.26 for the compatibility of hydrogenated bisphenol A fumarate polyester resin. Ref. 1 provides additional listings for both resins with selected corrodents.

Halogenated Polyesters

Halogenated resins consist of chlorinated or brominated polyesters. The chlorinated polyester resins cured at room temperature are also known as chlorendic polyesters. These resins have the highest heat resistance of the polyesters. They are also inherently fire retardant. A noncombustible rating of 20 can be achieved, making this the safest possible polyester for stacks, hoods, or wherever a fire hazard may exist.

Refer to Table 8.27 for the performance of chlorinated polyesters at elevated temperatures. This permits them to survive high-temperature upsets in flue gas desulfurization scrubbers, some of which can reach a temperature of 400°F (204°C).

TABLE 8.26
Compatibility of Hydrogenated Bisphenol A Fumarate Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetic acid, 10%	200	93	Carbon disulfide	x	x
Acetic acid, 50%	160	71	Carbon tetrachloride	x	x
Acetic anhydride	x	x	Chlorine gas, dry	210	99
Acetone	x	x	Chlorine gas, wet	210	99
Acetyl chloride	x	x	Chloroacetic acid, 50% water	90	32
Acrylonitrile	x	x	Chloroform	x	x
Aluminum acetate			Chromic acid, 50%	x	x
Aluminum chloride, aq.	200	93	Citric acid, 15%	200	93
Aluminum fluoride	x	x	Citric acid, conc.	210	99
Aluminum sulfate	200	93	Copper acetate	210	99
Ammonium chloride, sat.	200	93	Copper chloride	210	99
Ammonium nitrate	200	93	Copper cyanide	210	99
Ammonium persulfate	200	93	Copper sulfate	210	99
Ammonium sulfide	100	38	Cresol	x	x
Amyl acetate	x	x	Cyclohexane	210	99
Amyl alcohol	200	93	Dichloroethane (ethylene	x	x
Amyl chloride	90	32	dichloride)		
Aniline	x	x	Ferric chloride	210	99
Antimony trichloride	80	27	Ferric chloride, 50% in water	200	93
Aqua regia, 3:1	x	x	Ferric nitrate, 10–50%	200	93
Barium carbonate	180	82	Ferrous chloride	210	99
Barium chloride	200	93	Ferrous nitrate	210	99
Benzaldehyde	x	x	Hydrobromic acid, 20%	90	32
Benzene	x	x	Hydrobromic acid, 50%	90	32
Benzoic acid	210	99	Hydrochloric acid, 20%	180	82
Benzyl alcohol	x	x	Hydrochloric acid, 38%	190	88
Benzyl chloride	x	x	Hydrocyanic acid, 10%	x	x
Boric acid	210	99	Hydrofluoric acid, 30%	x	x
Bromine, liquid	x	x	Hydrofluoric acid, 50%	210	99
Butyl acetate	x	x	Hydrofluoric acid, 70%	x	x
n-Butylamine	x	x	Hydrofluoric acid, 100%	x	x
Butyric acid	x	x	Lactic acid, 25%	210	99
Calcium bisulfide	120	49	Lactic acid, conc.	210	99
Calcium chlorate	210	99	Magnesium chloride	210	99
Calcium chloride	210	99	Methyl ethyl ketone	x	x
Calcium hypochlorite, 10%	180	82	Methyl isobutyl ketone	x	x
Carbon bisulfide	x	x	Muriatic acid	190	88

TABLE 8.26 (Continued)
Compatibility of Hydrogenated Bisphenol A Fumarate Polyester with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Nitric acid, 5%	90	32	Sulfuric acid, 10%	210	99
Oleum	x	x	Sulfuric acid, 50%	210	99
Perchloric acid, 10%	x	x	Sulfuric acid, 70%	90	32
Perchloric acid, 70%	x	x	Sulfuric acid, 90%	x	x
Phenol	x	x	Sulfuric acid, 98%	x	x
Phosphoric acid, 50–80%	210	99	Sulfuric acid, 100%	x	x
Sodium carbonate, 10%	100	38	Sulfuric acid, fuming	x	x
Sodium chloride	210	99	Sulfurous acid, 25%	210	99
Sodium hydroxide, 10%	100	38	Toluene	90	32
Sodium hydroxide, 50%	x	x	Trichloroacetic acid	90	32
Sodium hydroxide, conc.	x	x	Zinc chloride	200	93
Sodium hypochlorite, 10%	160	71			

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

The halogenated polyesters exhibit excellent resistance in contact with oxidizing acids and solutions, such as 35% nitric acid at room temperature, 40% chromic acid, chlorine water, wet chlorine, and 15% hypochlorites. They also resist neutral and acid salts, nonoxidizing acids, organic acids, mercaptans, ketones, aldehydes, alcohols, glycols, organic esters, and fats and oils.

These polyesters are not resistant to highly alkaline solutions of sodium hydroxide; concentrated sulfuric acid; alkaline solutions with pH greater than 10; aliphatic, primary, and aromatic amines; amides and other alkaline organics; phenol; and acid halides. Table 8.28 lists the compatibility of halogenated polyesters with selected corrodents. Ref. 1 provides additional information.

Halogenated polyesters are widely used in the pulp and paper industry in bleach atmospheres.

Silicones

The silicone systems are quite expensive, being based on organic silicon compounds (which have silicon rather than carbon linkages in the structure). They are primarily used for high-temperature service, where carbon-based coatings would oxidize.

TABLE 8.27
General Application Guide for Chlorinated Polyesters

Environment	Comments
Acid halides	Not recommended
Acids, mineral nonoxidizing	Resistant to 250°F/121°C
Acids, organic	Resistant to 250°F/121°C; glacial acetic acid to 120°F/49°C
Alcohols	Resistant to 180°F/82°C
Aldehydes	Resistant to 180°F/82°C
Alkaline solutions pH > 10	Not recommended for continuous exposure
Amines, aliphatic, primary aromatic	Can cause severe attack
Amides, other alkaline organics	Can cause severe attack
Esters, organic	Resistant to 180°F/82°C
Fats and oils	Resistant to 200°F/95°C
Glycols	Resistant to 180°F/82°C
Ketones	Resistant to 180°F/82°C
Mercaptans	Resistant to 180°F/82°C
Phenol	Not recommended
Salts, acid	Resistant to 250°F/121°C
Salts, neutral	Resistant to 250°F/121°C
Water, demineralized, distilled, deionized, steam and condensate	Resistant to 212°F/100°C; lowest absorption of any polyester

Typically, the silicon atoms will have one or more side groups attached to them, generally phenol (C_6H_5–), methyl (CH_3–), or vinyl (CH_2=CH–) units. These groups impart properties such as solvent resistance, lubricity, and reactivity with organic chemicals and polymers. Because these side groups affect the corrosion resistance of the resin, it is necessary to check with the supplier as to the properties of the resin being supplied.

The maximum allowable operating temperature is 572°F (300°C). These resins are also suitable for operation at cryogenic temperatures.

A second high-temperature formulation with aluminum can be operated up to 1200°F (649°C). This high-temperature type requires baking for a good cure. It is also water repellent.

The silicone resins can be used in contact with dilute acids and alkalies, alcohols, animal and vegetable oils, and lubrication oils. They are also resistant to aliphatic hydrocarbons, but aromatic solvents such as benzene, toluene, gasoline, and chlorinated solvents will cause excessive swelling.

Table 8.29 lists the corrosion resistance of methyl-appended silicone with selected corrodents. Ref. 1 provides additional listings.

The silicones are used primarily as coatings for high-temperature exhaust stacks, ovens, and space heaters.

TABLE 8.28
Compatibility of Halogenated Polyesters with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	x	x	Barium carbonate	250	121
Acetic acid, 10%	140	60	Barium chloride	250	121
Acetic acid, 50%	90	32	Barium hydroxide	x	x
Acetic acid, glacial	110	43	Barium sulfate	180	82
Acetic anhydride	100	38	Barium sulfide	x	x
Acetone	x	x	Benzaldehyde	x	x
Acetyl chloride	x	x	Benzene	90	32
Acrylic acid	x	x	Benzene sulfonic acid, 10%	120	49
Acrylonitrile	x	x	Benzoic acid	250	121
Adipic acid	220	104	Benzyl alcohol	x	x
Allyl alcohol	x	x	Benzyl chloride	x	x
Allyl chloride	x	x	Borax	190	88
Alum, 10%	200	93	Boric acid	180	82
Aluminum chloride, aq.	120	49	Bromine gas, dry	100	38
Aluminum fluoride, 10%	90	32	Bromine gas, moist	100	38
Aluminum hydroxide	170	77	Bromine, liquid	x	x
Aluminum nitrate	160	71	Butyl acetate	80	27
Aluminum oxychloride			Butyl alcohol	100	38
Aluminum sulfate	250	121	n-Butylamine	x	x
Ammonia gas	150	66	Butyric acid, 20%	200	93
Ammonium carbonate	140	60	Calcium bisulfide	x	x
Ammonium chloride, 10%	200	93	Calcium bisulfite	150	66
Ammonium chloride, 50%	200	93	Calcium carbonate	210	99
Ammonium chloride, sat.	200	93	Calcium chlorate	250	121
Ammonium fluoride, 10%	140	60	Calcium chloride	250	121
Ammonium fluoride, 25%	140	60	Calcium hydroxide, sat.	x	x
Ammonium hydroxide, 25%	90	32	Calcium hypochlorite, 20%	80	27
Ammonium hydroxide, sat.	90	32	Calcium nitrate	220	104
Ammonium nitrate	200	93	Calcium oxide	150	66
Ammonium persulfate	140	60	Calcium sulfate	250	121
Ammonium phosphate	150	66	Caprylic acid	140	60
Ammonium sulfate, 10–40%	200	93	Carbon bisulfide	x	x
Ammonium sulfide	120	49	Carbon dioxide, dry	250	121
Ammonium sulfite	100	38	Carbon dioxide, wet	250	121
Amyl acetate	190	85	Carbon disulfide	x	x
Amyl alcohol	200	93	Carbon monoxide	170	77
Amyl chloride	x	x	Carbon tetrachloride	120	49
Aniline	120	49	Carbonic acid	160	71
Antimony trichloride, 50%	200	93	Cellosolve	80	27
Aqua regia, 3:1	x	x	Chlorine gas, dry	200	93

(*continued*)

TABLE 8.28 (Continued)
Compatibility of Halogenated Polyesters with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Chlorine gas, wet	220	104	Lactic acid, 25%	200	93
Chlorine, liquid	x	x	Lactic acid, conc.	200	93
Chloroacetic acid, 25%	90	32	Magnesium chloride	250	121
Chloroacetic acid, 50% water	100	38	Malic acid, 10%	90	32
Chlorobenzene	x	x	Methyl chloride	80	27
Chloroform	x	x	Methyl ethyl ketone	x	x
Chlorosulfonic acid	x	x	Methyl isobutyl ketone	80	27
Chromic acid, 10%	180	82	Muriatic acid	190	88
Chromic acid, 50%	140	60	Nitric acid, 20%	80	27
Chromyl chloride	210	99	Nitric acid, 5%	210	99
Citric acid, 15%	250	121	Nitric acid, 70%	80	27
Citric acid, conc.	250	121	Nitrous acid, conc.	90	32
Copper acetate	210	99	Oleum	x	x
Copper chloride	250	121	Perchloric acid, 10%	90	32
Copper cyanide	250	121	Perchloric acid, 70%	90	32
Copper sulfate	250	121	Phenol, 5%	90	32
Cresol	x	x	Phosphoric acid, 50–80%	250	121
Cyclohexane	140	60	Picric acid	100	38
Dibutyl phthalate	100	38	Potassium bromide, 30%	230	110
Dichloroacetic acid	100	38	Salicylic acid	130	54
Dichloroethane (ethylene dichloride)	x	x	Sodium carbonate, 10%	190	88
			Sodium chloride	250	121
Ethylene glycol	250	121	Sodium hydroxide, 10%	110	43
Ferric chloride	250	121	Sodium hydroxide, 50%	x	x
Ferric chloride, 50% in water	250	121	Sodium hypochlorite, 20%	x	x
			Sodium hypochlorite, conc.	x	x
Ferric nitrate, 10–50%	250	121	Sodium hypochlorite, conc.	x	x
Ferrous chloride	250	121	Sodium sulfide, to 50%	x	x
Ferrous nitrate	160	71	Stannic chloride	80	27
Hydrobromic acid, 20%	160	71	Stannous chloride	250	121
Hydrobromic acid, 50%	200	93	Sulfuric acid, 10%	260	127
Hydrobromic acid, dilute	200	93	Sulfuric acid, 100%	x	x
Hydrochloric acid, 20%	230	110	Sulfuric acid, 50%	200	93
Hydrochloric acid, 38%	180	82	Sulfuric acid, 70%	190	88
Hydrocyanic acid, 10%	150	66	Sulfuric acid, 90%	x	x
Hydrofluoric acid, 10%	100	38	Sulfuric acid, 98%	x	x
Hydrofluoric acid, 30%	120	49	Sulfuric acid, fuming	x	x

TABLE 8.28 (Continued)
Compatibility of Halogenated Polyesters with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sulfurous acid, 10%	80	27	Trichloroacetic acid, 50%	200	93
Thionyl chloride	x	x	White liquor	x	x
Toluene	110	43	Zinc chloride	200	93

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable.

Source: Ref. 1.

TABLE 8.29
Compatibility of Methyl-Appended Silicone with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetic acid, 10%	90	32	Aqua regia, 3:1	x	x
Acetic acid, 50%	90	32	Benzene	x	x
Acetic acid, 80%	90	32	Benzyl chloride	x	x
Acetic acid, glacial	90	32	Boric acid	390	189
Acetone	100	43	Butyl alcohol	80	27
Acrylic acid, 75%	80	27	Calcium bisulfide	400	204
Acrylonitrile	x	x	Calcium chloride	300	149
Alum	220	104	Calcium hydroxide, 30%	200	93
Aluminum sulfate	410	210	Calcium hydroxide, sat.	400	204
Ammonium chloride, 10%	x	x	Carbon bisulfide	x	x
Ammonium chloride, 50%	80	27	Carbon disulfide	x	x
Ammonium chloride, sat.	80	27	Carbon monoxide	400	204
Ammonium fluoride, 25%	80	27	Carbonic acid	400	204
Ammonium hydroxide, 25%	x	x	Chlorobenzene	x	x
Ammonium nitrate	210	99	Chlorosulfonic acid	x	x
Amyl acetate	80	27	Ethylene glycol	400	204
Amyl alcohol	x	x	Ferric chloride	400	204
Amyl chloride	x	x	Hydrobromic acid, 50%	x	x
Aniline	x	x	Hydrochloric acid, 20%	90	32
Antimony trichloride	80	27	Hydrochloric acid, 38%	x	x

(*continued*)

TABLE 8.29 (Continued)
Compatibility of Methyl-Appended Silicone with Selected Corrodents

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Hydrofluoric acid, 30%	x	x	Stannic chloride	80	27
Lactic acid, all conc.	80	27	Sulfuric acid, 10%	x	x
Lactic acid, conc.	80	27	Sulfuric acid, 50%	x	x
Magnesium chloride	400	204	Sulfuric acid, 70%	x	x
Methyl alcohol	410	210	Sulfuric acid, 90%	x	x
Methyl ethyl ketone	x	x	Sulfuric acid, 98%	x	x
Methyl isobutyl ketone	x	x	Sulfuric acid, 100%	x	x
Nitric acid, 20%	x	x	Sulfuric acid, fuming	x	x
Nitric acid, 5%	80	27	Sulfurous acid	x	x
Nitric acid, 70%	x	x	Tartaric acid	400	204
Nitric acid, anhydrous	x	x	Tetrahydrofuran	x	x
Oleum	x	x	Toluene	x	x
Phenol	x	x	Tributyl phosphate	x	x
Phosphoric acid, 50–80%	x	x	Turpentine	x	x
Propyl alcohol	400	204	Vinegar	400	204
Sodium carbonate	300	149	Water, acid mine	210	99
Sodium chloride, 10%	400	204	Water, demineralized	210	99
Sodium hydroxide, 10%	90	27	Water, distilled	210	99
Sodium hydroxide, 50%	90	27	Water, salt	210	99
Sodium hydroxide, conc.	90	27	Water, sea	210	99
Sodium hypochlorite, 20%	x	x	Xylene	x	x
Sodium sulfate	400	204	Zinc chloride	400	204

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature. Incompatibility is shown by an x.

Source: Ref. 1.

REFERENCES

1. Schweitzer, Philip A., *Corrosion Resistance Tables, 4th ed.,* Vols. 1–3, Marcel Dekker, New York, 1995.
2. Fry, J.S., Merriam, C.N., and Boyd, W.H., Chemistry and Technology of Phenolic Resins and Coatings, in *ACS Symposium Series Applied Polymer Science,* American Chemical Society, Washington, D.C.,1985.
3. Morrison, R.T. and Boyd, R.N., *Organic Chemistry, 3rd. ed.,* Allyn Bacon, 1973, Boston, p. 1147.
4. Schweitzer, P.A., *Mechanical and Corrosion Resistant Properties of Plastics and Elastomers,* Marcel Dekker, New York, 2000.

9 Comparative Resistance of Organic Coatings for Immersion Service

Following is a series of tables comparing the corrosion resistance of various organic materials when immersed in commonly used corrodents.

The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. An "X" shows incompatibility. A blank space indicates that data is unavailable.

One must keep in mind that most of the coating materials listed are capable of being formulated to meet specific conditions. In the tables, when a coating material is listed as being satisfactory, it means that at least one formulation is acceptable. Therefore, before being used, the manufacturer should be contacted to be sure that his formulation will be compatible with the application.

More extensive listings will be found in:

Schweitzer, Philip A, *Corrosion Resistance Tables, 5th ed.,* Vols. 1–4, Marcel Dekker, New York, 2004.

Acetic Acid, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	212 (100)	PFA	450 (232)
Epoxy	190 (88)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	200 (93)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	100 (38)	Fluoroelastomers	190 (88)
Coal tar		PVDF	300 (149)
Urethanes	90 (32)	Isophthalic polyesters	180 (82)
Neoprene	160 (71)	Bisphenol A fumurate	220 (104)
Polysulfides	80 (27)	Hydrogenated polyester	200 (93)
Hypalon	200 (93)	Halogenated polyester	140 (60)
Plastisols	100 (38)	Methyl-appended silicone	90 (32)

Acetic Acid, 50%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	450 (232)
Epoxy	110 (43)	FEP	400 (204)
Furans	160 (71)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy, 20%	100 (38)	Fluoroelastomers	180 (82)
Coal tar		PVDF	300 (149)
Urethanes, 20%	90 (32)	Isophthalic polyesters	110 (43)
Neoprene	160 (71)	Bisphenol A fumurate	160 (71)
Polysulfides	80 (27)	Hydrogenated polyester	160 (71)
Hypalon	200 (93)	Halogenated polyester	90 (32)
Plastisols	90 (32)	Methyl-appended silicone	90 (32)

Acetic Acid, 80%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	450 (232)
Epoxy	110 (43)	FEP	400 (204)
Furans	80 (27)	PTFE	450 (232)
Vinyl ester	150 (66)	ETFE	230 (110)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy		Fluoroelastomers	180 (82)
Coal tar		PVDF	190 (88)
Urethanes		Isophthalic polyesters	X
Neoprene	160 (71)	Bisphenol A fumurate	160 (71)
Polysulfides	80 (27)	Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	
Plastisols	X	Methyl-appended silicone	90 (32)

Acetic Acid, glacial

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	70 (21)	PFA	450 (232)
Epoxy		FEP	400 (204)
Furans	80 (27)	PTFE	450 (232)
Vinyl ester	150 (66)	ETFE	230 (110)
Epoxy polyamide	X	ECTFE	200 (93)
Coal tar epoxy		Fluoroelastomers	X
Coal tar		PVDF	190 (88)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	80 (87)	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	110 (43)
Plastisols	X	Methyl-appended silicone	90 (32)

Acetic Acid, vapors

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	110 (43)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans		PTFE	400 (204)
Vinyl ester		ETFE	
Epoxy polyamide	X	ECTFE	200 (93)
Coal tar epoxy	100 (38)	Fluoroelastomers	90 (32)
Coal tar		PVDF	180 (82)
Urethanes	90 (32)	Isophthalic polyesters, 50%	110 (43)
Neoprene	90 (32)	Bisphenol A fumurate	
Polysulfides	90 (32)	Hydrogenated polyester	
Hypalon	90 (32)	Halogenated polyester, 25%	180 (82)
Plastisols	X	Methyl-appended silicone	

Acetic Anhydride

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	200 (93)
Epoxy	X	FEP	400 (202)
Furans	200 (93)	PTFE	450 (232)
Vinyl ester	100 (38)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	100 (38)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar		PVDF	100 (38)
Urethanes	X	Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	100 (38)
Polysulfides		Hydrogenated polyester	X
Hypalon	200 (93)	Halogenated polyester	100 (38)
Plastisols	X	Methyl-appended silicone	

Acetone

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	110 (43)	FEP	400 (204)
Furans	80 (27)	PTFE	450 (232)
Vinyl ester	X	ETFE	150 (66)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	X
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	80 (27)	Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	100 (43)

Ammonium Carbonate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	90 (32)	PFA	450 (232)
Epoxy	140 (60)	FEP	400 (204)
Furans	240 (116)	PTFE	450 (232)
Vinyl ester	150 (66)	ETFE	300 (149)
Epoxy polyamide		ECTFE	300 (149)
Coal tar epoxy		Fluoroelastomers	190 (88)
Coal tar		PVDF	280 (138)
Urethanes		Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	90 (32)
Polysulfides		Hydrogenated polyester	
Hypalon	140 (60)	Halogenated polyester	140 (60)
Plastisols	140 (60)	Methyl-appended silicone	

Ammonium Hydroxide, 25%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	140 (60)	FEP	400 (204)
Furans	250 (121)	PTFE	450 (232)
Vinyl ester	100 (38)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	110 (43)	Fluoroelastomers	190 (88)
Coal tar		PVDF	280 (138)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate, 20%	140 (60)
Polysulfides	X	Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	90 (32)
Plastisols	140 (60)	Methyl-appended silicone	X

Ammonium Hydroxide, sat.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	150 (66)	FEP	400 (204)
Furans	200 (93)	PTFE	450 (232)
Vinyl ester	130 (54)	ETFE	300 (149)
Epoxy polyamide		ECTFE	300 (149)
Coal tar epoxy		Fluoroelastomers	190 (88)
Coal tar		PVDF	280 (138)
Urethanes		Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	
Polysulfides	X	Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	90 (32)
Plastisols	140 (60)	Methyl-appended silicone	X

Aniline

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	150 (66)	FEP	400 (204)
Furans	80 (27)	PTFE	450 (232)
Vinyl ester	X	ETFE	230 (110)
Epoxy polyamide		ECTFE	90 (32)
Coal tar epoxy		Fluoroelastomers	230 (110)
Coal tar		PVDF	200 (93)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	140 (60)	Halogenated polyester	120 (49)
Plastisols	X	Methyl-appended silicone	X

Benzoic Acid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics, 10%	100 (38)	PFA	450 (232)
Epoxy	200 (93)	FEP	400 (204)
Furans	260 (127)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	270 (132)
Epoxy polyamide	100 (38)	ECTFE	250 (121)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	250 (121)
Urethanes	X	Isophthalic polyesters	180 (82)
Neoprene	150 (66)	Bisphenol A fumurate	180 (82)
Polysulfides	150 (66)	Hydrogenated polyester	210 (99)
Hypalon	200 (93)	Halogenated polyester	250 (121)
Plastisols	140 (60)	Methyl-appended silicone	

Bromine Gas, dry

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	450 (232)
Epoxy	X	FEP	200 (93)
Furans	X	PTFE	450 (232)
Vinyl ester	100 (38)	ETFE	150 (66)
Epoxy polyamide	X	ECTFE	X
Coal tar epoxy	100 (38)	Fluoroelastomers, 25%	180 (82)
Coal tar	X	PVDF	210 (99)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	90 (32)
Polysulfides		Hydrogenated polyester	
Hypalon	60 (16)	Halogenated polyester	100 (38)
Plastisols	X	Methyl-appended silicone	

Bromine Gas, moist

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	X	FEP	200 (93)
Furans	X	PTFE	250 (121)
Vinyl ester	100 (38)	ETFE	
Epoxy polyamide	X	ECTFE	
Coal tar epoxy	X	Fluoroelastomers, 25%	180 (82)
Coal tar	X	PVDF	210 (99)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	100 (38)
Polysulfides		Hydrogenated polyester	
Hypalon	60 (16)	Halogenated polyester	100 (38)
Plastisols	X	Methyl-appended silicone	

Bromine, liquid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans, 3% max.	300 (149)	PTFE	450 (232)
Vinyl ester	X	ETFE	
Epoxy polyamide		ECTFE	150 (66)
Coal tar epoxy		Fluoroelastomers	350 (177)
Coal tar		PVDF	140 (60)
Urethanes		Isophthalic polyesters, 50%	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	60 (16)	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	

Calcium Hydroxide

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	180 (32)	FEP	400 (204)
Furans	260 (170)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	300 (149)
Epoxy polyamide	140 (60)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	280 (138)
Urethanes	90 (32)	Isophthalic polyesters	160 (71)
Neoprene	230 (110)	Bisphenol A fumurate	160 (71)
Polysulfides	X	Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	400 (201)

Carbon Tetrachloride

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	450 (232)
Epoxy	170 (77)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	270 (132)
Epoxy polyamide	212 (100)	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	110 (43)
Polysulfides		Hydrogenated polyester	X
Hypalon	200 (93)	Halogenated polyester	120 (49)
Plastisols	X	Methyl-appended silicone	X

Chlorine Gas, wet

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	250 (121)	PTFE	450 (232)
Vinyl ester	250 (121)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	190 (88)
Coal tar	X	PVDF, 10%	210 (99)
Urethanes	X	Isophthalic polyesters	160 (71)
Neoprene	X	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	210 (99)
Hypalon	90 (32)	Halogenated polyester	220 (104)
Plastisols	X	Methyl-appended silicone	X

Chlorine, liquid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	X
Epoxy		FEP	400 (204)
Furans, 3% max.	X	PTFE	X
Vinyl ester	X	ETFE	
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy		Fluoroelastomers	190 (88)
Coal tar		PVDF	210 (99)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	
Hypalon		Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Chlorobenzene

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	260 (127)	PFA	450 (232)
Epoxy	150 (66)	FEP	400 (204)
Furans	260 (127)	PTFE	450 (232)
Vinyl ester	110 (43)	ETFE	210 (99)
Epoxy polyamide	100 (38)	ECTFE	150 (66)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	220 (104)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Chloroform

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	450 (232)
Epoxy	110 (43)	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	230 (110)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	250 (121)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Chlorosulfonic Acid

	Max Temp. °F (°C)		Max Temp. °F (C)
Phenolics	140 (60)	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	260 (127)	PTFE	450 (232)
Vinyl ester	X	ETFE	80 (27)
Epoxy polyamide	X	ECTFE	80 (27)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	110 (43)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	
Hypalon	X	Halogenated polyester	X
Plastisols	60 (16)	Methyl-appended silicone	X

Citric Acid, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	450 (232)
Epoxy	190 (88)	FEP	400 (204)
Furans	250 (121)	PTFE	450 (232)
Vinyl ester	210 (99)	ETFE	120 (49)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	300 (149)
Coal tar		PVDF	250 (121)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	150 (66)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	200 (93)
Hypalon	200 (93)	Halogenated polyester	250 (121)
Plastisols	140 (60)	Methyl-appended silicone	X

Citric Acid, conc.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 ((71)	PFA	370 (188)
Epoxy	X	FEP	400 (204)
Furans	250 (121)	PTFE	450 (232)
Vinyl ester	200 (93)	ETFE	
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	250 (121)
Urethanes		Isophthalic polyesters	200 (93)
Neoprene	200 (93)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	210 (99)
Hypalon	250 (121)	Halogenated polyester	250 (121)
Plastisols	140 (60)	Silicone	390 (199)

Dextrose

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	100 (38)	FEP	400 (204)
Furans, 3% max.	260 (127)	PTFE	450 (232)
Vinyl ester	240 (116)	ETFE	
Epoxy polyamide	100 (38)	ECTFE	240 (116)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	220 (104)
Polysulfides		Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	220 (104)
Plastisols	140 (60)	Methyl-appended silicone	170 (77)

Dichloroacetic Acid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	400 (204)
Vinyl ester	100 (38)	ETFE	150 (66)
Epoxy polyamide	X	ECTFE	
Coal tar epoxy	X	Fluoroelastomers	
Coal tar		PVDF	120 (49)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	100 (38)
Polysulfides		Hydrogenated polyester	
Hypalon		Halogenated polyester	100 (38)
Plastisols, 20%	100 (38)	Methyl-appended silicone	

Diesel Fuels

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	100 (38)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	220 (104)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	280 (138)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	80 (27)	Bisphenol A fumurate	180 (82)
Polysulfides	80 (27)	Hydrogenated polyester	
Hypalon	80 (27)	Halogenated polyester	180 (82)
Plastisols	100 (38)	Methyl-appended silicone	

Diethylamine

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	X	ETFE	200 (93)
Epoxy polyamide	X	ECTFE	X
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	100 (38)
Urethanes		Isophthalic polyesters	120 (49)
Neoprene	120 (49)	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	

Dimethyl Formamide

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	100 (38)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	X
Urethanes		Isophthalic polyesters	X
Neoprene	160 (71)	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	

Ethyl Acetate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	X	ETFE	150 (66)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	160 (71)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	80 (27)	Hydrogenated polyester	X
Hypalon	140 (60)	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	

Ethyl Alcohol

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	110 (43)	PFA	200 (93)
Epoxy	140 (60)	FEP	200 (93)
Furans	140 (60)	PTFE	400 (204)
Vinyl ester	100 (38)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	300 (149)
Coal tar		PVDF	280 (138)
Urethanes	90 (32)	Isophthalic polyesters	80 (27)
Neoprene	200 (93)	Bisphenol A fumurate	90 (32)
Polysulfides	150 (66)	Hydrogenated polyester	90 (32)
Hypalon	200 (93)	Halogenated polyester	140 (60)
Plastisols	140 (60)	Silicone	400 (204)

Hydrobromic Acid, dil.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	450 (232)
Epoxy	180 (82)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	260 (127)
Urethanes		Isophthalic polyesters	120 (49)
Neoprene	X	Bisphenol A fumurate	220 (104)
Polysulfides		Hydrogenated polyester	
Hypalon	90 (32)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	X

Hydrobromic Acid, 20%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	450 (232)
Epoxy	180 (82)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	280 (138)
Urethanes		Isophthalic polyesters	140 (60)
Neoprene	X	Bisphenol A fumurate	220 (104)
Polysulfides		Hydrogenated polyester	90 (32)
Hypalon	100 (38)	Halogenated polyester	160 (71)
Plastisols	190 (60)	Methyl-appended silicone	X

Hydrobromic Acid, 50%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	450 (232)
Epoxy	110 (43)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	200 (93)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	280 (138)
Urethanes		Isophthalic polyesters	140 (60)
Neoprene	X	Bisphenol A fumurate	160 (71)
Polysulfides		Hydrogenated polyester	90 (32)
Hypalon	100 (38)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	X

Hydrochloric Acid, dilute

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	450 (232)
Epoxy	200 (93)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	220 (104)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	160 (71)
Neoprene	X	Bisphenol A fumurate	190 (88)
Polysulfides	X	Hydrogenated polyester	180 (82)
Hypalon	160 (71)	Halogenated polyester	230 (110)
Plastisols	140 (60)	Methyl-appended silicone	90 (32)

Hydrochloric Acid, 20%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	450 (232)
Epoxy	200 (93)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	220 (104)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	160 (71)
Neoprene	X	Bisphenol A fumurate	190 (88)
Polysulfides	X	Hydrogenated polyester	180 (82)
Hypalon	160 (71)	Halogenated polyester	230 (110)
Plastisols	140 (60)	Methyl-appended silicone	90 (32)

Hydrochloric Acid, 35%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	450 (232)
Epoxy	140 (60)	FEP	400 (204)
Furans	80 (27)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	160 (71)
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	190 (88)
Hypalon	140 (60)	Halogenated polyester	180 (82)
Plastisols	140 (60)	Methyl-appended silicone	X

Hydrofluoric Acid, 30%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	230 (110)	PTFE	450 (232)
Vinyl ester	X	ETFE	270 (132)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	210 (99)
Coal tar	X	PVDF	260 (127)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	90 (32)	Halogenated polyester	120 (49)
Plastisols	120 (49)	Methyl-appended silicone	X

Hydrofluoric Acid, 70%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	140 (60)	PTFE	450 (232)
Vinyl ester	X	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	240 (116)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	200 (93)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	X
Hypalon	90 (32)	Halogenated polyester	
Plastisols	68 (20)	Methyl-appended silicone	X

Hydrofluoric Acid, 100%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	140 (60)	PTFE	450 (232)
Vinyl ester	X	ETFE	230 (110)
Epoxy polyamide	X	ECTFE	240 (116)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	200 (93)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	90 (32)	Halogenated polyester	
Plastisols		Methyl-appended silicone	X

Hypochlorous Acid, 100%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	450 (232)
Epoxy	200 (93)	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	150 (66)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar		PVDF	280 (138)
Urethanes		Isophthalic polyesters	90 (32)
Neoprene	X	Bisphenol A fumurate, 20%	90 (32)
Polysulfides		Hydrogenated polyester, 50%	210 (99)
Hypalon	X	Halogenated polyester, 10%	100 (38)
Plastisols	140 (60)	Methyl-appended silicone	

Lactic Acid, 25%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	450 (232)
Epoxy	220 (104)	FEP	400 (204)
Furans	212 (100)	PTFE	450 (232)
Vinyl ester	210 (99)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	300 (149)
Coal tar	X	PVDF	130 (54)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	140 (60)	Bisphenol A fumurate	210 (99)
Polysulfides	X	Hydrogenated polyester	210 (99)
Hypalon	140 (60)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	X

Lactic Acid, conc.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	450 (232)
Epoxy	200 (93)	FEP	400 (204)
Furans	160 (71)	PTFE	450 (232)
Vinyl ester	200 (93)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	110 (43)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	90 (32)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	210 (99)
Hypalon	80 (27)	Halogenated polyester	200 (93)
Plastisols	80 (27)	Methyl-appended silicone	X

Methyl Alcohol

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	140 (60)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	160 (71)	PTFE	400 (204)
Vinyl ester	90 (32)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	X
Coal tar		PVDF	200 (93)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	140 (60)	Bisphenol A fumurate	140 (60)
Polysulfides	80 (27)	Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	140 (60)
Plastisols	140 (60)	Methyl-appended silicone	410 (210)

Methyl Cellosolve

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	100 (38)	PFA	190 (88)
Epoxy	80 (27)	FEP	400 (204)
Furans	X	PTFE	400 (204)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide		ECTFE	300 (149)
Coal tar epoxy		Fluoroelastomers	X
Coal tar		PVDF	280 (138)
Urethanes		Isophthalic polyesters	
Neoprene	200 (93)	Bisphenol A fumurate	
Polysulfides		Hydrogenated polyester	
Hypalon	X	Halogenated polyester	
Plastisols		Methyl-appended silicone	X

Methyl Chloride

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	120 (49)	PTFE	400 (204)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	190 (88)
Coal tar		PVDF	300 (149)
Urethanes	X	Isophthalic polyesters	
Neoprene	X	Bisphenol A fumurate	
Polysulfides	140 (60)	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	80 (27)
Plastisols	X	Methyl-appended silicone	

Methyl Ethyl Ketone

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	450 (232)
Epoxy	90 (32)	FEP	400 (204)
Furans	80 (27)	PTFE	450 (232)
Vinyl ester	X	ETFE	230 (110)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	X
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Methyl Isobutyl Ketone

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	140 (60)	FEP	400 (204)
Furans	160 (71)	PTFE	450 (232)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	110 (43)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	80 (27)	Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	80 (27)
Plastisols	X	Methyl-appended silicone	X

Methylene Chloride

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	280 (138)	PTFE	400 (204)
Vinyl ester	X	ETFE	210 (99)
Epoxy polyamide	X	ECTFE	X
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	120 (49)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Mineral Oil

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy	210 (99)	FEP	400 (204)
Furans		PTFE	400 (204)
Vinyl ester	250 (121)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	250 (121)
Urethanes	90 (32)	Isophthalic polyesters	200 (93)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides	80 (27)	Hydrogenated polyester	
Hypalon	200 (93)	Halogenated polyester	90 (32)
Plastisols	140 (60)	Silicone	300 (149)

Motor Oil

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy	110 (43)	FEP	400 (204)
Furans		PTFE	400 (204)
Vinyl ester	250 (121)	ETFE	
Epoxy polyamide		ECTFE	300 (149)
Coal tar epoxy	110 (43)	Fluoroelastomers	190 (88)
Coal tar		PVDF	250 (121)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene		Bisphenol A fumurate	
Polysulfides	80 (27)	Hydrogenated polyester	
Hypalon		Halogenated polyester	
Plastisols	140 (60)	Methyl-appended silicone	

Naphtha

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	110 (43)	PFA	200 (93)
Epoxy	100 (38)	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	280 (138)
Urethanes	90 (32)	Isophthalic polyesters	200 (93)
Neoprene	X	Bisphenol A fumurate	150 (66)
Polysulfides	80 (27)	Hydrogenated polyester	200 (93)
Hypalon	X	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	X

Nitric Acid, 5%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	200 (93)	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	150 (66)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	200 (93)
Urethanes	X	Isophthalic polyesters	120 (49)
Neoprene	X	Bisphenol A fumurate	160 (71)
Polysulfides	X	Hydrogenated polyester	90 (32)
Hypalon	100 (38)	Halogenated polyester	210 (99)
Plastisols	100 (38)	Methyl-appended silicone	80 (27)

Nitric Acid, 20%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	100 (38)	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	150 (66)	ETFE	150 (66)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	180 (82)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	100 (38)
Polysulfides	X	Hydrogenated polyester	
Hypalon	100 (38)	Halogenated polyester	80 (27)
Plastisols	140 (60)	Methyl-appended silicone	X

Nitric Acid, dilute

Coatings for immersion service	Max Temp. °F (°C)	Paints (S = splash resistant W = immersion resistant)	
Phenolics	X	Acrylics	R, S
Epoxy	160 (71)	Alkyds:	
Furans	200 (93)	Long oil	
Vinyl ester	180 (82)	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	R, W
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	100 (38)	Polyamide	X
Plastisols	100 (38)	Polyamine	X
PFA	450 (232)	Phenolic	X
FEP	400 (204)	Polyesters	R
PTFE	450 (232)	Polyvinyl butyral	
ETFE	150 (66)	Polyvinyl formal	
ECTFE	300 (149)	Silicone (methyl)	R
Fluoroelastomers	400 (204)	Urethanes:	
PVDF	200 (93)	Aliphatic	R
Isophthalic PE	120 (49)	Aromatic	R
Bis. A fum. PE	160 (71)	Vinyls	R, W
Hydrogenated PE	90 (32)	Vinyl ester	R

Nitric Acid, dilute

Coatings for immersion service	Max Temp. °F (°C)	Paints (S = splash resistant W = immersion resistant)	
Halogenated PE	210 (99)	Zinc rich	R
Silicone (methyl)	80 (27)		
	Mortars		
Sodium silicate	450 (232)		
Potassium silicate	450 (232)		
Silica	450 (232)		
Furan	X		
Polyester	140 (60)		
Epoxy	X		
Vinyl ester	180 (82)		
Acrylic	X		
Urethane	X		

Nitric Acid, 70%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	80 (27)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	190 (88)
Coal tar	X	PVDF	120 (49)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	XX	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	80 (27)
Plastisols	70 (23)	Methyl-appended silicone	X

Nitric Acid, conc.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	210 (99)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	90 (32)
Coal tar	X	PVDF	210 (99)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	90 (32)
Plastisols	60 (16)	Methyl-appended silicone	X

Nitrobenzene

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	80 (27)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	100 (38)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	140 (60)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	140 (60)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Oil, vegetable

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	90 (32)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	180 (82)	ETFE	290 (143)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	200 (93)
Coal tar		PVDF	220 (104)
Urethanes		Isophthalic polyesters	150 (66)
Neoprene	240 (116)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	
Hypalon		Halogenated polyester	220 (104)
Plastisols	140 (60)	Methyl-appended silicone	

Oxalic Acid, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	
Epoxy	100 (38)	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	200 (93)
Epoxy polyamide	100 (38)	ECTFE	140 (60)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	140 (60)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides	X	Hydrogenated polyester	200 (93)
Hypalon	200 (93)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	

Oxalic Acid, sat.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics (dry)	110 (43)	PFA	
Epoxy	100 (38)	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	200 (93)
Epoxy polyamide	100 (38)	ECTFE	140 (60)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	120 (49)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	X	Bisphenol A fumurate	200 (93)
Polysulfides	X	Hydrogenated polyester	200 (93)
Hypalon	X	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	

Perchloric Acid, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	400 (204)
Vinyl ester	140 (60)	ETFE	200 (93)
Epoxy polyamide	X	ECTFE	140 (60)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	200 (93)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	90 (32)	Halogenated polyester	90 (32)
Plastisols	X	Methyl-appended silicone	X

Perchloric Acid, 70%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics (dry)		PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	X	ETFE	140 (60)
Epoxy polyamide	X	ECTFE	140 (60)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	100 (38)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	90 (32)	Halogenated polyester	90 (32)
Plastisols	X	Methyl-appended silicone	X

Phenol

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	210 (99)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	210 (99)
Coal tar	X	PVDF	200 (93)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	X
Hypalon	X	Halogenated polyester, 5%	90 (32)
Plastisols	X	Methyl-appended silicone	X

Phosphoric Acid, 50–80%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics (dry)	X	PFA	450 (232)
Epoxy	110 (43)	FEP	400 (204)
Furans, 50%	212 (100)	PTFE	450 (232)
Vinyl ester	210 (99)	ETFE	270 (132)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	300 (149)
Coal tar	X	PVDF	220 (104)
Urethanes		Isophthalic polyesters	180 (82)
Neoprene	150 (66)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	210 (99)
Hypalon	200 (93)	Halogenated polyester	250 (121)
Plastisols	140 (60)	Methyl-appended silicone	X

Phthalic Acid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics (dry)	100 (38)	PFA	
Epoxy	X	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	200 (93)
Epoxy polyamide		ECTFE	200 (93)
Coal tar epoxy		Fluoroelastomers	90 (32)
Coal tar		PVDF	200 (93)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	200 (93)
Hypalon	140 (60)	Halogenated polyester	80 (27)
Plastisols	X	Methyl-appended silicone	

Potassium Acetate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	250 (121)
Epoxy	160 (71)	FEP	200 (93)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	
Epoxy polyamide	100 (38)	ECTFE	
Coal tar epoxy	100 (38)	Fluoroelastomers	80 (27)
Coal tar		PVDF	200 (93)
Urethanes		Isophthalic polyesters	160 (71)
Neoprene		Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	
Hypalon		Halogenated polyester	200 (93)
Plastisols		Methyl-appended silicone	X

Potassium Bromide, 30%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics, 10%	160 (71)	PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	300 (149)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	190 (88)
Coal tar		PVDF	200 (93)
Urethanes	90 (32)	Isophthalic polyesters	160 (71)
Neoprene	160 (71)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	
Hypalon	240 (116)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	

Potassium Carbonate, 50%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	120 (49)	ETFE	280 (138)
Epoxy polyamide, 25%	100 (38)	ECTFE	280 (138)
Coal tar epoxy, 25%	100 (38)	Fluoroelastomers	180 (82)
Coal tar		PVDF	200 (38)
Urethanes		Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate, 10%	180 (82)
Polysulfides		Hydrogenated polyester	X
Hypalon	200 (93)	Halogenated polyester	110 (43)
Plastisols	140 (60)	Methyl-appended silicone	

Potassium Chloride, 30%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (38)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	200 (38)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	260 (127)
Urethanes	110 (43)	Isophthalic polyesters	160 (71)
Neoprene	160 (71)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	190 (88)
Hypalon	240 (116)	Halogenated polyester	190 (88)
Plastisols	140 (60)	Silicone	400 (204)

Potassium Cyanide, 30%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide	140 (160)	ECTFE	300 (149)
Coal tar epoxy	140 (60)	Fluoroelastomers	400 (204)
Coal tar		PVDF	240 (116)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	200 (93)
Hypalon	200 (93)	Halogenated polyester	140 (60)
Plastisols	140 (60)	Silicone	400 (204)

Potassium Hydroxide, 50%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy	100 (38)	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	X	ETFE	200 (93)
Epoxy polyamide	100 (38)	ECTFE	140 (60)
Coal tar epoxy	100 (38)	Fluoroelastomers	X
Coal tar		PVDF	200 (93)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	160 (71)
Polysulfides	80 (27)	Hydrogenated polyester	X
Hypalon	200 (93)	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	

Potassium Hydroxide, 90%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	100 (38)	FEP	400 (204)
Furans	200 (93)	PTFE	400 (204)
Vinyl ester	X	ETFE	
Epoxy polyamide	X	ECTFE	140 (60)
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	200 (93)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	
Polysulfides		Hydrogenated polyester	X
Hypalon	200 (93)	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	X

Potassium Nitrate, 80%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	260 (127)
Urethanes	90 (32)	Isophthalic polyesters	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	180 (82)
Hypalon	240 (116)	Halogenated polyester	180 (82)
Plastisols	140 (60)	Methyl-appended silicone	400 (204)

Potassium Permanganate, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	80 (27)	PFA	200 (93)
Epoxy	140 (60)	FEP	400 (204)
Furans	260 (127)	PTFE	460 (238)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	160 (71)
Coal tar		PVDF	260 (127)
Urethanes	100 (38)	Isophthalic polyesters	X
Neoprene	100 (38)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	210 (99)
Hypalon	240 (116)	Halogenated polyester	150 (66)
Plastisols	140 (60)	Methyl-appended silicone	

Potassium Permanganate, 20%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	90 (32)	PFA	200 (93)
Epoxy	140 (60)	FEP	400 (204)
Furans	160 (71)	PTFE	400 (204)
Vinyl ester		ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	160 (71)
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters	100 (38)
Neoprene	100 (38)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	
Hypalon	240 (116)	Halogenated polyester	140 (60)
Plastisols	90 (32)	Methyl-appended silicone	

Potassium Sulfate, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	260 (127)
Urethanes	90 (32)	Isophthalic polyesters	100 (38)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides	90 (32)	Hydrogenated polyester	200 (93)
Hypalon	240 (116)	Halogenated polyester	190 (88)
Plastisols	140 (60)	Methyl-appended silicone	

Propylene Glycol

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	400 (204)
Epoxy	100 (38)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	
Epoxy polyamide	100 (38)	ECTFE	
Coal tar epoxy	100 (38)	Fluoroelastomers	300 (149)
Coal tar		PVDF	240 (116)
Urethanes		Isophthalic polyesters	180 (82)
Neoprene	90 (32)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	200 (93)
Hypalon		Halogenated polyester	100 (38)
Plastisols	X	Methyl-appended silicone	

Pyridine

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	460 (238)
Vinyl ester	X	ETFE	140 (60)
Epoxy polyamide	X	ECTFE	X
Coal tar epoxy	X	Fluoroelastomers	X
Coal tar	X	PVDF	X
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Salicylic Acid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	140 (60)	ETFE	240 (116)
Epoxy polyamide	100 (38)	ECTFE	240 (116)
Coal tar epoxy	100 (38)	Fluoroelastomers	280 (138)
Coal tar		PVDF	200 (93)
Urethanes		Isophthalic polyesters	100 (38)
Neoprene	X	Bisphenol A fumurate	140 (60)
Polysulfides		Hydrogenated polyester	
Hypalon	X	Halogenated polyester	120 (49)
Plastisols	X	Methyl-appended silicone	

Sodium Acetate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	X
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	180 (82)
Polysulfides		Hydrogenated polyester	200 (93)
Hypalon	X	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	X

Sodium Bicarbonate, 20%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters, 10%	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	160 (71)
Polysulfides		Hydrogenated polyester	
Hypalon	240 (116)	Halogenated polyester	140 (60)
Plastisols	140 (60)	Silicone	400 (204)

Sodium Bisulfate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	260 (127)	PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	180 (82)
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	
Hypalon	100 (38)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	

Sodium Carbonate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy	200 (38)	FEP	400 (204)
Furans, 50%	240 (116)	PTFE	400 (204)
Vinyl ester	180 (82)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	180 (82)
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters, 20%	90 (32)
Neoprene	200 (93)	Bisphenol A fumurate	160 (71)
Polysulfides	X	Hydrogenated polyester, 10%	100 (38)
Hypalon	240 (116)	Halogenated polyester, 10%	180 (82)
Plastisols	140 (60)	Methyl-appended silicone	300 (149)

Sodium Chlorate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics, 50%	160 (71)	PFA	200 (93)
Epoxy	100 (38)	FEP	400 (204)
Furans	160 (71)	PTFE	400 (204)
Vinyl ester	220 (104)	ETFE	280 (138)
Epoxy polyamide		ECTFE	280 (138)
Coal tar epoxy, 50%	100 (38)	Fluoroelastomers	180 (82)
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters	X
Neoprene	80 (27)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	200 (93)
Hypalon	240 (116)	Halogenated polyester, 48%	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	

Sodium Chloride

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	180 (82)	ETFE	280 (138)
Epoxy polyamide	110 (43)	ECTFE	280 (138)
Coal tar epoxy	110 (43)	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	260 (127)
Urethanes	80 (27)	Isophthalic polyesters	200 (93)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides	80 (27)	Hydrogenated polyester	200 (93)
Hypalon	240 (116)	Halogenated polyester	210 (99)
Plastisols	140 (60)	Methyl-appended silicone, 10%	400 (204)

Sodium Cyanide

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	240 (116)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	280 (138)
Epoxy polyamide	100 (38)	ECTFE	280 (138)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	260 (127)
Urethanes		Isophthalic polyesters	150 (66)
Neoprene	180 (82)	Bisphenol A fumurate	160 (71)
Polysulfides		Hydrogenated polyester	
Hypalon	240 (116)	Halogenated polyester, 50%	140 (60)
Plastisols	140 (60)	Silicone	140 (60)

Sodium Hydroxide, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	450 (232)
Epoxy	190 (88)	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	170 (77)	ETFE	230 (110)
Epoxy polyamide	100 (38)	ECTFE	300 (149)
Coal tar epoxy	100 (38)	Fluoroelastomers	X
Coal tar		PVDF	230 (110)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	230 (110)	Bisphenol A fumurate	130 (54)
Polysulfides	X	Hydrogenated polyester	100 (38)
Hypalon	200 (93)	Halogenated polyester	110 (43)
Plastisols	140 (60)	Methyl-appended silicone	90 (27)

Sodium Hydroxide, 50%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	200 (93)	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	220 (104)	ETFE	230 (110)
Epoxy polyamide	100 (38)	ECTFE	250 (121)
Coal tar epoxy	100 (38)	Fluoroelastomers	X
Coal tar		PVDF	220 (104)
Urethanes	90 (32)	Isophthalic polyesters	X
Neoprene	230 (110)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	X
Hypalon	200 (93)	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	90 (27)

Sodium Hypochlorite, 20%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar		PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	160 (71)
Hypalon	200 (93)	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	X

Sodium Hypochlorite, conc.

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	100 (38)	ETFE	300 (149)
Epoxy polyamide		ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar		PVDF	280 (138)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	X

Sodium Nitrate

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	80 (27)	PFA	200 (93)
Epoxy	200 (93)	FEP	400 (204)
Furans	160 (71)	PTFE	400 (204)
Vinyl ester	200 (93)	ETFE	300 (149)
Epoxy polyamide		ECTFE	300 (149)
Coal tar epoxy	80 (27)	Fluoroelastomers	X
Coal tar		PVDF	280 (138)
Urethanes	90 (32)	Isophthalic polyesters	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	220 (104)
Polysulfides		Hydrogenated polyester	210 (99)
Hypalon	140 (60)	Halogenated polyester	250 (121)
Plastisols	140 (60)	Methyl-appended silicone	X

Sodium Peroxide, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	200 (93)
Epoxy	90 (32)	FEP	400 (204)
Furans		PTFE	400 (204)
Vinyl ester	160 (71)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	260 (127)
Urethanes		Isophthalic polyesters	X
Neoprene	200 (93)	Bisphenol A fumurate	220 (104)
Polysulfides		Hydrogenated polyester	
Hypalon	250 (121)	Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	X

Stearic Acid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	210 (99)	PFA	200 (93)
Epoxy	220 (164)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	220 (104)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	100 (38)
Coal tar	X	PVDF	280 (138)
Urethanes	90 (32)	Isophthalic polyesters	180 (82)
Neoprene	200 (93)	Bisphenol A fumurate	200 (93)
Polysulfides		Hydrogenated polyester	210 (99)
Hypalon	140 (60)	Halogenated polyester	250 (121)
Plastisols	140 (60)	Methyl-appended silicone	X

Styrene

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics		PFA	
Epoxy	100 (38)	FEP	100 (38)
Furans	360 (182)	PTFE	350 (177)
Vinyl ester	100 (38)	ETFE	210 (99)
Epoxy polyamide		ECTFE	
Coal tar epoxy	X	Fluoroelastomers	300 (149)
Coal tar	X	PVDF	190 (88)
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	100 (38)
Polysulfides		Hydrogenated polyester	100 (38)
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Sulfur Dioxide, wet

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	200 (93)
Epoxy	150 (66)	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	210 (99)	ETFE	230 (110)
Epoxy polyamide	100 (38)	ECTFE	150 (66)
Coal tar epoxy	100 (38)	Fluoroelastomers	X
Coal tar		PVDF	210 (99)
Urethanes		Isophthalic polyesters	90 (32)
Neoprene	X	Bisphenol A fumurate	220 (104)
Polysulfides		Hydrogenated polyester	210 (99)
Hypalon	X	Halogenated polyester	250 (121)
Plastisols	X	Methyl-appended silicone	

Sulfur Trioxide

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	300 (149)	PFA	200 (93)
Epoxy		FEP	400 (204)
Furans	X	PTFE	400 (204)
Vinyl ester	210 (99)	ETFE	80 (27)
Epoxy polyamide	X	ECTFE	80 (27)
Coal tar epoxy	X	Fluoroelastomers	190 (88)
Coal tar	X	PVDF	X
Urethanes		Isophthalic polyesters	90 (32)
Neoprene	X	Bisphenol A fumurate	250 (121)
Polysulfides		Hydrogenated polyester	
Hypalon	X	Halogenated polyester	120 (49)
Plastisols	140 (60)	Methyl-appended silicone	X

Sulfuric Acid, 10%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	250 (121)	PFA	450 (232)
Epoxy	140 (60)	FEP	400 (204)
Furans	160 (71)	PTFE	450 (232)
Vinyl ester	200 (93)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	250 (121)
Urethanes	X	Isophthalic polyesters	180 (71)
Neoprene	150 (66)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	210 (99)
Hypalon	200 (93)	Halogenated polyester	260 (127)
Plastisols	140 (60)	Methyl-appended silicone	X

Sulfuric Acid, 50%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	250 (121)	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	260 (127)	PTFE	450 (232)
Vinyl ester	210 (99)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	220 (104)
Urethanes	X	Isophthalic polyesters	150 (66)
Neoprene	100 (38)	Bisphenol A fumurate	220 (104)
Polysulfides	X	Hydrogenated polyester	210 (99)
Hypalon	200 (93)	Halogenated polyester	200 (93)
Plastisols	140 (60)	Methyl-appended silicone	X

Sulfuric Acid, 70%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	210 (93)	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans		PTFE	450 (232)
Vinyl ester	180 (82)	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	250 (121)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	220 (104)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	160 (71)
Polysulfides	X	Hydrogenated polyester	90 (32)
Hypalon	160 (71)	Halogenated polyester	190 (88)
Plastisols	140 (60)	Methyl-appended silicone	X

Sulfuric Acid, 90%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	210 (99)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Sulfuric Acid, 98%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	350 (177)
Coal tar	X	PVDF	140 (66)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	X
Hypalon	X	Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	X

Sulfuric Acid, 100%

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy	X	FEP	400 (204)
Furans	X	PTFE	450 (232)
Vinyl ester	X	ETFE	300 (149)
Epoxy polyamide	X	ECTFE	80 (27)
Coal tar epoxy	X	Fluoroelastomers	180 (82)
Coal tar	X	PVDF	X
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	X
Hypalon	X	Halogenated polyester, 50%	X
Plastisols	X	Methyl-appended silicone	X

Sulfurous Acid

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	X	PFA	450 (232)
Epoxy, 20%	240 (116)	FEP	400 (204)
Furans	160 (71)	PTFE	450 (232)
Vinyl ester, 10%	120 (49)	ETFE	210 (99)
Epoxy polyamide	110 (43)	ECTFE	250 (121)
Coal tar epoxy	100 (38)	Fluoroelastomers	400 (204)
Coal tar		PVDF	220 (104)
Urethanes		Isophthalic polyesters	X
Neoprene	100 (38)	Bisphenol A fumurate	110 (43)
Polysulfides		Hydrogenated polyester, 25%	210 (99)
Hypalon	160 (71)	Halogenated polyester, 10%	80 (27)
Plastisols	140 (60)	Methyl-appended silicone	X

Thionyl Chloride

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA[a]	450 (232)
Epoxy	X	FEP[a]	400 (204)
Furans	X	PTFE[a]	450 (232)
Vinyl ester	X	ETFE	210 (99)
Epoxy polyamide		ECTFE	150 (66)
Coal tar epoxy		Fluoroelastomers	X
Coal tar		PVDF	X
Urethanes		Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides		Hydrogenated polyester	
Hypalon		Halogenated polyester	X
Plastisols	X	Methyl-appended silicone	

[a] Corrodent will permeate.

Toluene

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	200 (93)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	212 (100)	PTFE	400 (204)
Vinyl ester	120 (49)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	140 (60)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	210 (99)
Urethanes	X	Isophthalic polyesters	100 (38)
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	80 (27)
Hypalon	X	Halogenated polyester	100 (38)
Plastisols	X	Methyl-appended silicone	X

Trichloroethylene

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	160 (71)	PTFE	400 (204)
Vinyl ester	X	ETFE	270 (132)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	260 (127)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	X
Polysulfides	X	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	120 (49)
Plastisols	X	Methyl-appended silicone	X

Turpentine

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	110 (43)	PFA	200 (93)
Epoxy	150 (66)	FEP	400 (204)
Furans		PTFE	400 (204)
Vinyl ester	150 (66)	ETFE	270 (132)
Epoxy polyamide	X	ECTFE	300 (149)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	80 (27)
Neoprene	X	Bisphenol A fumurate	80 (27)
Polysulfides	80 (27)	Hydrogenated polyester	
Hypalon	X	Halogenated polyester	120 (49)
Plastisols	X	Methyl-appended silicone	X

Water, salt

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	200 (93)
Epoxy, 10%	210 (99)	FEP	400 (204)
Furans		PTFE	400 (204)
Vinyl ester	160 (71)	ETFE	250 (121)
Epoxy polyamide	130 (54)	ECTFE	300 (149)
Coal tar epoxy	130 (54)	Fluoroelastomers	190 (88)
Coal tar	100 (38)	PVDF	280 (138)
Urethanes	X	Isophthalic polyesters	160 (71)
Neoprene	210 (99)	Bisphenol A fumurate	180 (82)
Polysulfides	80 (27)	Hydrogenated polyester	210 (99)
Hypalon	250 (121)	Halogenated polyester	
Plastisols	140 (60)	Methyl-appended silicone	210 (99)

White Liquor

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	160 (71)	PFA	
Epoxy	200 (93)	FEP	400 (204)
Furans	140 (60)	PTFE	400 (204)
Vinyl ester	180 (82)	ETFE	
Epoxy polyamide	150 (66)	ECTFE	250 (121)
Coal tar epoxy	100 (38)	Fluoroelastomers	190 (88)
Coal tar	X	PVDF	200 (93)
Urethanes	X	Isophthalic polyesters	X
Neoprene	140 (60)	Bisphenol A fumurate	180 (82)
Polysulfides		Hydrogenated polyester	
Hypalon		Halogenated polyester	X
Plastisols	140 (60)	Methyl-appended silicone	

Xylene

	Max Temp. °F (°C)		Max Temp. °F (°C)
Phenolics	150 (66)	PFA	200 (93)
Epoxy	X	FEP	400 (204)
Furans	260 (127)	PTFE	400 (204)
Vinyl ester	140 (60)	ETFE	250 (121)
Epoxy polyamide	X	ECTFE	150 (66)
Coal tar epoxy	X	Fluoroelastomers	400 (204)
Coal tar	X	PVDF	210 (99)
Urethanes	X	Isophthalic polyesters	X
Neoprene	X	Bisphenol A fumurate	90 (32)
Polysulfides	80 (27)	Hydrogenated polyester	90 (32)
Hypalon	X	Halogenated polyester	150 (66)
Plastisols	X	Methyl-appended silicone	X

10 Metallic Coatings

Metallic coatings are applied to metal substrates for several purposes. Typical purposes include improved corrosion resistance, wear resistance, and appearance. Of primary concern is corrosion resistance.

By providing a barrier between the substrate and the environment, or by cathodically protecting the substrate, metallic coatings protect the substrate from corrosion. Coatings of chromium, copper, and nickel provide increased wear resistance and good corrosion resistance. However, these noble metals make the combination of the substrate (mostly steel or an aluminum alloy) with the protective layer sensitive to galvanically induced local corrosion. Nonnoble metallic layers such as zinc or cadmium provide good cathodic protection but show poor wear resistance.

From a corrosion point of view, metal coatings can be divided into two classes: noble and sacrificial. Silver, copper, nickel, chromium, tin, and lead coatings on steel constitute the former group, whereas the coatings of zinc, aluminum, and cadmium belong to the latter group. Any damage or discontinuity in the noble metal coating creates a small anode–large cathode condition that leads to a rapid localized attack on the substrate at the damaged areas. Such damage in the sacrificial coating will not pose a problem as the exposed substrate will be cathodic with respect to the coating metal and will be protected at the cost of the corrosion of the coating metal. Naturally, the noble metals should be free of pores and this is usually accomplished through an increase in coating thickness.

Reversal of polarity between zinc and steel occurs in many aerated waters above 140°F (60°C), which means that the zinc coating behaves as a noble metal coating on steel. Under these circumstances, the base steel becomes vulnerable to attack at coating discontinuities. Tin is cathodic to iron, but the tin coating inside food cans becomes anodic to steel because stannous (Sn^{2+}) ions are complexed with the food product, thereby greatly reducing the stannous ion activity. The galvanic protection of steel provided by tin is lost in the presence of dissolved oxygen, and food should not be retained inside the tin cans after opening to avoid contamination by corrosion products.

A coating of a corrosion-resistant metal on a corrosion-prone substrate can be formed by various methods. The choice of coating material and the selection of an application method are determined by the end use.

METHODS OF PRODUCING COATINGS

Electroplating

Electroplating is one of the most versatile methods. The metal to be coated is made the cathode in an electrolytic cell. A potential is applied between the cathode

on which the plating occurs and the anode, which may be the metal or an inert material such as graphite. This method can be used for all metals that can be electrically reduced from the ionic state to the metallic state when present in an electrolyte. Aluminum, titanium, sodium, magnesium, and calcium cannot be electrodeposited from aqueous solution because the competing cathodic reaction ($2H^+ + 2e^- = H_2$) is strongly thermodynamically favored and takes place in preference to the reduction of the metal ion. These metals can be electrodeposited from conducting organic solutions or molten salt solutions in which the H^+ concentration is negligible. Many alloys can be electrodeposited, including copper-zinc, copper-tin, lead-tin, cobalt-tin, nickel-cobalt, nickel-iron, and nickel-tin. The copper-zinc alloys are used to coat steel wire used in tire-cord. Lead-tin alloys are known as terneplate and have many corrosion-resistant applications.

The thickness of the coating can be accurately controlled because the amount deposited is a function of the number of coulombs passed.

Electroless Plating

This method is also known as chemical plating or immersion plating. It is based on the formation of metal coatings resulting from the chemical reduction of metal ions from solution. The surface that is to be coated must be catalytically active as the deposition proceeds in a solution that must contain a reducing agent. If the catalyst is a reduction product (metal) itself, autocatalysis is ensured and, in this case, it is possible to deposit a coating, in principle, of unlimited thickness. The advantages of electroless plating are:

1. Deposits have fewer pinholes.
2. Electric power supply is not required.
3. Nonconductive materials are metallized.
4. A functional layer is deposited.
5. A uniform layer is deposited, even on complex parts.
6. The equipment for electroless plating is simple.

Electroless plating is limited by the fact that:

1. It is more expensive than electroplating because the reducing agents cost more than an equivalent amount of electricity.
2. It is less intensive because the metal deposition rate is limited by metal ion reduction in the bulk of the solution.

Copper, silver, cobalt, and palladium are the most commonly plated metals using this process. The silvering of mirrors falls into this category.

Hypophosphite, amine boranes, formaldehyde, borohydride, and hydrazine are typical reducing agents. Deposits of nickel formed with hypophosphite as a

TABLE 10.1
Coating Obtained by Electroless Plating

	Reducing Agent						
Metal	**$H_2PO_4^-$**	**N_2H_2**	**CH_2O**	**BH_4^-**	**RBH_3**	**Me ions**	**Others**
Ni	Ni-P	Ni		Ni-B	Ni-B		
Co	Co-P	Co	Co	Co-B	Co-B		
Fe				Fe-B			
Cu	Cu	Cu	Cu	Cu	Cu	Cu	
Ag		Ag	Ag	Ag	Ag	Ag	Ag
Au		Au	Au	Au	Au		Au
Pd	Pd-P	Pd	Pd	Pd-B	Pd-B		
Rh		Rh					Rh
Ru				Ru			
Pt		Pt		Pt			Pt
Sn						Sn	
Pb			Pb				

reducing agent contain phosphorus. This alloying constituent determines many of the properties. Table 10.1 shows coatings obtained by electroless plating.

Electrophoretic Deposition

Finely divided materials suspended in an electrolyte develop a change as a result of asymmetry in the charge distribution caused by the selective adsorption of one of the constituent ions. When the substrate metal is immersed in the electrolyte and a potential is applied, a coating will form. If the particles have a negative charge, they will be deposited on the anode; and if they have a positive charge, they will be deposited on the cathode. Commercial application of this method in the case of metals is limited.

Cathodic Sputtering

This method is carried out under partial vacuum. The substrate to be coated is attached to the anode. Argon, or a similar inert gas, is admitted at low pressure. A discharge is initiated and the positively charged gas ions are attracted to the cathode. Atoms are dislodged from the cathode as the gas ions collide with the cathode. These atoms are attracted to the anode and coat the substrate. This method can be used for nonconducting as well as conducting materials. The major disadvantages are the heating of the substrate and low deposition rates.

Some of the most commonly used metals deposited by sputtering include aluminum, copper, chromium, gold, molybdenum, nickel, platinum, silver, tantalum, titanium, tungsten, vanadium, and zirconium.

Sputtered coatings are used for a wide variety of applications, including:

1. Metals and alloys used as conductors, contacts, and resistors, and in other components such as capacitors.
2. Some high-performance magnetic data storage media are deposited via sputtering.
3. Thin metal and dielectric coatings are used to construct mirrors, anti-reflection coatings, light valves, laser optics, and lens coatings.
4. Hard coatings such as titanium, carbide, nitride, and carbon produce wear-resistant coatings for cutting tools.
5. Thin-film coatings can be used to provide high-temperature environmental corrosion resistance for aerospace and engine parts, gas barrier layers, and lightweight battery components.
6. Titanium nitride is deposited on watchbands and jewelry as a hard, gold-colored coating.

Diffusion Coating

Diffusion coating is a process for coating the base metal by diffusing another element onto the surface. The coating layer consists not of pure metal, but of its alloys and intermetallic compounds. Coating processes with sacrificial metals include *sherardising* and *colorizing.*

Sherardising Process

This process was developed by Sherard Cowper-Coles in 1900. In the Sherardising process, iron and steel components are coated by heating them with zinc dust and an inert medium in a sealed container. The container is rotated in a furnace for 2 to 4 hours at a temperature of 660 to 750°F (350 to 400°C).[1] This process can produce uniform coatings of up to 50 to 60 μm thick without any significant change in the profile of the substrate. The resulting coating layer exhibits good abrasion resistance. The Sherardising process has been used to coat such items as hinges, nuts, bolts, screws, nails, chains, clips, and washers.

Calorizing Process

In the calorizing process, developed by the General Electric Company in 1915, iron and steel components are coated at 1560 to 1760°F (850 to 960°C) in a drum containing powdered aluminum, alumina, and ammonium chloride.

Alumina is added to prevent the coalescence of aluminum particles. The resultant coating layer consists of an aluminum-rich compound, $FeAl_3$, in the outer layer and a solid solution of aluminum in the inner layer. The calorizing coating is used for protection against oxidation at high temperatures because the aluminum oxide layers formed on the surface by heating prohibit further oxidation of the substrate. The coating thickness is commonly 0.001 to 0.004 in. Thicker coatings can be formed by heat treatment.

Metal Spraying (Combustion Flame Spraying)

Spraying processes are classified as combustion flame spraying, electric arc spraying, and plasma spraying. This section describes combustion flame spraying.

Combustion flame spraying is a process to apply coatings by spraying molten particles on a prepared surface. This process is divided into the wire and powder methods by the form of coating materials supplied to the spray gun. The wire-spray process is widely used for metal spraying. Zinc and aluminum are the primary metals used in this process.

Coating by metal spraying is carried out in four steps:

1. Degreasing
2. Abrasive blasting
3. Spraying
4. Sealing

The coating layer adheres mechanically to the surface. An intermediate alloy layer is not formed at the interface. Consequently, a uniform rough surface is required on the substrate. The surface of the base metal is degreased, then abrasive blasted. Alumina, silica sand, steel grit, steel shot, and slag are used as abrasives. Alumina is superior in surface contamination to metallic grit and other abrasives. Alumina and steel grit provide satisfactory bond strength. The bond strength increases with surface roughness.[2]

The molten coating metal is produced in a "spray gun" from which the molten particles are sprayed. A high-pressure jet of hot gas, usually acetylene, produced by the spray gun breaks up the molten metal into droplets that are carried with the gas at speeds of 200 to 270 m/sec. The surfaces of the particles are almost completely oxidized because they are carried through the air. The spray-coated layer is porous so that the apparent specific gravity of the zinc coating layer is about 6.4 g/cm^3 compared to 7.1 g/cm^3 for cast zinc,[3] and that of an aluminum coating layer is 2.4 g/cm^3. The surface sprayed is commonly coated with a sealer such as a low-viscosity epoxy or acrylic system resin.

The advantages of metal spraying are found in the thick coating and the fact that the process can be applied to any form, any size of object, and in any place. Coating thicknesses range from 80 to 500 μm for zinc and 75 to 250 μm for aluminum.

Hot Dipping

Hot dipping is the oldest and most popular process. In the hot dipping process, base metals are coated by immersion in a molten metal bath. Therefore, the melting points of the coating metals must be lower than those of the base metals to be coated. Sacrificial metals, except manganese, are suitable for coating metals by hot dipping. The hot dipping process has been used for tin, and lead and its alloy coatings. Thin sheet steel and steel wire are coated by the continuous hot dipping process, and die castings, pipes, and forgings are treated by the batch process.

The rapid reaction of molten metal with base metal is required to produce a well-bonded metal coating; therefore, the pretreatment process is very important. The pretreatment process consists of the following steps:

Degreasing → Pickling → Water rinsing → Fluxing or reducing → Hot dipping

Degreasing is accomplished by solvent cleaning or alkali cleaning. Solvent cleaning is suitable for metals, except iron, that readily dissolve in alkaline solution. Typical solvents used are gasoline, benzene, trichloroethylene, or perchloroethylene. Alkali cleaning is used to remove oils and fats on the surfaces of iron and steel products. Alkali cleaning solutions that are used include sodium hydroxide, sodium carbonate, sodium silicate, orthosodium silicate, sodium phosphate, and their combinations. After cleaning, the surface is rinsed with water.

Pickling is accomplished by immersion in an agitated acid solution. A 10 to 20% concentration of hydrochloric acid at room temperature or a 5 to15% concentration of sulfuric acid at 140 to 175°F (60 to 80°C) is used for iron or steel. Hydrochloric acid is superior to sulfuric acid in rust prevention ability, and hydrogen embrittlement and blistering tend not to occur in coated materials treated with hydrochloric acid.

Copper alloys with thick scales are treated with a 50% nitric acid or sulfuric acid solution, while dilute hydrochloric acid is used for cast iron. After pickling, the surface is rinsed with hot water. Residual sulfates on the surfaces of iron, steel, and cast iron are removed by immersion in 1 to 2% sodium cyanide solution. Copper alloys after pickling are neutralized with a 3% sodium carbonate solution containing $KHC_4H_4O_6 \cdot H_2O$.

The fluxing process is used in both batch and continuous coating systems. In zinc coating, alloying is promoted by removal of FeO on the steel substrate and ZnO on the surface of molten zinc with the flux of $ZnCl_2$ and NH_4Cl. The fluxing reaction proceeds as follows:

$$ZnCl_2 + NH_4Cl \rightarrow ZnCl_2 \cdot NH_3 + HCl$$

$$2HCl + FeO \rightarrow Fe + H_2O\uparrow + 2Cl$$

$$ZnO + ZnCl_2 \rightarrow ZnCl_2 \cdot ZnO$$

$$ZnO + 2NH_4Cl \rightarrow ZnCL_2 \cdot NH_3 + NH_3\uparrow + H_2O$$

The reducing process is used in the continuous coating process of galvanized and aluminized steels. In the reducing process, the steel surface is activated. Steel sheet is heated and iron oxide films are reduced with hydrogen gas as follows:

$$Fe_3O_4 + 4H_2 \rightarrow 3Fe + 4H_2O$$

$$FeO + H_2 \rightarrow Fe + H_2O$$

In the hot dipping process, when substrate metal is immersed in the molten metal, an alloy layer is formed at the interface by diffusion of both the substrate metal and molten metal. The adhesion of the coating results from the formation of the alloy layer. The condition of the alloy layer strongly influences the mechanical and chemical properties of a coating layer, so that the alloy layer is treated according to the purpose of its intended use. The alloy layer is reduced by the addition of effective elements, and its growth is promoted by heating.

Vacuum Vapor Deposition

This coating method deposits evaporated metal on a base metal in a vacuum (10^{-4} torr). Metallic vapor is produced mainly by one of two processes: resistance heating or electron-beam bombardment.

In 1966, the aluminum coating process with electron-beam bombardment (600 kW class) was developed by the Manfred von Ardenne Institute in the D.D.R.[4,5] In this coating process, the deposition rate is 80 μm per second, the high vacuum condition of 10^{-5} torr is maintained in the coating station by the lock system, and the line speed is 200 m/min. A 1- to 3-μm aluminum layer is deposited continuously on the coil strip (strip width: 635 mm; thickness: 0.25 to 0.65 mm).

A production line with zinc vapor deposition was developed by Misskin Steel Company and Mitsubishi Heavy Industry Company in Japan[6] and commercial products have been produced since 1987. This production line, with a resistance heating system, has a special-design evaporation bath and continuous zinc supply system.

Gas Plating

Some metal compounds can be decomposed by heat to form the metal. Outstanding examples include metal carbonyls, metal halides, and metal methyl compounds. Nickel deposits can be obtained by thermal decomposition of nickel carbonyl, a compound with high volatility and high toxicity. Old production processes for titanium and zirconium were based on the formation of iodides, which were transported in the gas phase to a hot wire, where the iodide was decomposed to form the metal.

Plasma Spraying

This method is similar to flame spraying except that forms of heating other than flame are used.

Fusion Bonding

Coatings of low-melting metals such as tin, lead, zinc, and aluminum can be applied by cementing the metal powder on the substrate and then heating the substrate to a temperature above the melting point of the coating metal.

Cladding (Explosive Bonding)

Cladding is the process of metallurgically bonding two or more metals or alloys to form a composite material. Cladding can take place in several ways, including cold- and hot-roll bondings, extrusion bonding, explosive bonding, and their combinations. The shape and size of the base metal and the thickness of the clad metal determine the production method. Clad steels are most often produced by cold- and hot-roll bondings and explosive bonding.

In the hot-roll bonding method, the cladding metal and steel are cleaned by pickling, buffing, and other processes. The two prepared metals are placed face to face. In some instances, a nickel film, such as foil or an electrode-deposited film, is placed between the faces to inhibit the formation of an alloy layer, oxidation, and the diffusion of carbon. The edges of the assembly are welded, sealing the entire assembly. The assembled materials are heated and then hot-rolled by the regular strip practice.

Clad metals provide excellent corrosion resistance because of low porosity.

NOBLE COATINGS

Because of the high corrosion resistance of the noble metals, these materials are used where a high degree of corrosion resistance and decorative appearance are requirements. They find application in domestic appliances, window frames, bicycles, motorbikes, parts for car bodies, furniture, tools, flanges, hydraulic cylinders, shock absorbers for cars, and parts of equipment for the chemical and food processing industries.

Noble metal coatings protect substrates from corrosion by means of anodic control of the EMF. Coating metals that provide protection by means of anodic control include nickel, chromium, tin, lead, and their alloys.

They can protect the substrate metal as a result of their resistance to corrosion insofar as they form a well-adhering and nonporous barrier layer. However, when the coating is damaged, galvanically induced corrosion will lead to severe attack. This corrosion process is extremely fast for coated systems due to the high current density on the defect as a result of the large ratio between the surface areas of the cathodic outer surface and the anodic defect, as shown in Figure 10.1. To compensate for these defects in the coating, multilayer coating systems have been developed. The corrosion resistance of a single-layer noble metal coating results from the original barrier action of the noble metal, the surface of the noble metal being passivated. With the exception of lead, a secondary barrier of corrosion products is not formed. Noble metals do not provide cathodic protection for the steel substrate because their corrosion potential is more noble than that of iron or steel in a natural environment (see Table 10.2). In multilayer coating systems, a small difference in potential between coating layers results in galvanic action on coating layers.

Noble coating metals that provide corrosion protection by means of EMF control include copper, silver, platinum, gold, and their alloys. The standard single

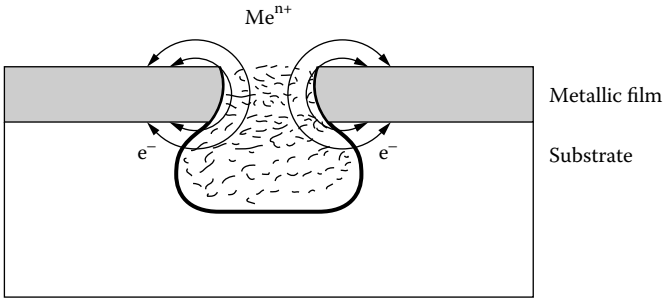


FIGURE 10.1 Dissolution of substrate metal in coating defect.

potentials of these metals are more noble than those of hydrogen (refer to Table 10.3). Therefore, the oxidizer in corrosion cells formed on these metals in a natural environment, containing no other particular oxidizers, is dissolved oxygen. Consequently, the electromotive force that causes corrosion is so small that coating with noble metals is an effective means of providing corrosion protection. With the exception of copper, the other members of this group are precious metals, and are used primarily for electrical conduction and decorative appearance.

Nickel Coatings

The corrosion protection afforded by nickel layers is often combined with an improved decorative effect, especially important for applications in automobiles. In decorative applications of chromium-plated steel substrates, nickel provides the corrosion protection to the steel substrate. Nickel layers can be applied by electrodeposition or electrolessly from an aqueous solution without the use of an externally applied current.

The application of electrodeposited nickel has diminished considerably in recent years due to the decreasing application of nickel-chromium layers in the

TABLE 10.2
Corrosion Potential of Noble Metals

	Corrosion Potential (V, SCE)	
pH	**2.9**	**6.5**
Chromium	−0.119	−0.186
Nickel	−0.412	−0.430
Tin	−0.486	−0.554
Lead	−0.435	−0.637
. . . . .		
Steel	−0.636	−0.505

TABLE 10.3
Standard Single Potentials, E^o (V, SHE, 25°C)

Inert	
Electrode	E^o
H_2/H^+	±0
Cu/Cu^{2+}	+0.34
Cu/Cu^+	+0.52
Ag/Ag^+	+0.799
Pt/Pt^{2+}	+1.2
Au/Au^{3+}	+1.42
Au/Au^+	+1.7

automotive industry. Measured in the treated surface area, electrodeposited nickel still takes second place after zinc. Applications are in bicycles, automobiles, pumps, domestic appliances, bolts, screws, buildings, food processing plants, and the pulp and paper industry. It can also be used in marine surroundings. See Table 10.4 for the compatibility of nickel with selective corrodents.

There are three types of nickel coating: bright, semibright, and dull bright. The difference between the coatings is in the quantity of sulfur contained in them, as shown below:

Bright nickel deposits	> 0.04% sulfur
Semibright nickel deposits	< 0.005% sulfur
Dull bright nickel deposits	< 0.001% sulfur

The corrosion potentials for the nickel deposits depend on the sulfur content. Figure 10.2 shows the effect of sulfur content on the corrosion potential of a nickel deposit. A single-layer nickel coating must be greater than 30 μm to ensure the absence of defects.

As the sulfur content increases, the corrosion potential of a nickel deposit becomes more negative; a bright nickel coating is less protective than a semibright or dull nickel coating. The difference in the potential of bright nickel and semibright nickel deposits is more than 50 mV.

Use is made of the differences in the potential in the application of multilayer coatings. The more negative bright nickel deposits are used as sacrificial intermediate layers. When bright nickel is used as an intermediate layer, the corrosion behavior is characterized by sideways diversion. Pitting corrosion is diverted laterally when it reaches the more noble semibright nickel deposit. Thus, the corrosion behavior of bright nickel prolongs the time it takes for pitting penetration to reach the base metal.

TABLE 10.4
Compatibility of Nickel 200 with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetaldehyde	200	93	Amyl acetate	300	149
Acetamide			Amyl alcohol		
Acetic acid, 10%	90	32	Amyl chloride	90	32
Acetic acid, 50%	90	32	Aniline	210	99
Acetic acid, 80%	120	49	Antimony trichloride	210	99
Acetic acid, glacial	x	x	Aqua regia, 3:1	x	x
Acetic anhydride	170	77	Barium carbonate	210	99
Acetone	190	88	Barium chloride	80	27
Acetyl chloride	100	38	Barium hydroxide	90	32
Acrylic acid			Barium sulfate	210	99
Acrylonitrile	210	99	Barium sulfide	110	43
Adipic acid	210	99	Benzaldehyde	210	99
Allyl alcohol	220	104	Benzene	210	99
Allyl chloride	190	88	Benzene sulfonic acid, 10%	190	88
Alum	170	77	Benzoic acid	400	204
Aluminum acetate			Benzyl alcohol	210	99
Aluminum chloride, aq.	300	149	Benzyl chloride	210	99
Aluminum chloride, dry	60	16	Borax	200	93
Aluminum fluoride	90	32	Boric acid	210	99
Aluminum hydroxide	80	27	Bromine gas, dry	60	16
Aluminum nitrate			Bromine gas, moist	x	x
Aluminum oxychloride			Bromine liquid		
Aluminum sulfate	210	99	Butadiene	80	27
Ammonia gas	90	32	Butyl acetate	80	27
Ammonium bifluoride			Butyl alcohol	200	93
Ammonium carbonate	190	88	n-Butylamide		
Ammonium chloride, 10%	230	110	Butyl phthalate	210	99
Ammonium chloride, 50%	170	77	Butyric acid	x	x
Ammonium chloride, sat.	570	299	Calcium bisulfide		
Ammonium fluoride, 10%	210	99	Calcium bisulfite	x	x
Ammonium fluoride, 25%	200	93	Calcium carbonate		
Ammonium hydroxide, 25%	x	x	Calcium chlorate	140	60
Ammonium hydroxide, sat.	320	160	Calcium chloride	80	27
Ammonium nitrate	90	32	Calcium hydroxide, 10%	210	99
Ammonium persulfate	x	x	Calcium hydroxide, sat.	200	93
Ammonium phosphate, 30%	210	99	Calcium hypochlorite	x	x
Ammonium sulfate, 10–40%	210	99	Calcium nitrate		
Ammonium sulfide			Calcium oxide	90	32
Ammonium sulfite	x	x	Calcium sulfate	210	99

(*continued*)

TABLE 10.4 (Continued)
Compatibility of Nickel 200 with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Caprylic acid[b]	210	99	Ferrous chloride	x	x
Carbon bisulfide	x	x	Ferrous nitrate		
Carbon dioxide, dry	210	99	Fluorine gas, dry	570	290
Carbon dioxide, wet	200	93	Fluorine gas, moist	60	16
Carbon disulfide	x	x	Hydrobromic acid, 20%	x	x
Carbon monoxide	570	290	Hydrobromic acid, 50%	x	x
Carbon tetrachloride	210	99	Hydrobromic acid, dilute	x	x
Carbonic acid	80	27	Hydrochloric acid, 20%	80	27
Cellosolve	210	99	Hydrochloric acid, 38%	x	x
Chloracetic acid	210	99	Hydrocyanic acid, 10%		
Chloracetic acid, 50% water			Hydrofluoric acid, 30%[c]	170	77
Chlorine gas, dry	200	93	Hydrofluoric acid, 70%[c]	100	38
Chlorine gas, wet	x	x	Hydrofluoric acid, 100%[c]	120	49
Chlorine liquid			Hypochlorous acid	x	x
Chlorobenzene	120	49	Iodine solution, 10%		
Chloroform	210	99	Ketones, general	100	38
Chlorosulfonic acid	80	27	Lactic acid, 25%	x	x
Chromic acid, 10%	100	38	Lactic acid, conc.	x	x
Chromic acid, 50%	x	x	Magnesium chloride	300	149
Chromyl chloride	210	99	Malic acid	210	99
Citric acid, 15%	210	99	Manganese chloride, 37%	90	32
Citric acid, conc.	80	27	Methyl chloride	210	99
Copper acetate	100	38	Methyl isobutyl ketone	200	93
Copper carbonate	x	x	Methylethyl ketone		
Copper chloride	x	x	Muriatic acid	x	x
Copper cyanide	x	x	Nitric acid, 5%	x	x
Copper sulfate	x	x	Nitric acid, 20%	x	x
Cresol	100	38	Nitric acid, 70%	x	x
Cupric chloride, 5%	x	x	Nitric acid, anhydrous	x	x
Cupric chloride, 50%	x	x	Nitrous acid, conc.	x	x
Cyclohexane	80	27	Oleum		
Cyclohexanol	80	27	Perchloric acid, 10%	x	x
Dichloroacetic acid			Perchloric acid, 70%		
Dichloroethane (ethylene dichloride)	x	x	Phenol, sulfur-free	570	299
			Phosphoric acid, 50–80%	x	x
Ethylene glycol	210	99	Picric acid	80	27
Ferric chloride	x	x	Potassium bromide, 30%		
Ferric chloride, 50% in water	x	x	Salicylic acid	80	27
Ferric nitrate, 10–15%	x	x	Silver bromide, 10%		

TABLE 10.4 (Continued)
Compatibility of Nickel 200 with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Sodium carbonate, to 30%	210	99	Sulfuric acid, 70%	x	x
Sodium chloride, to 30%	210	99	Sulfuric acid, 90%	x	x
Sodium hydroxide, 10%c	210	99	Sulfuric acid, 98%	x	x
Sodium hydroxide, 50%[c]	300	149	Sulfuric acid, 100%	x	x
Sodium hydroxide, conc.	200	93	Sulfuric acid, fuming	x	x
Sodium hypochlorite, 20%	x	x	Sulfurous acid	x	x
Sodium hypochlorite, conc.	x	x	Thionyl chloride	210	99
Sodium sulfide, to 50%	x	x	Toluene	210	99
Stannic chloride	x	x	Trichloroacetic acid	80	27
Stannous chloride, dry	570	299	White liquor		
Sulfuric acid, 10%	x	x	Zinc chloride, to 80%	200	93
Sulfuric acid, 50%	x	x			

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable. When compatible, corrosion rate is <20 mpy.

[b] Material subject to pitting.

[c] Material subject to stress cracking.

Source: P.A. Schweitzer, *Corrosion Resistance Tables, 4th ed.,* Vols. 1–3, Marcel Dekker, New York, 1995.

The most negative of all nickel deposits is trinickel. In this triplex layer coating system, a coating of trinickel approximately 1 μm thick containing 0.1 to 0.25% sulfur is applied between bright nickel and semibright nickel deposits. The high sulfur/nickel layer dissolves preferentially, even when pitting corrosion reaches the surface of the semibright nickel deposit. Because the high sulfur layer reacts with the bright nickel layer, pitting corrosion does not penetrate the high sulfur/nickel layer in the tunneling form. The application of a high sulfur/nickel strike definitely improves the protective ability of a multilayer nickel coating.

In the duplex nickel coating system, the thickness ratio of semibright nickel deposit to bright nickel deposit is nominally 3:1, and a thickness of 20 to 25 μm is required to provide high corrosion resistance. The properties required for a semibright nickel deposit include:

1. The deposit contains little sulfur.
2. Internal stress must be slight.
3. Surface appearance is semibright and extremely level.

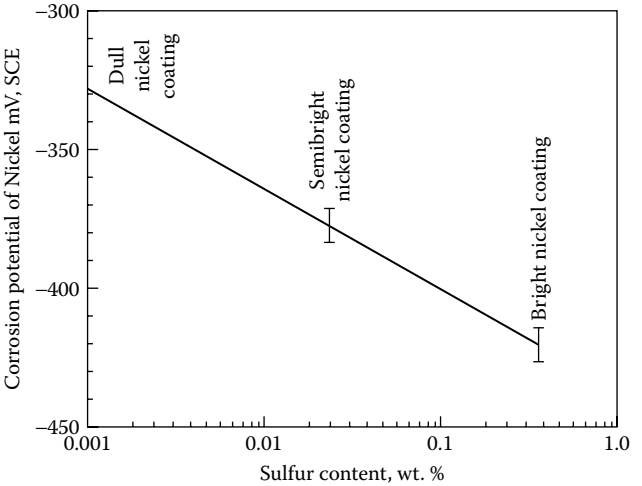


FIGURE 10.2 Effect of sulfur content on the corrosion protection of nickel.

For a trinickel (high sulfur) strike, the following properties are required:

1. The deposit contains a stable 0.1 to 0.25% sulfur.
2. The deposit provides good adhesion for semibright nickel deposits.

Nickel coatings can be applied by electrodeposition or electrolessly from an externally applied current.

Depending on the production facilities and the electrolyte composition, electrodeposited nickel can be relatively hard (120 to 140 HV). Despite competition from hard chromium and electroless nickel, electrodeposited nickel is still being used as an engineering coating because of its relatively low price. Some of its properties are:

1. Good general corrosion resistance
2. Good protection from fretting corrosion
3. Good machineability
4. The ability of layers of 50 to 75 μm to prevent scaling at high temperatures
5. Mechanical properties, including the internal stress and hardness, that are variable and that can be fixed by selecting the manufacturing parameters
6. Excellent combination with chromium layers
7. A certain porosity
8. A tendency for layer thicknesses below 10 to 12 μm on steel to give corrosion spots due to porosity

The electrodeposition can be either directly on steel or over an intermediate coating of copper. Copper is used as an underlayment to facilitate buffing, because it is softer than steel, and to increase the required coating thickness with a material less expensive than nickel.

The most popular electroless nickel plating process is the one in which hypophosphite is used as the reducer. Autocatalytic nickel ion reduction by hypophosphite takes place in both acidic and alkaline solutions. In a stable solution with a high coating quality, the deposition rate may be as high as 20 to 25 μm/h. However, a relatively high temperature of 194°F (90°C) is required. Because hydrogen ions are formed in the reaction

$$N_i^{2+} + 2H_2PO_2 + 2H_2O \rightarrow Ni + 2H_2 + 2H^-$$

a high buffering capacity of the solution is necessary to ensure a steady-state process. For this reason, acetate, citrate, proprionate, glycolate, lactate, or aminoacetate is added to the solution. These substances, along with buffering, can form complexes with nickel ions. Bonding Ni^{2+} ions into a complex is required in alkaline solution (here, ammonia and pyrophosphate can be added in addition to citrate and aminoacetate). In addition, such bonding is desirable in acidic solutions because free nickel ions form a compound with the reaction product (phosphate) that precipitates and prevents further use of the solution.

When hypophosphite is used as the reducing agent, phosphorus will be present in the coating. Its amount (in the range of 2 to 15 mass percent) depends on pH, buffering capacity, ligands, and other parameters of electroless solutions.

Borohydride and its derivatives can also be used as reducing agents. When borohydride is used in the reduction, temperatures of 140°F (60°C) to 194°F (90°C) are required. The use of dimethylaminoborane (DMAB) enables the deposition of Ni-B coatings with a small amount of boron (0.5 to 1.0 mass percent at temperatures in the range of 86°F (30°C) to 140°F (60°C).

Neutral and alkaline solutions can be used.

Depending on exposure conditions, certain minimum coating thicknesses to control porosity are recommended for the coating to maintain its appearance and have a satisfactory life:

- Indoor exposures 0.3 to 0.5 mil (0.008 to 0.013 mm)
- Outdoor exposure 0.5 to 1.5 mil (0.013 to 0.04 mm)
- Chemical industry 1 to 10 mil (0.025 to 0.25 mm)

For applications near the seacoast, thicknesses in the range of 1.5 mil (0.04 mm) should be considered. This also applies to automobile bumpers and applications in general industrial atmospheres.

Nickel is sensitive to attack by industrial atmospheres and forms a film of basic sulfate that causes the surface to “fog” or lose its brightness. To overcome this fogging, a thin coating of chromium (0.01 to 0.03 mil; 0.003 to 0.007 mm) is electrodeposited over the nickel. This finish is applied to all materials for which continued brightness is desired.

Single-layer coatings of nickel exhibit less corrosion resistance than multilayer coatings due to their discontinuities. The electroless plating process produces a coating with fewer discontinuous deposits. Therefore, single-layer deposits by electroless plating provide more corrosion resistance than an electroplated single layer.

Most electroless-plated nickel deposits contain phosphorus, which enhances corrosion resistance. In the same manner, an electroplated nickel deposit containing phosphorous will also be protective.

Satin Finish Nickel Coatings

A satin finish nickel coating consists of nonconductive materials such as aluminum oxide, kaolin, and quartz, which are co-deposited with chromium on the nickel deposit. Some particles are exposed on the surface of the chromium deposit so the deposit has a rough surface. Because the reflectance of the deposit is decreased to less than half that of a level surface, the surface appearance looks like satin.

A satin finish nickel coating provides good corrosion resistance due to the discontinuity of the top coat of aluminum.

Nickel-Iron Alloy Coatings

To reduce production costs of bright nickel, the nickel-iron alloy coating was developed. The nickel-iron alloy deposits full brightness, high leveling, and excellent ductility, and good reception for chromium.

This coating has the disadvantage of forming red rust when immersed in water; consequently, nickel-iron alloy is suitable for use in mild atmospheres only. Typical applications include kitchenware and tubular furniture.

Chromium Coatings

In the northern part of the United States immediately after World War II, it was not unusual for the chromium-plated bumpers on cars to show severe signs of rust after a few months of winter exposure. This was partially the result of trying to extend the short supply of strategic metals by economizing on the amount used. However, the more basic reason was the lack of sufficient knowledge of the corrosion process needed to control the attack by the atmosphere. Consequently, an aggressive industrial program was undertaken to obtain a better understanding of the corrosion process and ways to control it.

Chromium-plated parts on automobiles consist of steel substrates with an intermediate layer of nickel or, in some cases, layered deposits of copper and nickel. The thin chromium deposit provides a bright appearance and stain-free surface, while the nickel layer provides the corrosion protection to the steel substrate. With this system it is essential that the nickel cover the steel substrate completely because the iron will be the anode and the nickel will be the cathode. Any breaks, or pores, in the coating will result in the condition shown in

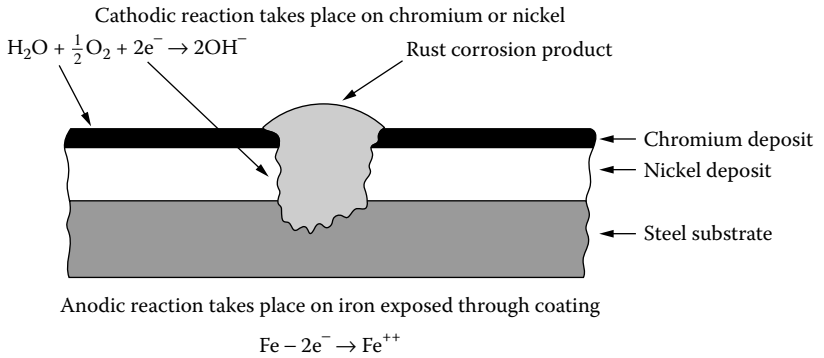


FIGURE 10.3 Corrosion of steel at breaks in a nickel/chromium coating when exposed to the atmosphere.

Figure 10.3. This figure illustrates the reason for the corrosion of chrome trim on automobiles after World War II.

The corrosion problem was made worse by the fact that additional agents used in the plating bath resulted in a bright deposit. Bright deposits contain sulfur, which makes the nickel more active from a corrosion standpoint, which is discouraging. However, it occurred to the investigators that this apparent disadvantage of bright nickel could be put to good use.

To solve this problem, a duplex nickel coating was developed, as shown in Figure 10.4. An initial layer of sulfur-free nickel is applied to the steel substrate, followed by an inner layer of bright nickel containing sulfur, along with an outer layer of micro-cracked chromium.

Any corrosion that takes place is limited to the bright nickel layer containing sulfur. The corrosion spreads laterally between the chromium and sulfur-free

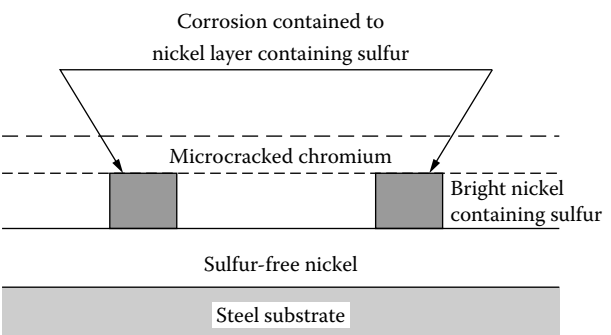


FIGURE 10.4 Duplex nickel electrode deposit to prevent corrosion of steel substrate.

nickel deposits because the outer members of this sandwich (chromium and sulfur-free nickel) are cathodic to the sulfur-containing nickel.

A potential problem that could result from this system of corrosion control would be the undermining of the chromium and the possibility that brittle chromium deposits could flake off the surface. This potential problem was prevented by the development of a microcracked or microporous chromium coating. This coating contains microcracks or micropores that do not detract from the bright appearance of the chromium. They are formed very uniformly over the exterior of the plated material and serve to distribute the corrosion process over the entire surface. The result has been to extend the life of the chromium-plated steel exposed to outdoor atmospheric conditions.

Microcracked chromium coatings are produced by first depositing a high-stress nickel strike on a sulfur-free nickel layer and then a decorative chromium deposit. The uniform crack network results from the interaction of the thin chromium layer and the high-stress nickel deposit. The result is a mirror-like surface as well as a decorative chromium coating.

Microporous chromium coatings are produced by first electroplating a bright nickel layer containing suspended nonconductive fine particles. Over this, a chromium layer is deposited that results in a mirror finish. As the chromium thickness increases, the number of pores decreases. For a chromium deposit of 0.25-μm thickness, a porosity of more than 10,000 pores/cm^2 is required. A porosity of 40,000 pores/cm^2 provides the best corrosion resistance.

Hard (engineering) chromium layers are also deposited directly on a variety of metals. The purpose in applying these layers is to obtain wear-resistant surfaces with high hardness or to restore original dimensions to a workpiece. In addition, the excellent corrosion resistance resulting from these layers makes them suitable for outdoor applications.

Thick chromium deposits have high residual internal stress and may be brittle due to the electrodeposition process, in which hydrogen can be incorporated in the deposited layer. Cracks result during plating when the stress exceeds the tensile stress of the chromium. As plating continues, some cracks are filled. This led to the development of controlled cracking patterns that produce wettable porous surfaces that can spread oil, which is important for engine cylinders, liners, etc.

Some of the properties of "engineering" chromium layers are:

1. Excellent corrosion resistance
2. Wear resistance
3. Hardness up to 950 HV
4. Controlled porosity is possible

The Armoloy Chromium Process

The Armoloy process is a low-temperature, multi-state chromium alloy process of electrocoating based on a modified chromium plating technology. The Armoloy

process uses a proprietary chemical solution instead of customary chromium plating solutions. This process produces a satin finish chromium coating that is very hard, thin, and dense. Conventional chromium plating processes deposit 82 to 88% chromium in most applications, whereas the Armoloy process deposits a 99% chromium coating on the basic metallic surface. The Armoloy process actually becomes part of the metallic substrate itself and the result is a continuous, smooth, hard surface with a lasting bond. The surface will not chip, flake, crack, peel, or separate from the substrate under extreme conditions of heat or cold, or when standard ASTM bend tests are applied.

The Armoloy coating supplies the substrate with increased wear, added lubricity, and excellent corrosion resistance.

As with other coatings, proper surface preparation is important. The substrate surfaces must be free of oil, grease, oxides, and sulfides before Armoloy further prepares the surface by proprietary means. Armoloy does not fill scratches, pits, or dents, but rather conforms to such imperfections and may highlight them.

The Armoloy process does not use acids, etching, or reversing methods, which are used in conventional chromium plating operations. Therefore, there is no detrimental effect to the substrate metal. Note that Armoloy is a satin-silver finish and does not have the reflective properties of some conventional chromium processes.

Coating thicknesses will range from 0.000040 to 0.0006 in. (1 to 15 μm) per side. Normal average deposits are in the 0.0001- to 0.0002-in. (2.5 to 5 μm) range. There is no change in the conductivity or magnetic properties of the substrate metal.

Armoloy resists attack by most organic and inorganic compounds (except hydrochloric and sulfuric acids). The Armoloy coating is more noble than the substrate and therefore protects against corrosion by being free of cracks, pores, and discontinuities, and by providing a uniform structure and chemical composition. The corrosion resistance properties will be affected by the porosity, hardness, and imperfect surface finish of the substrate. However, the corrosion resistance of all substrates treated will improve.

Unlike other electrochemical plating processes that can cause hydrogen embrittlement, it is extremely unlikely to occur with the Armoloy process because:

1. No acids are used in the preparation process.
2. The vapor blast (liquid hone) or dry hone procedure aids in relieving residual surface stress.
3. No reverse clean or etchant is used before the part is Armoloy processed.
4. The plating cycle times are very short and the Armoloy chrome is deposited so rapidly that Armoloy seals the surface porosity of the substrate before hydrogen ions can invade the surface of the substrate.

Armoloy is one of the hardest chromium surfaces available, measuring 70 to 72 Re as applied. The substrate metal determines how wear-resistant the Armoloy

surface will be. In general, Armoloy increases measurable hardness by 10 to 15 points.

Armoloy itself is always 70 to 72 Re. However, the hardness that can be achieved is the result of the hardness of the base substrate metal. The harder the substrate metal, the higher the Armoloy measurable hardness will be.

Good wear resistance is indicated by high hardness values. However, other factors must be considered. Corrosion and lubrication also affect wear. Armoloy, by being very hard, improves wear resistance, but also its corrosion resistance and improved lubricity help to improve wear resistance.

Techniques used in the application of Armoloy make it self-lubricating, creating a modular surface. The low friction factor of the coating is invaluable under conditions of extreme temperatures.

Armoloy has an operating temperature range of −200 to 1600°F (−128 to 871°C). At temperatures above 1600°F (871°C), Armoloy will react with carbon monoxide, sulfur vapor, and phosphorous and begin to soften. Hardness, wear resistance, and corrosion resistance will be reduced at temperatures above 1600°F (871°C). Armoloy will remain stable at temperatures below −200°F (−128°C).

Armoloy coating can be applied to all ferrous and most nonferrous materials. However, aluminum, magnesium, and titanium substrates are not recommended for Armoloy treatment.

Because Armoloy is a thin, dense coating, it exhibits its best wear and lubricity properties on hardened surfaces. It is most effective when the substrate metal is 40 Re or harder. In severe-wear applications, the substrate metal should be hardened to the 58 to 62 Re range before Armoloy application.

Ferrous steels coated with Armoloy can be used in place of stainless steels in many applications, including food processing, medical environments, and ball or roller bearing applications.

Armoloy is superior to type 440C stainless steel for corrosion resistance.

Chromium–Chromium Oxide Layers

The high price of tin, together with the instability of the tin-producing countries, has led to the search for alternative protective layers in food containers.[7] A good tinplate substitute should meet the following requirements:

1. Substantial corrosion resistance to a wide variety of chemicals
2. Nontoxicity
3. Good formability
4. Good adhesion to lacquers and adhesives
5. Speedy manufacturing process

Tin-free steel (TFS) cans, often denoted as TFS-CT (chromium type), are produced in considerable amounts as an alternative that meets all given requirements. These cans are coated with a very thin layer of chromium-covered chromium oxide for increased corrosion resistance and improved adherence of the organic coating and lifetime of the cans.[7,8]

For electrolytic chromium/chromium oxide coated steel (ECCS), 70 mg/m^2 of chromium and 12 mg/m^2 of chromium oxide are applied electrolytically. Despite the overall good corrosion resistance of such layers, the very thin character makes them unfit for direct exposure to corrosive environments. They are, however, always used in combination with an organic coating.

Tin Coatings (Tinplate)

Tinplate is produced mainly by the electroplating process. Alkaline and acid baths are used in the production line. The acid baths are classified as either ferrostan or halogen baths.

A thermal treatment above the melting point of tin follows the electrolytic deposition. The intermetallic compound $FeSn_2$ forms at the interface between the iron and tin during this thermal processing. The corrosion behavior of the tinplate is determined by the quality of the $FeSn_2$ formed, particularly when the amount of the free tin is small. The best-performing tinplate is that in which the $FeSn_2$ uniformly covers the steel so that the area of iron exposed is very small in case the tin should dissolve. Good coverage requires good and uniform nucleation of $FeSn_2$. Many nuclei form when electrodeposition of tin is carried out from the alkaline stannate bath.

Compared to either iron or tin, $FeSn_2$ is chemically inert in all but the strongest oxidizing environments.

Most of the tinplate (tincoating on steel) produced is used for the manufacture of food containers (tin cans). The nontoxic nature of the tin salts makes tin an ideal material for the handling of foods and beverages.

An inspection of the galvanic series indicates that tin is more noble than steel and, consequently, the steel would corrode at the base of the pores. On the outside of a tinned container, this is what happens — the tin is cathodic to the steel. However, on the inside of the container, there is a reversal of polarity because of the complexing of the stannous ions by many food products. This greatly reduces the activity of the stannous ions, resulting in a change in the potential of tin in the active direction.

This change in polarity is absolutely necessary because most tin coatings are thin and therefore porous. To avoid perforation of the can, tin must act as a sacrificial coating. Figure 10.5 illustrates this reversal of activity between the outside and inside of the can.

The environment inside a hermetically sealed can varies, depending upon the contents, which include general foods, beverages, oils, aerosol products, liquid gases, etc. For example, pH values vary for different contents as shown below:

- Acidic beverage 2.4–4.5
- Beer and wine 3.5–4.5
- Meat, fish marine products, vegetables 4.1–7.4
- Fruit juices, fruit products 3.1–4.3
- Non-food products 1.2–1.5

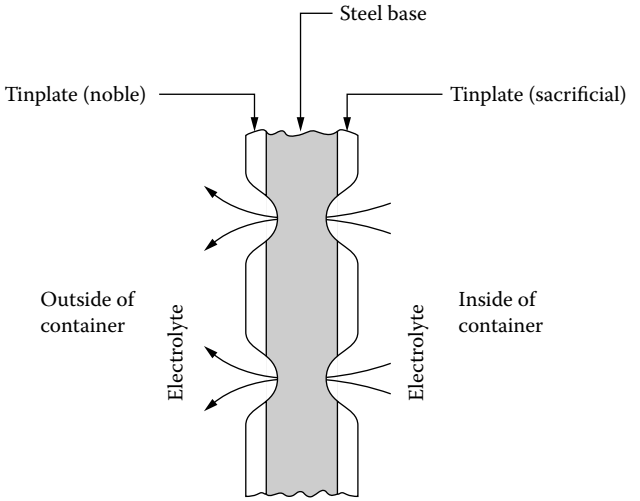


FIGURE 10.5 Tin acting as both a noble and sacrificial coating.

The interior of cans is subject to general corrosion and discoloration. The coating system for tinplate consists of tin oxide, metallic tin, and alloy. The dissolution of the tin layer in acidic fruit products is caused by acids such as citric acid. In acidic fruit products, the potential reversal occurs between the tin layer and the steel substrate, as shown in Figure 10.6. The potential reversal of a tin layer for steel substrate occurs in the pH range <3.8 in a citric acid solution. This phenomenon results from the potential shift of the tin layer to a more negative direction, namely, the activity of the stannous ion (Sn^{2+}) is reduced by the formation of soluble tin complexes, and thereby the corrosion potential of the tin layer becomes more negative than that of steel. Thus, the tin layer acts as a sacrificial anode for steel so that the thickness and density of the pores in the tin layer are important factors affecting the service life of the coating. A thicker tin layer prolongs the service life of a tin can. The function of the alloy layer (Fe-Sn) is to reduce the active area of the steel by covering it because it is inert in acidic fruit products. When some parts of the steel substrate are exposed, the corrosion of the tin layer is accelerated by galvanic coupling with the steel. The corrosion potential of the alloy layer is between that of the tin layer and that of the steel. A less defective layer exhibits a potential closer to that of the tin layer. Therefore, the covering with an alloy layer is important in decreasing the dissolution of the tin layer.

In carbonated beverages, the potential reversal does not take place; therefore, the steel dissolves preferentially at the defects in the tin layer. Under such conditions, pitting corrosion sometimes results in perforation. Consequently, except for fruit cans, almost all tinplate cans are lacquered.

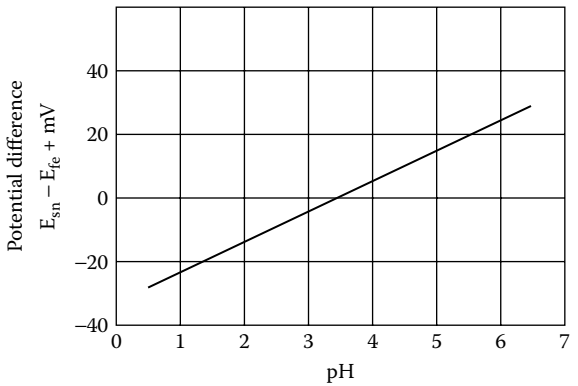


FIGURE 10.6 Potential reversal in tinplate.

When tinplate is used for structural purposes such as roofs, an alloy of 12 to 25 parts tin to 88 to 95 parts lead is frequently used. This is called *terneplate.* It is less expensive and more resistant to the weather than a pure tin coating. Terneplate is used for fuel tanks of automobiles, as well as in the manufacture of fuel lines, brake lines, and radiators in automobiles.

Lead Coatings

Coatings of lead and its alloy (S–10% tin) protect steel substrate, especially in industrial areas having an SO_x atmosphere. At the time of initial exposure, pitting occurs on the lead surface; however, the pits are self-healed and then the lead surface is protected by the formation of insoluble lead sulfate. Little protection is provided by these coatings when in contact with the soil.

Lead coatings are usually applied by either hot dipping or electrodeposition. When the coating is applied by hot dipping, a small percentage of tin is added to improve the adhesion to the steel plate. If 25% more of tin is added, the resulting coating is termed "terneplate."

Lead coating is electrodeposited in such baths as nitrate, acetate, fluorosilicate, and fluoroborate solution. The pretreatment is conducted by electrocleaning in alkaline solution and pickling (hydrochloric acid or sulfuric acid). Pickling strongly influences the adhesion of the deposit. The use of a copper or nickel strike before plating improves the corrosion resistance of the coating. Refer to Table 10.5 for the compatibility of lead with selected corrodents.

Caution: Do not used lead coatings where they will come into contact with drinking water or food products. Lead salts can be formed that are poisonous.

Terneplate

Terneplate is a tin-lead alloy coated sheet and is produced either by hot dipping or electrodeposition. The hot dipping process with a chloride flux is used to produce most terneplates. The coating layer, whose electrode potential is more noble than

TABLE 10.5
Compatibility of Lead with Selected Corrodents

Corrodent	°F/°C	Corrodent	°F/°C
Acetic acid	U	Hypochlorous acid	U
Acetic anhydride	80/27	Jet fuel, JP-4	170/77
Acetone	190/88	Kerosene	170/77
Acetone, 50% water	212/100	Lactic acid	U
Acetophenone	140/60	Lead acetate	U
Allyl alcohol	220/104	Lead sulfate	150/66
Allyl chloride	U	Magnesium chloride	U
Aluminum chloride	U	Magnesium hydroxide	U
Ammonium nitrate	U	Magnesium sulfate	150/66
Arsenic acid	U	Mercuric chloride	U
Barium hydroxide	U	Methyl alcohol	150/66
Barium sulfide	U	Methyl ethyl ketone	150/66
Boric acid	130/54	Methyl isobutyl ketone	150/66
Butyric acid	U	Monochlorobenzene	U
Calcium bisulfite	U	Nickel nitrate	212/100
Calcium chloride	U	Nickel sulfate	212/100
Calcium hydroxide	U	Nitric acid	U
Calcium hypochlorite	U	Oleic acid	U
Carbon bisulfide	170/77	Oleum	80/27
Carbon dioxide, dry	170/77	Oxalic acid	U
Carbon dioxide, wet	180/82	Phenol	90/32
Carbonic acid	U	Phosphoric acid, to 80%	150/66
Chlorobenzene	150/66	Picric acid	U
Chloroform	140/60	Potassium carbonate	U
Chromic acid, 10–50%	212/100	Potassium cyanide	U
Citric acid	U	Potassium dichromate, to 30%	130/54
Copper sulfate	140/60	Potassium hydroxide	U
Cresylic acid	U	Potassium nitrate	80/27
Dichloroethane	150/66	Potassium permanganate	U
Ethyl acetate	212/100	Potassium sulfate, 10%	80/27
Ethyl chloride	150/66	Propane	80/27
Ferric chloride	U	Pyridine	100/38
Ferrous chloride	U	Salicylic acid	100/38
Fluorine gas	200/93	Silver nitrate	U
Formic acid, 10–85%	U	Sodium bicarbonate	80/27
Hydrobromic acid	U	Sodium bisulfate	90/32
Hydrochloric acid	U	Sodium bisulfite	90/32
Hydrocyanic acid	U	Sodium carbonate	U
Hydrofluoric acid, 70%	U	Sodium chloride, to 30%	212/100
Hydrofluoric acid, to 50%	100/38	Sodium cyanide	U
Hydrogen perioxide	U	Sodium hydroxide, 70%	120/149
Hydrogen sulfide, wet	U	Sodium hydroxide, to 50%	U

TABLE 10.5 (Continued)
Compatibility of Lead with Selected Corrodents

Corrodent	°F/°C	Corrodent	°F/°C
Sodium hypochlorite	U	Sulfite liquors	100/38
Sodium nitrate	U	Sulfur dioxide, dry	180/82
Sodium perborate	U	Sulfur dioxide, wet	160/71
Stannic chloride	U	Sulfuric acid, to 50%	212/100
Stannous chloride	U	Sulfuric acid, 60–70%	180/82
Stearic acid	U	Sulfuric acid, 80–100%	100/38

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by a U. When compatible, the corrosion rate is less than 20 mpy.

that of the steel substrate, contains 8 to 16% tin. Because the electrode potential of the coating layer is more noble than that of the steel substrate, it is necessary to build a uniform and dense alloy layer ($FeSn_2$) to form a pinhole-free deposit.

Terneplate exhibits excellent corrosion resistance, especially under wet conditions, as well as excellent weldability and formability, with only small amounts of corrosion products forming on the surface. A thin nickel deposit can be applied as an undercoat for the terne layer. Nickel reacts rapidly with the tin-lead alloy to form a nickel-tin alloy layer. This alloy provides good corrosion resistance and inhibits localized corrosion.

The main application for terneplate is in the production of fuel tanks for automobiles.

Gold Coatings

Gold deposits are primarily used to coat copper in electronic applications to protect the copper connectors and other copper components from corrosion. It is desirable to obtain the corrosion protection with the minimum thickness of gold because of the cost of the gold. As the thickness of the electrodeposit is decreased, there is a tendency for the deposit to provide inadequate coverage of the copper. For this reason, it is necessary that there be a means whereby the coverage of the copper can be determined. Such a test, using corrosion principles as a guide, has been developed. In a 0.1*M* NH_4Cl solution, gold serves as the cathode and copper serves as the anode. At a high cathode/anode surface area fraction, the corrosion potential is linearly related to the area fraction of copper exposed, as shown in Figure 10.7. By measuring the corrosion potential of the gold-plated copper in a 0.1*M* NH_4Cl solution, the area fraction of copper exposed is determined.

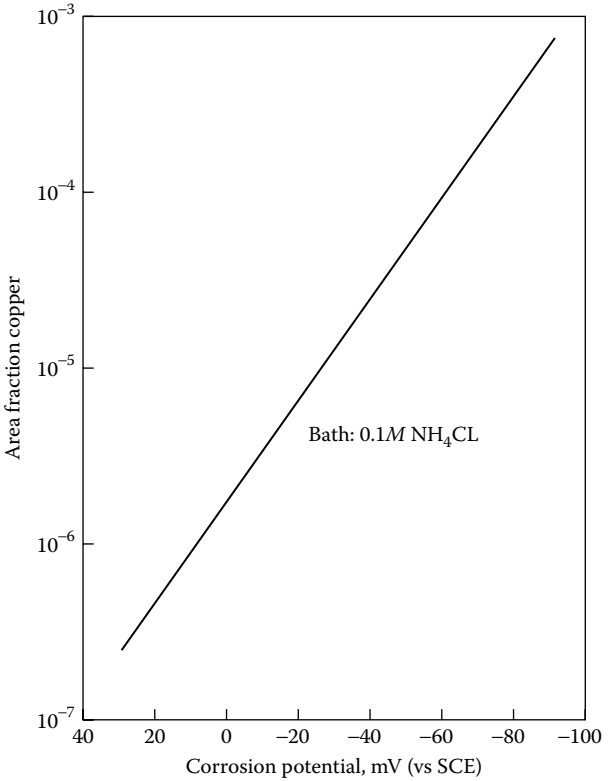


FIGURE 10.7 Data showing that the fractional exposed area of a copper/gold system is linearly related to the corrosion potential at low exposed copper areas.

Gold coatings can also be deposited by means of electroless plating. Borohydride and DMAB are used as reducers with a stable cyanide complex. Thin gold coatings can be deposited on plastics by an aerosol spray method using gold complexes with amines and hydrazine as the reducer. A relatively thick coat can be obtained.

Copper Coatings

Although copper is soft, it has many engineering applications in addition to its decorative function. One such application is the corrosion protection of steel. It can be used as an alternative to nickel to prevent fretting and scaling corrosion. Copper can be deposited electrochemically from various aqueous solutions. The properties of the deposit will depend on the chosen bath and the applied procedures. The hardness of the layers varies from 40 to 160 HV.

Because copper is very noble, it causes extreme galvanically induced local corrosion of steel and aluminum substrates. Because of this, extreme care must be taken to produce well-adhering nonporous layers.

The corrosion protection provided by a copper coating is twofold, consisting of an original barrier action of the coating layer and a secondary barrier action of corrosion products. The low EMF of copper is responsible for the formation of the original barrier action. The electrochemical reactions in the corrosion cells on copper are as follows:

Anodic reaction: $Cu \rightarrow Cu^{+} + e$

$Cu \rightarrow Cu^{2+} + 2e$

Cathodic reaction: $O_2 + H_2O \rightarrow 4e + 40H^{-}$

Chloride ions in a natural environment stabilize cuprous ions. Cupric ions are more stable. Because the EMF of corrosion on copper is less than that on iron, the reactivity of a steel surface is decreased by coating it with copper.

Over a period of time, corrosion products gradually build up a secondary layer against corrosion. Initially, a cuprous oxide layer is formed, followed by the copper surface covered with basic salts. Pollutants in the atmosphere determine the formation of basic copper salts as follows:

Mild atmosphere	Malachite: $CuCO_3$:CuH_2O
SO_X atmosphere	Brochanite: $CuSo_4$:$3Cu(OH)_2$
Chloride atmosphere	Atacamite: $CuCl_2$:$3Cu(OH)_2$

In most coastal areas, the amount of sulfates in the atmosphere exceeds the amount of chlorides. As a layer of copper grows on the surface of the corrosion product layer, the protective ability of the corrosion layer increases. As exposure time increases, the average corrosion rate of copper gradually decreases. After 20 years, the corrosion rate of copper is reduced to half the value of the first year as a result of the secondary barrier of corrosion products.

The initial corrosion rate of copper coating depends on atmospheric conditions such as time of wetness and type and amount of pollutants. Time of wetness is the most important factor affecting the corrosion rate of copper. The corrosion rate of copper usually obeys parabolic law:

$$M^2 = kt$$

where:

M = mass increase
k = a constant
t = exposure time

Accordingly, the average corrosion rate decreases with increased exposure time, which means that the surface of the copper is covered with basic salts by degrees and thereafter the corrosion rate approaches a constant value.

Copson[9] conducted 20-year exposure tests and found the average corrosion rate of copper as follows:

- 0.0034 mil/year in dry rural areas
- 0.143 mil/year in rural atmospheres
- 0.0476 to 0.515 mil/year in industrial atmospheres
- 0.0198 to 0.0562 mil/year in marine atmospheres

Until the base metal is exposed, the corrosion process of a copper-coated layer is similar to that of copper plate. Galvanic corrosion of copper-coated steel is induced when the steel substrate is exposed. However, in the case of copper-coated stainless steel, the occurrence of galvanic action depends on the composition of the stainless steel.

In chloride atmospheres, galvanic pitting takes place at the pores in the copper layers and galvanic tunneling at cut edges of types 409 and 430 stainless steels; whereas in SO_x atmospheres, uniform corrosion takes place on the copper coating.

Copper coatings are used both for decorative purposes and for corrosion protection from the atmosphere. Copper-coated steels are used as roofs, flashings, leaders, gutters, and architectural trim. Copper undercoats also improve the corrosion resistance of multilayered coatings, specifically in the plating of nickel and chromium.

Refer to Table 10.6 for the compatibility of copper with selected corrodents.

NONNOBLE COATINGS

The fact that the cathodic member in the galvanic couple remains free from corrosion is utilized to protect a structure or component by making it the cathode. This is accomplished by coupling the structure or coating it with a less-noble metal. The anode protects the structure by sacrificing its life through preferential dissolution — hence the name "sacrificial anode." A ship hull made of steel is protected by insertion of magnesium blocks in places. Such protection is referred to as galvanic protection.

Nonnoble metals protect the substrate by means of cathodic control. The cathodic overpotential of the surface is increased by a coating that makes the corrosion potential more negative than that of the substrate. The coating metals used for cathodic control protection include zinc, aluminum, manganese, and cadmium, and their alloys, of which the electrode potentials are more negative than those of iron and steel. Consequently, the coating layers of these metals act as sacrificial anodes for iron and steel substrates when the substrates are exposed to the atmospheres or corrodents. The coating layer provides cathodic protection for the substrate through galvanic action. These metals are called "sacrificial metals."

The electrical conductivity of the electrolyte, the temperature, and the surface condition determines the galvanic action of the sacrificial coating. An increase in the cathodic overpotential is responsible for the corrosion resistance of the coating layer. Figure 10.8 shows the principle of cathodic control protection by a sacrificial metal coating.

TABLE 10.6
Compatibility of Copper with Selected Corrodents

Chemical	°F/°C	Chemical	°F/°C
Acetaldehyde	x	Aniline	x
Acetamide		Antimony trichloride	80/27
Acetic acid, 10%	100/38	Aqua regia, 3:1	x
Acetic acid, 50%	x	Barium carbonate	80/27
Acetic acid, 80%	x	Barium chloride	80/27
Acetic acid, glacial	x	Barium hydroxide	80/27
Acetic anhydride	80/27	Barium sulfate	80/27
Acetone	140/60	Barium sulfide	x
Acetyl chloride	x	Benzaldehyde	80/27
Acrylonitrile	80/27	Benzene	100/38
Adipic acid	80/27	Benzoic acid, 10%	80/27
Allyl alcohol	90/32	Benzyl alcohol	80/27
Alum	90/32	Benzyl chloride	x
Aluminum acetate	60/16	Benzyl sulfonic acid, 10%	
Aluminum chloride, aq.	x	Borax	80/27
Aluminum chloride, dry	60/16	Boric acid	100/38
Aluminum fluoride	x	Bromine gas, dry	60/16
Aluminum hydroxide	90/32	Bromine gas, moist	x
Aluminum nitrate		Bromine liquid	
Aluminum oxychloride		Butadiene	80/27
Aluminum sulfate	80/27	Butyl acetate	80/27
Ammonia gas	x	Butyl alcohol	80/27
Ammonium bifluoride	x	Butyl phthalate	80/27
Ammonium carbonate	x	Butyric acid	60/16
Ammonium chloride, 10%	x	Calcium bisulfite	80/27
Ammonium chloride, 50%	x	Calcium carbonate	80/27
Ammonium chloride, sat.	x	Calcium chlorate	x
Ammonium fluoride, 10%	x	Calcium chloride	210/99
Ammonium fluoride, 25%	x	Calcium hydroxide, 10%	210/99
Ammonium hydroxide, 25%	x	Calcium hydroxide, sat.	210/99
Ammonium hydroxide, sat.	x	Calcium hypochlorite	x
Ammonium nitrate	x	Calcium nitrate	
Ammonium persulfate	90/32	Calcium sulfate	80/27
Ammonium phosphate	x	Caprylic acid	x
Ammonium sulfate, 10–40%	x	Carbon bisulfide	80/27
Ammonium sulfide	x	Carbon dioxide, dry	90/32
Ammonium sulfite	x	Carbon dioxide, wet	90/32
Amyl acetate	90/32	Carbon disulfide	80/27
Amyl alcohol	80/27	Carbon monoxide	
Amyl chloride	80/27	Carbon tetrachloride	210/99

(*continued*)

TABLE 10.6 (Continued)
Compatibility of Copper with Selected Corrodents

Chemical	°F/°C	Chemical	°F/°C
Carbonic acid	80/27	Hydrofluoric acid, 70%	x
Cellosolve	80/27	Hydrofluoric acid, 100%	x
Chloracetic acid	x	Hypochlorous acid	x
Chloracetic acid, 50% water	x	Iodine solution, 10%	
Chlorine gas, dry	210/99	Ketones, general	
Chlorine gas, wet	x	Lactic acid, 25%	
Chlorine, liquid		Lactic acid, conc.	90/32
Chlorobenzene	90/32	Magnesium chloride	300/149
Chloroform	80/27	Malic acid	x
Chlorosulfonic acid	x	Manganese chloride	x
Chromic acid, 10%	x	Methyl chloride	90/32
Chromic acid, 50%	x	Methyl ethyl ketone	80/27
Citric acid, 15%	210/99	Methyl isobutyl ketone	90/32
Citric acid, conc.	x	Muriatic acid	x
Copper acetate	90/32	Nitric acid, 20%	x
Copper carbonate	90/32	Nitric acid, 5%	x
Copper chloride	x	Nitric acid, 70%	x
Copper cyanide	x	Nitric acid, anhydrous	x
Copper sulfate	x	Nitrous acid, conc.	80/27
Cupric chloride, 5%	x	Oleum	
Cupric chloride, 50%		Perchloric acid, 10%	
Cyclohexane	80/27	Perchloric acid, 70%	
Cyclohexanol	80/27	Phenol	x
Dichloroethane		Phosphoric acid, 50–80%	x
Ethylene glycol	100/38	Picric acid	x
Ferric chloride	80/27	Potassium bromide, 30%	80/27
Ferric chloride, 50% in water	x	Salicylic acid	90/32
Ferric nitrate, 10–15%	x	Silver bromide, 10%	x
Ferrous chloride		Sodium carbonate	120/49
Ferrous nitrate		Sodium chloride, to 30%	210/99
Fluorine gas, dry	x	Sodium hydroxide, 10%	210/99
Fluorine gas, moist	x	Sodium hydroxide, 50%	x
Hydrobromic acid, 20%	x	Sodium hydroxide, conc.	x
Hydrobromic acid, 50%	x	Sodium hypochlorite, 20%	x
Hydrobromic acid, dilute	x	Sodium hypochlorite, conc.	x
Hydrochloric acid, 20%	x	Sodium sulfide, to 50%	x
Hydrochloric acid, 38%	x	Stannic chloride	x
Hydrocyanic acid, 10%	x		
Hydrofluoric acid, 30%	x		

TABLE 10.6 (Continued)
Compatibility of Copper with Selected Corrodents

Chemical	°F/°C	Chemical	°F/°C
Stannous chloride	x		
Sulfuric acid, 10%	x		
Sulfuric acid, 50%	x		
Sulfuric acid, 70%	x		
Sulfuric acid, 90%	x		
Sulfuric acid, 98%	x		
Sulfuric acid, 100%	x		
Sulfuric acid, fuming	x		
Sulfurous acid	x		
Toluene	210/99		
Trichloroacetic acid	80/27		
Zinc chloride	x		

Note: The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an x. A blank space indicates that the data is unavailable. When compatible, the corrosion rate is <20 mpy.

Source: P.A. Schweitzer, *Corrosion Resistance Tables, 4th ed.,* Vols. 1–3, Marcel Dekker, New York, 1995.

The corrosion rate of zinc-coated iron $i_{corr.}$ of the zinc coating becomes lower than that of uncoated iron $i_{corr.}$ of uncoated iron because the cathodic overpotential of the surface is increased by zinc coating, and the exchange current density of dissolved oxygen on zinc $i_{oc\ on\ zinc}$ is lower than that on iron $i_{oc\ on\ iron}$.

If a small part of the iron is exposed to the atmosphere, the electrode potential of the exposed iron is equal to the corrosion potential of zinc $E_{corr.\ of\ zinc\ coating}$ because the exposed iron is polarized cathodically by the surrounding zinc, so that little corrosion occurs on the exposed iron $i_{corr.\ of\ exposed\ iron}$. Zinc ions dissolved predominately from the zinc coating form the surrounding barrier of corrosion products at the defect, thereby protecting the exposed iron.

Sacrificial metal coatings protect iron and steel by two or three protective abilities, to include:

1. Original barrier action of the coating layer
2. Secondary barrier action of the corrosion product layer
3. Galvanic action of the coating layer

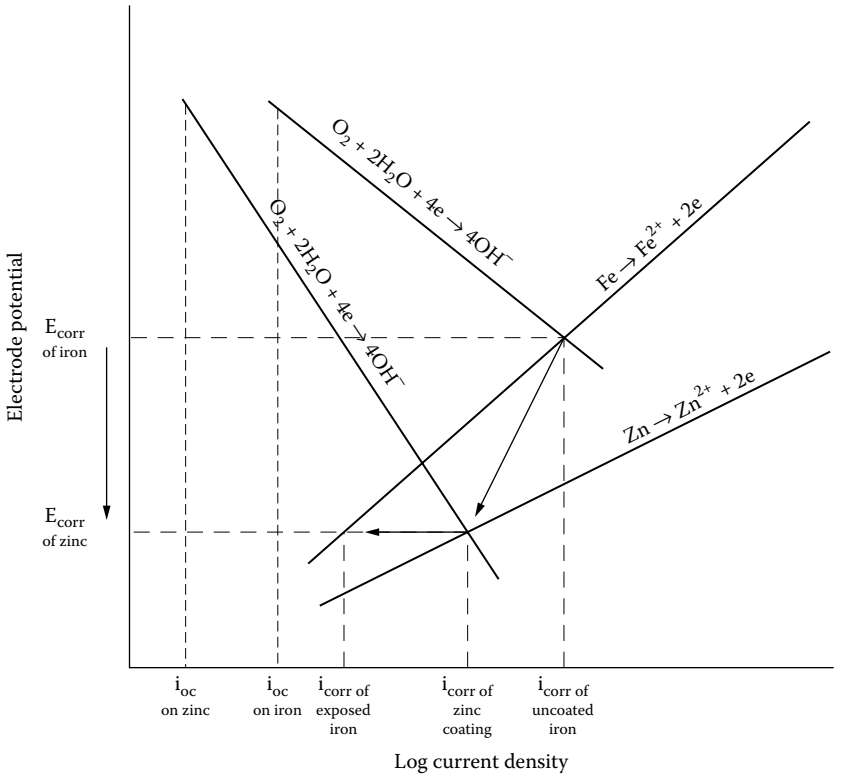


FIGURE 10.8 Cathodic control protection.

The surface oxide film and the electrochemical properties based on the metallography of the coating material provide the original barrier action.

An air-formed film of $A1_2O_3$ approximately 25 Å thick forms on aluminum. This film is chemically inert and its rapid formation of an oxide film by a self-healing ability leads to satisfactory performance in natural environments.

Zinc, however, does not produce a surface oxide film that is as effective a barrier as the oxide film on aluminum. The original barriers of zinc and zinc alloy coatings result from electrochemical properties based on the structure of the coating layer.

Nonuniformity of the surface condition generally induces the formation of a corrosion cell. Such nonuniformity results from defects in the surface oxide film, localized distribution of the elements, and the difference in crystal face or phase. These surface nonuniformities cause the potential difference between portions of the surface, thereby promoting the formation of a corrosion cell.

Most corrosion cells form on the surface, thus accelerating the corrosion rate, as a sacrificial metal and its alloy-coated materials are exposed in the natural

TABLE 10.7
Corrosion Products Formed on Various Sacrificial Metal Coatings

Metal	Corrosion Product
Al	Al_2O_3, β-$Al_2O_3 \cdot 3H_2O$, α-AlOOH, $Al(OH)_3$, amorphous Al_2O_3
Zn	ZnO, $Zn(OH)_2$, $2ZnCO_3 \cdot 3Zn(OH)_2$, $ZnSO_4 \cdot 4Zn(OH)_2$, $ZnC1_2 \cdot 4Zn(OH)_2$, $ZnCl_2 \cdot 6Zn(OH)_2$
Mn	γ-Mn_2O_3, $MnCO_3$, γ-MnOOH
Cd	CdO, $CdOH_2$, $2CdCO_3 \cdot 3Cd(OH)_2$

atmosphere. During this time, corrosion products are gradually formed and converted to a stable layer after a few months of exposure. Typical corrosion products formed are shown in Table 10.7. Once the stable layer has formed, the corrosion rate becomes constant. This secondary barrier of corrosion protection regenerates continuously over a long period of time. In most cases, the service life of a sacrificial metal coating depends on the secondary barrier action of the corrosion product layer.

Sacrificial metal coatings are characterized by their galvanic action. Exposure of the base metal, as a result of mechanical damage, polarizes the base metal cathodically to the corrosion potential of the coating layer, as shown in Figure 10.8, so that little corrosion takes place on the exposed base metal. A galvanic couple forms between the exposed part of the base metal and the surrounding coating metal. Because sacrificial metals are more negative in electrochemical potential than iron or steel, a sacrificial metal acts as an anode and the exposed base metal behaves as a cathode. Table 10.8 shows the corrosion potentials of sacrificial metals and steel in a 3% NaCl solution. Consequently, the dissolution of the

TABLE 10.8
Corrosion Potentials of Sacrificial Metals in a 3% NaCl Solution

Metal	Corrosion Potential (V, SCE)
Mn	−1.50
Zn	−1.03
Al	−0.79
Cd	−0.70
. . . . .	
Steel	−0.61

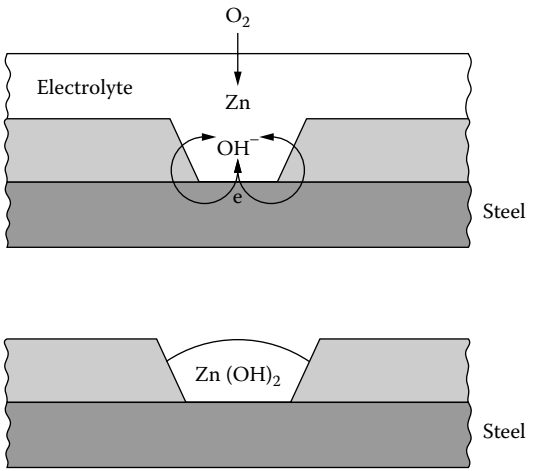


FIGURE 10.9 Schematic illustration of the galvanic action of sacrificial metal coating.

coating layer around the defect accelerates and the exposed part of the base metal protects against corrosion. Figure 10.9 shows a schematic illustration of the galvanic action of a sacrificial metal coating.

The loss of metal coating resulting from corrosion determines the life of the coating. The degree of loss depends on the time of wetness on the metal surface, and the type and concentration of pollutants in the atmosphere. Table 10.9 shows the average corrosion losses of zinc, aluminum, and 55% Al-Zn coatings in various locations and atmospheres. The losses were calculated from the mean values of time of wetness and the average corrosion rate during wet duration. The time of wetness of walls is 40% of that of roofs. Coating metals and coating thickness can be decided from Table 10.9 because the corrosion losses of zinc, aluminum, and Al-Zn alloy are proportional to exposure time.

As seen from Table 10.9, a G90 sheet, which has a 1-mil zinc coating, cannot be used for a roof having a durability of 10 years in any atmosphere except in a rural area. Were this sheet to be used in an urban, marine, or industrial atmosphere, it would have to be painted for protection.

Aluminum and 55% Al-Zn alloy provide galvanic protection for the steel substrate. In rural and industrial atmospheres, an aluminum coating does not act as a sacrificial anode. However, in a chloride atmosphere, such as a marine area, it does act as a sacrificial anode.

The choice as to which sacrificial metal coating to use will be based on the environment to which it will be exposed and the service life required. The service life required will also determine the coating thickness to be applied, which in turn will influence the coating process to use. Sacrificial metal coatings have been used successfully for roofs, walls, shutters, doors, and window frames in the

TABLE 10.9
Average Corrosion Loss of Sacrificial Metal Coatings

		Average Corrosion Loss (mil[a]/10 yr)					
		Zinc		50% Al-Zn		Aluminum	
Location	Atmosphere	Roof	Wall	Roof	Wall	Roof	Wall
Inland	Rural	0.42	0.17	0.15	0.06	0.06	0.02
	Urban	1.48	0.59				
	Industrial	1.40	0.56	0.25	0.06	0.06	0.02
	Severe industrial	1.59	0.64				
Inland shore of lake or marsh	Rural	0.59	0.24	0.20	0.08	0.07	0.03
	Urban	1.97	0.79				
	Industrial	1.40	0.56	0.20	0.08	0.08	0.03
	Severe industrial	2.12	0.85				
Coast	Rural	0.74	0.23	0.25	0.10	0.08	0.04
	Urban	2.47	0.99				
	Industrial	1.75	0.70	0.25	0.10	0.10	0.04
	Severe industrial	2.65	1.06				
Seashore	Severe industrial	2.06	0.82	0.46	0.18	0.19	0.07

[a] 1 mil = 25.4 μm.

Source: Ref. 2.

housing industry, and on structural materials such as transmission towers, structural members of a bridge, antennae, chimney structures, grandstands, steel frames, high-strength steel bolts, guardrails, corrugated steel pipe, stadium seats, bridge I-beams, footway bridges, road bridges, and fencing.

Zinc Coatings

Approximately half of the world's production of zinc is used to protect steel from rust. Zinc coatings are probably the most important type of metallic coating for corrosion protection of steel. The reasons for this wide application include:

1. Prices are relatively low.
2. Due to large reserves, an ample supply of zinc is available.
3. There is great flexibility in application procedures, resulting in many different qualities with well-controlled layer thicknesses.
4. Steel provides good cathodic protection.
5. Many special alloy systems have been developed with improved corrosion-protection properties.

The ability to select a particular alloy or to specify a particular thickness of coating depends on the type of coating process used. Zinc coatings can be applied in many ways. The six most commonly used procedures are:

1. Hot dipping
2. Zinc electroplating
3. Mechanical coating
4. Sherardising
5. Thermally sprayed coatings
6. Zinc dust painting

Corrosion of Zinc Coatings

Depending on the nature of the environment, zinc has the ability to form a protective layer made up of basic carbonates, oxides, or hydrated sulfates. Once the protective layers have formed, corrosion proceeds at a greatly reduced rate. Consideration of the corrosion of zinc is primarily related to the slow dissolution from the surface. Even with a considerable moisture content, air is only slightly corrosive to zinc. Below 390°F (200°C), the film grows very slowly and is very adherent. Zinc-coated steel behaves similarly to pure zinc.

The pH of the environment governs the formation and maintenance of the protective film. Within the pH range of 6 to 12.5, the corrosion rate is low. Corrosive attack is most severe at pH values below 6 and above 12.5.

Uniform corrosion rates of zinc are not appreciably affected by the purity of the zinc. However, the addition of some alloying elements can increase the corrosion resistance of zinc.

In general, zinc coatings corrode in a similar manner as solid zinc. However, there are some differences. For example, the iron-zinc alloy present in most galvanized coatings has a higher corrosion resistance than solid zinc in neutral and acid solutions. At points where the zinc coating is defective, the bare steel is protected, under most conditions, cathodically.

There is an approximately linear relationship between weight loss and time of zinc coatings in air. Because the protective film on zinc increases with time in rural and marine atmospheres of some types, under these conditions the life of zinc may increase more than in proportion to thickness. However, this does not always happen.

Zinc coatings are used primarily to protect ferrous parts against atmospheric corrosion. These coatings have good resistance to abrasion caused by solid pollutants in the atmosphere. General points to consider include the facts that:

1. Corrosion increases with time of wetness.
2. The corrosion rate increases with an increase in the amount of sulfur compounds in the atmosphere. (Chlorides and nitrogen oxides usually have a lesser effect but are often very significant in combination with sulfate.)

Zinc coatings resist atmospheric corrosion by forming protective films consisting of basic salts, notably carbonate. The most widely accepted formula is $3Zn(OH)_2 \cdot 2ZnCO_3$.

Environmental conditions that prevent the formation of such films, or the conditions that lead to the formation of soluble films, may cause rapid attack on the zinc.

The duration and frequency of moisture contact is one such factor. Another factor is the rate of drying, because a thin film of moisture with high oxygen concentration promotes reaction. For normal exposure conditions, the films dry quite rapidly. It is only in sheltered areas that drying times are slow, so that the attack on zinc is accelerated significantly.

The effect of atmospheric humidity on the corrosion of a zinc coating is related to the conditions that may cause condensation of moisture on the metal surface and the frequency and duration of the moisture contact. If the air temperature drops below the dewpoint, moisture will be deposited. The thickness of the piece, its surface roughness, and its cleanliness also influence the amount of dew deposited. Lowering the temperature of the metal surface below the air temperature in a humid atmosphere will cause moisture to condense on the metal. If the water evaporates quickly, corrosion is usually not severe and a protective film is formed on the surface. If the water from rain or snow remains in contact with zinc when access to air is restricted and the humidity is high, the resulting corrosion can appear to be severe because the formation of a protective zinc carbonate is prevented. (See white rust following.)

In areas having atmospheric pollutants, particularly sulfur oxides and other acid-forming pollutants, the time of wetness becomes of secondary importance. The pollutants can also make rain more acid. However, in less corrosive areas, time of wetness assumes a greater proportional significance.

In the atmospheric corrosion of zinc, the most important atmospheric contaminant to consider is sulfur dioxide. At relative humidities of about 70% or above, it usually controls the corrosion rate.

Sulfur dioxide and other corrosive species react with the zinc coating in two ways: (1) dry deposition and (2) wet deposition. Sulfur dioxide can deposit on a dry surface of galvanized steel panels until a monolayer of SO_2 is formed. In either case, the sulfur dioxide that deposits on the surface of the zinc forms a sulfurous or other strong acid, which reacts with the film of zinc oxide, hydroxide, or basic carbonate to form zinc sulfate. The conversion of sulfur dioxide to sulfur-based acids can be catalyzed by nitrogen compounds in the air (i.e., NO_X compounds). This factor can affect corrosion rates in practice. The acids partially destroy the film of corrosion products, which will then reform from the underlying metal, thereby causing continuous corrosion by an amount equivalent to the film dissolved, and hence the amount of SO_2 absorbed.

Chloride compounds have a lesser effect than sulfur compounds in determining the corrosion rate of zinc. Chloride is most harmful when combined with acidity due to sulfur gases. This is prevalent on the coast in highly industrial areas.

Atmospheric chlorides will lead to the corrosion of zinc, but to a lesser degree than the corrosion of steel, except in brackish water and flowing seawater. Any salt deposit should be removed by washing. The salt content of the atmosphere will usually decrease rapidly inland, further away from the coast. Corrosion also decreases with distance from the coast, but the change is more gradual and erratic because chloride is not the primary pollutant affecting zinc corrosion. Chloride is most harmful when combined with acidity resulting from sulfur gases.[10]

Other pollutants also have an effect on the corrosion of galvanized surfaces. Deposits of soot or dust can be detrimental because they have the potential to increase the risk of condensation onto the surface and hold more water in position. This is prevalent on upward-facing surfaces. Soot (carbon) absorbs large quantities of sulfur, which is released by rainwater.

In rural areas, over-manuring of agricultural land tends to increase the ammonia content of the air. The presence of normal atmospheric quantities of ammonia does not accelerate zinc corrosion, and petrochemical plants where ammonium salts are present show no accelerated attack on galvanized steel. However, ammonia will react with atmospheric sulfur oxides, producing ammonium sulfate, which accelerates paint film corrosion as well as zinc corrosion. When ammonium reacts with NO_X^- compounds in the atmosphere, ammonium nitrite and nitrate are produced. Both compounds increase the rate of zinc corrosion, but less than SO_2 or SO_3.

Because of the Mears effect (wire corrodes faster per unit of area than more massive materials), galvanized wire corrodes some 10 to 80% faster than galvanized steel. However, the life of rope made from galvanized steel wires is greater than the life of the individual wire. This is explained by the fact that the parts of the wire that lie on the outside are corroded more rapidly; and when the zinc film is penetrated in those regions, the uncorroded zinc inside the rope provides cathodic protection for the outer regions.

Table 10.10 lists the compatibility of galvanized steel with selected corrodents.

White Rust (Wet Storage Stain)

"White rust" is a form of general corrosion that is not protective. It is more properly called *wet storage stain* because it occurs in storage where water is present, but only a limited supply of oxygen and carbon dioxide is available. Wet storage stain formation will be accelerated by the presence of chlorides and sulfates. White rust is a white, crumbly, and porous coating consisting of $2ZnCO_3 \cdot 3Zn(OH)_2$. The surface underneath the white products is often dark gray.

This coating is frequently found on newly galvanized bright surfaces, particularly in crevices between closely packed sheets whose surfaces have come into contact with condensate or rainwater and the moisture cannot dry up quickly. If the zinc surfaces have already formed a protective film prior to storage, the chances are that no attack will take place.

TABLE 10.10
Compatibility of Galvanized Steel with Selected Corrodents

Acetic acid	U	Chlorine water	U
Acetone	G	Chromium chloride	U
Acetonitrile	G	Chromium sulfate solution	U
Acrylic latex	U	Copper chloride solution	U
Acrylonitrile	G	Decyl acrylate	G
Aluminum chloride, 26%	U	Diamylamine	G
Aluminum hydroxide	U	Dibutyl cellosolve	G
Aluminum nitrate	U	Dibutyl phthalate	G
Ammonia, dry vapor	U	Dibutylamine	G
Ammonium acetate solution	U	Dichloroethyl ether	G
Ammonium bisulfate	U	Diethylene glycol	G
Ammonium bromide	U	Dipropylene glycol	G
Ammonium carbonate	U	Ethanol	G
Ammonium chloride, 10%	U	Ethyl acetate	G
Ammonium dichloride	U	Ethyl acrylate	G
Ammonium hydroxide		Ethyl amine, 69%	G
Vapor	U	2-Ethyl butyric acid	G
Reagent	U	Ethyl ether	G
Ammonium molybdate	G	Ethyl hexanol	G
Ammonium nitrate	U	Fluorine, dry, pure	G
Argon	G	Formaldehyde	G
Barium hydroxide		Fruit juices	S
Barium nitrate solution	S	Hexanol	G
Barium sulfate solution	S	Hexylamine	G
Beeswax	U	Hexylene glycol	G
Borax	S	Hydrochloric acid	U
Bromine moist	U	Hydrogen peroxide	S
2-Butanol	G	Iodine, gas	U
Butyl acetate	G	Isohexanol	G
Butyl chloride	G	Isooctanol	G
Butyl ether	G	Isopropyl ether	G
Butylphenol	G	Lead sulfate	U
Cadmium chloride solution	U	Lead sulfite	S
Cadmium nitrate solution	U	Magnesium carbonate	S
Cadmium sulfate solution	U	Magnesium chloride	U
Calcium hydroxide		Magnesium fluoride	G
Sat. solution	U	Magnesium hydroxide, sat.	S
20% Solution	S	Magnesium sulfate	
Calcium sulfate, sat. solution	U	2% solution	S
Cellosolve acetate	G	10% solution	U
Chloric acid, 20%	U	Methyl amyl alcohol	G
Chlorine, dry	G	Methyl ethyl ketone	G

(*continued*)

TABLE 10.10 (Continued)
Compatibility of Galvanized Steel with Selected Corrodents

Methyl isobutyl ketone	G	Potassium peroxide	U
Methyl propyl ketone	G	Potassium persulfate, 10%	U
N-Ethyl butylamine	G	Propionaldehyde	G
Nickel ammonium sulfate	U	Propionic acid	U
Nickel chloride	U	Propyl acetate	G
Nickel sulfite	S	Propylene glycol	G
Nitric acid	U	Silver bromide	U
Nitrogen, dry, pure	G	Silver chloride	
Nonylphenol	G	Pure, dry	S
Oxygen		Moist, wet	U
Dry, pure	G	Silver nitrate solution	U
Moist	U	Sodium acetate	S
Paraldehyde	G	Sodium aluminum sulfate	U
Perchloric acid solution	S	Sodium bicarbonate solution	U
Permanganate solution	S	Sodium bisulfate	U
Peroxide		Sodium carbonate solution	U
Pure, dry	S	Sodium chloride solution	U
Moist	U	Sodium hydroxide solution	U
Phosphoric acid, 0.3–3%	G	Sodium nitrate solution	U
Polyvinyl acetate latex	U	Sodium sulfate solution	U
Potassium bichromate		Sodium sulfide	U
14.7%	G	Sodium sulfite	U
20%	S	Styrene monomeric	G
Potassium carbonate		Styrene oxide	G
10% solution	U	Tetraethylene glycol	G
50% solution	U	1,1,2-Trichloroethane	G
Potassium chloride solution	U	1,2,3-Trichloropropane	G
Potassium disulfate	S	Vinyl acetate	G
Potassium fluoride, 5–20%	G	Vinyl butyl ether	G
Potassium hydroxide	U	Vinyl ethyl ether	G
Potassium nitrate		Water	
5–10% solution	S	Potable, hard	G

Note: G = Suitable application; S = Borderline application; U = Not suitable.

Short-term protection against wet storage staining can be provided by chromating or phosphating. Painting after galvanizing will also provide protection.

Materials stored outdoors should be arranged so that all surfaces are well ventilated and water can easily run off of the surfaces. If possible, new zinc surfaces should not be allowed to come into contact with rain or condensate water during transit or storage. This is the best way of preventing wet storage staining. Figure 10.10 illustrates the stacking of galvanized parts out of doors.

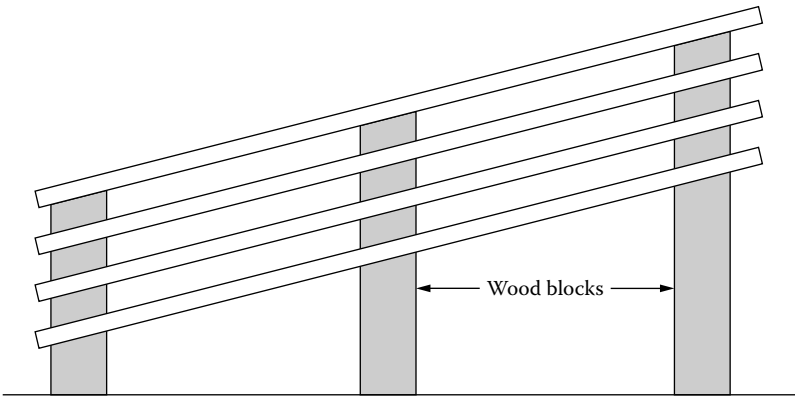


FIGURE 10.10 Stacking of galvanized parts out of doors.

Intergranular Corrosion

If pure zinc-aluminum alloys are exposed to temperatures in excess of 160°F (70°C) under wet or damp conditions, intergranular corrosion might take place. The use of these alloys should be restricted to temperatures below 160°F (170°C) and impurities controlled to specific limits of 0.006% each for lead and cadmium and 0.003% for tin.

Corrosion Fatigue

Galvanized coatings can stop corrosion fatigue by preventing contact of the corrosive substances with the base metal. Zinc, which is anodic to the base metal, provides electrochemical protection after mechanical protection has ceased.

Stress Corrosion

Zinc or zinc-coated steels are not usually subjected to stress corrosion. Zinc can also prevent stress corrosion cracking in other metals.

Zinc-5% Aluminum Hot Dip Coatings

This zinc alloy coating is known as Galfan. Galfan coatings have a corrosion resistance up to three times that of galvanized steel. The main difference between these two coatings lies in the degree of cathodic protection they afford. This increase in corrosion protection is evident in both relatively mild urban industrial atmospheres and marine atmospheres, as can be seen in Table 10.11. The latter is particularly significant because, unlike galvanizing, the corrosion rate appears

TABLE 10.11
Five-Year Outdoor Exposure Results of Galfan Coating

Atmosphere	Thickness Loss (μm)		Ratio of Improvement
	Galvanized	Galfan	
Industrial	15.0	5.2	2.9
Severe marine	>20.0	9.5	>2.1
Marine	12.5	7.5	1.7
Rural	10.5	3.0	3.5

Source: Ref. 4.

to be slowing after about 4 years, and conventional galvanized steel would show rust in 5 years (see Figure 10.11). The slower rate of corrosion also means that the zinc-5% aluminum coating provides full cathodic protection to cut edges over a longer period of time.

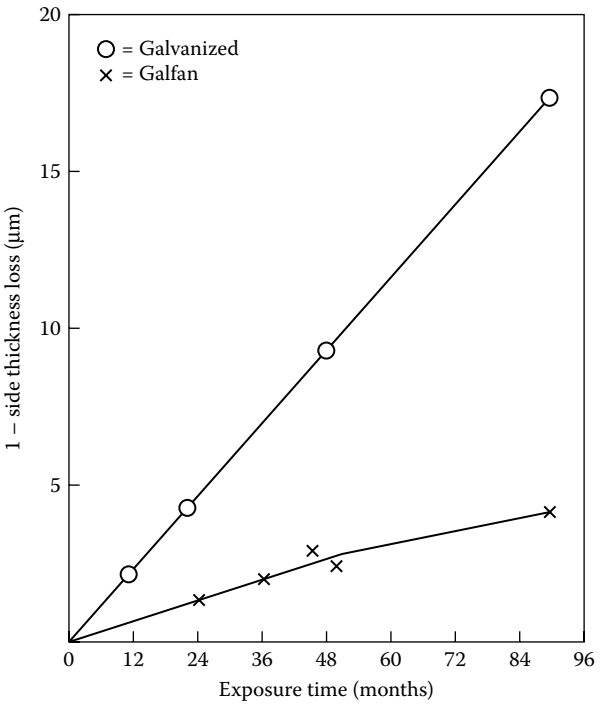


FIGURE 10.11 Seven-year exposure of Galfan and galvanized steel in a severe marine atmosphere.

TABLE 10.12
Comparison of Cathodic Protection for Galfan and Galvanized Coatings

	Amount (mm) of Bare Edge Exposed after 3 Years (coating recession from edge)	
Environment	**Galvanized**	**Galfan**
Severe marine	1.6	0.1
Marine	0.5	0.06
Industrial	0.5	0.05
Rural	0.1	0

Source: Ref. 11.

Refer to Table 10.12. Because Galfan can be formed with much smaller cracks than can be obtained in conventional galvanized coatings, it provides excellent protection at panel bulges. This reduced cracking means that less zinc is exposed to the environment, which increases the relative performance factor compared with galvanized steel.

Zinc-55% Aluminum Hot Dip Coatings

These coatings are known as Galvalume and consist of zinc-55% aluminum-1.5% silicon. This alloy is sold under such tradenames as Zaluite, Aluzene, Alugalva, Algafort, Aluzinc, and Zincalume. Galvalume exhibits superior corrosion resistance over galvanized coatings in rural, industrial, marine, and severe marine environments. However, this alloy has limited cathodic protection and less resistance to some alkaline conditions, and is subject to weathering, discoloration, and wet storage staining. The latter two disadvantages can be overcome by chromate passivation, which also improves its atmospheric corrosion resistance.

Initially, a relatively high corrosion rate is observed for Galvalume sheet as the zinc-rich portion of the coating corrodes and provides sacrificial protection at cut edges. This takes place in all environments, whereas aluminum provides adequate galvanic protection only in marine chloride environments. After approximately 3 years, the corrosion–time curve takes a more gradual slope, reflecting a change from active, zinc-like behavior to passive, aluminum-like behavior as the interdentric regions fill with corrosion products. It has been predicted that Galvalume sheets should outlast galvanized sheets of equivalent thickness by at least two to four times over a wide range of environments. A comparison of the corrosion performance of galvanized sheet and Galvalume sheet is depicted in Figure 10.12.

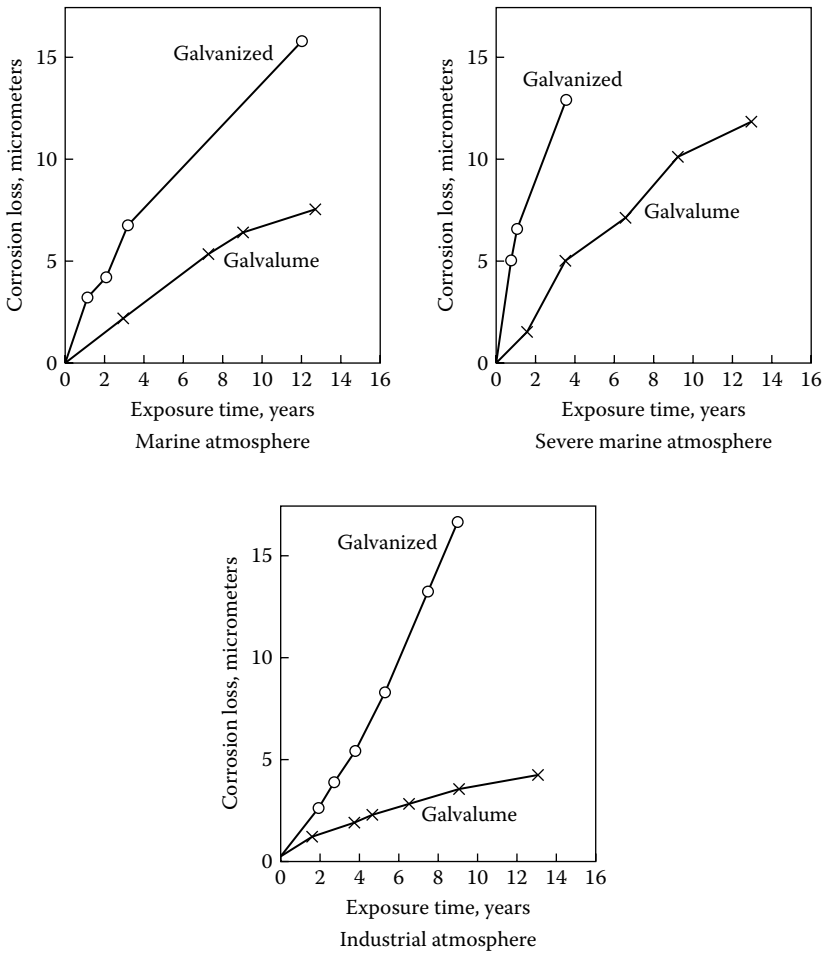


FIGURE 10.12 Thirteen-year exposure of Galvalume in marine and industrial atmospheres.

Galvalume sheets provide excellent cut-edge protection in very aggressive conditions, where the surface does not remain too passive. However, it does not offer as good a protection on the thicker sheets in mild rural conditions, where zinc-5% aluminum coatings provide good general corrosion resistance; and when sheared edges are exposed or localized damage to the coating occurs during fabrication or service, the galvanic protection is retained for a longer time period.

Zinc-15% Aluminum Thermal Spray

Zinc-15% aluminum coatings are available as thermally sprayed coatings. These coatings have a two-phase structure consisting of a zinc-rich phase and an aluminum-rich phase. The oxidation products formed are encapsulated in the

porous layer by the latter and do not build up a continuous surface layer as with pure zinc coatings. As a result, no thickness or weight loss is observed even after seven years of exposure in atmospheric field testing.

It is normally recommended that thermally sprayed coatings be sealed to avoid initial rust stains, to improve appearance, and to facilitate maintenance painting. Sealing is designed to fill pores and give only a thin overall coating, too thin to be directly measurable. Epoxy or acrylic system resin, having a low viscosity, is used as a sealer.

Zinc-Iron Alloy Coatings

As compared with pure zinc, the zinc-iron alloy coatings provide increased corrosion resistance in acid atmospheres but slightly reduced corrosion resistance in alkaline atmospheres.

Electroplated zinc-iron alloy layers containing more than 20% iron provide a corrosion resistance 30% higher than zinc in industrial atmospheres. In other atmospheres, the zinc-iron galvanized coatings provide as good a coating as coatings with an outer layer of zinc. Sherardised coatings are superior to electroplated coatings and equal to galvanized coatings of the same thickness. However, the structure of the outer layer and its composition affects the corrosion resistance.

If the zinc layer of a galvanized coating has weathered, or the zinc-iron alloy layer forms the top layer after galvanizing, brown areas may form. Brown staining can occur on sherardised or hot-dip galvanized coatings in atmospheric corrosion through the oxidation of iron from the zinc-iron alloy layers, or from the substrate. Such staining is usually a dull brown, rather than the bright red-brown of uncontrolled rust. Usually, there is a substantial, intact galvanized layer underneath, leaving the life of the coating unchanged. Unless the aesthetic appearance is undesirable, no action need be taken.

Aluminum Coatings

Aluminum coatings protect steel substrates by means of cathodic control, with an original barrier action of an air-formed film that is chemically inert, and the rapid formation of oxide film by a self-healing ability. Aluminum coatings are excellent in general corrosion resistance. However, they do not act as a sacrificial anode in rural and industrial atmospheres, but do so in a chloride area such as a marine environment. In a nonchloride environment, the formation of red rust occurs at sheared edges and in other defects of an aluminum coating layer. However, the growth of red rust is slow.

Aluminum coatings sealed with organic or composite layers such as etch primer, zinc chromate, etc. will provide long service in seawater environments. The recommended coating thickness plus sealing for the splash zone and submerged zone is 150 μm.

The melting point of aluminum, 1216°F (658°C), is higher than that of zinc, so that aluminum and steel substrate are readily oxidized in the atmosphere of

an aluminum bath. The protection of aluminum and steel against oxidation and the fluxing of aluminum oxide are important techniques. Aluminizing methods are characterized by their protection processes of steel substrate against oxidation before hot dipping. In general, the pretreatment system is as follows:

- Degreasing by alkali cleaning or by heating at 842 to 1112°F (450 to 600°C), water rinsing, pickling, water rinsing
- Activating (hydrogen gas) or fluxing, hot dipping, regulating coating thickness, cooling with air or water

As described above, the temperature of the aluminum bath is high so that steel reacts rapidly with molten aluminum, and a thicker iron-aluminum intermetallic layer grows as compared with hot-dip galvanized steel.

The intermetallic layer consists of an eta phase (Al_5Fe_2) and an alpha phase (20 to 30% Al-Fe alloy). The eta phase is very hard and brittle; therefore, severe working tends to cause peeling and cracking in the coating layer.

In general, aluminized steels are classified to type 1 and type 2. Type 1 aluminized steel is produced in an aluminum bath to which 5 to 10% silicon is added to minimize the intermetallic layer. The coating layer formed by the addition of silicon consists of an Al-Fe-Si intermetallic layer (3 to 4 μm) and an Al-Si layer, so that its formability is improved. Type 1 aluminized steel provides excellent corrosion resistance. Because an Al_2O_3 layer on the surface exhibits excellent heat resistance, aluminized steel has been used for heating and automobile exhaust systems, etc. For the purpose of heat resistance, another type of aluminized steel (alma-Ti) has been developed. This product is produced by the addition of titanium to steel substrate, and thereby the formation of voids in the coating layer is inhibited even at the temperatures above 1292°F (700°C).

Cadmium Coatings

Cadmium coatings are produced almost exclusively by electrodeposition. A cadmium coating on steel does not provide as much cathodic protection to the steel as does a zinc coating because the potential between cadmium and iron is not as great as between zinc and iron. Therefore, it becomes important to minimize defects in the cadmium coating.

Unlike zinc, a cadmium coating will retain a bright metallic appearance. It is more resistant to attack by salt spray and atmospheric condensate than zinc. In aqueous solutions, cadmium will resist attack by strong alkalies but will be corroded by dilute acids and aqueous ammonia.

Cadmium coatings should not be allowed to come in contact with food products because cadmium salts are toxic. This coating is commonly used on nuts and bolts; but because of its toxicity, usage is declining.

Manganese Coatings

Manganese is very active, having an electrode potential more negative than zinc (Mn, −1.5 V; Zn, −1.03 V, SCE). In a natural atmosphere, a dense corrosion layer builds on the surface of manganese, thereby shortening the life of the coating. Therefore, manganese is combined with zinc to form a duplex Mn/Zn alloy coating. The types of corrosion products found on these coatings are shown in Table 10.7. The compound γ-Mn_2O_3 is effective for the formation of a barrier. The more γ-Mn_2O_3 in the corrosion products, the more dense the layer on an Mn/Zn coating.

Manganese is so negative in electrochemical potential, and active, that its alloy and duplex coatings provide galvanic protection. An Mn/Zn alloy coating exhibits high corrosion resistance, and the corrosion potential of manganese is more negative than that of zinc; therefore, this alloy coating provides cathodic protection for a steel substrate. The structure on Mn/Zn alloy coatings is composed of the single phase of ε in the manganese content range less than 20%, and ε and γ phases in the range above 20%. As the manganese content in the deposit increases, the percentage of the γ-Mn phase increases.

REFERENCES

1. Evans, D.R., in *Coatings and Surface Treatment for Corrosion and Wear Resistance* (K.N. Strafford, P.K. Datta, and C.G. Googan, Eds.), Ellis Horwood Limited, 1984, p. 94.
2. Tower, B., *Flame Deposition,* The British Standards Institution and the Council of Engineering Institutions, Oxford University Press, England, 1978, p. 3.
3. *Zinc Handbook,* Japan Lead Zinc Development Association, 1977, p. 8.
4. Schiller, S., *7th International Conference on Vacuum Metallurgy,* Tokyo, 1982.
5. Pradel, G. and Buckwald, E., *New Huhe,* 28(2), 54, 1983.
6. Maeda, M., Ito, T., Umeda, S., Morita, A., Tsuji, N., Aiko, T., Kittaka, T., Hashimoto, K., Furukawa, H., and Yanagi, K., *TETSU-TO-HAGANE,* 72, 1070, 1986.
7. Azzerri, N. and Bando, G., *Br. Corros. J.,* 10, 28, 1975.
8. Product Information on Packaging Steel, Hoogovens Ijmuiden, 1990.
9. Copson, H.R., Report of Subcommittee VI of Committee B-3 on Atmospheric Corrosion of Nonferrous Metals, *ASTM Annual Meeting,* Atlantic City, NJ, June 25, 1955.
10. Schweitzer, Philip A., *Atmospheric Degradation and Corrosion Control,* Marcel Dekker, New York, 1999.
11. Porter, Frank C., *Corrosion Resistance of Zinc and Zinc Alloys,* Marcel Dekker, New York, 1994.

11 Conversion Coatings

INTRODUCTION

The corrosion protection of metallic substrates by simple organic layers is often not good enough due to, for example, poor adhesion. The term "conversion coating" is used to describe coatings in which the substrate metal provides ions that become part of the protective coating. The coating layers are composed of chemically inert inorganic compounds. These inert compounds on the surface reduce both anodic and cathodic areas and delay the transit of reactive species to the base metal. This results in increases in the slopes of anodic and cathodic polarization curves, thereby decreasing the rate of corrosion of the substrate.

Conversion layers are used for various reasons, including:

1. To improve the adherence of the organic layers
2. To obtain electrically insulating barrier layers
3. To provide a uniform grease-free surface
4. To provide active corrosion inhibition by reducing the rate of the oxygen reduction reaction, or by passivating the metallic substrate

Chemical conversion coatings also belong to the EMF control protection category because surfaces are converted to more stable states by coating. Coated metals generally exhibit a more noble potential than do uncoated metals, so the degree of anodic polarization is larger than that of cathodic polarization after coating.

Conversion coatings belonging in this group are phosphate, chromate, oxide, and anodized coatings. These coatings are composed of corrosion products that have been formed artificially by chemical or electrochemical reactions in selected solutions. The corrosion products thus formed build a barrier protection for the substrate metal. This barrier reduces the active surface area on the base metal, thereby delaying the transport of oxidizers and aggressive species. By so doing, the coating inhibits the formation of corrosion cells. The degree of secondary barrier action depends on the compactness, continuity, and stability of the corrosion product layer.

Each conversion coating protects the base metal against corrosion with two or three of the following protective abilities:

1. Secondary barrier action of corrosion products
2. Inhibiting action of soluble compounds contained in the corrosion products
3. Improvement in paint adhesion by the formation of a uniform corrosion product layer

Anodic oxidation forms a thin, dense, durable oxide film on a metal surface and has its greatest application in the protection of aluminum. On aluminum, the anodic oxide film is formed as follows:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^-$$

Two types of films can be produced on aluminum by anodic oxidation: porous films and nonporous films.

Porous oxide films are widely used for corrosion protection. They are composed of an outer porous layer of duplex structure and an inner nonporous layer (barrier type). The compounds of porous oxide films are amorphous Al_2O_3, γ-Al_2O_3, γ'-Al_2O_3, and α-Al_2O_3, and other compounds, depending on the electrolyte used. Anodic oxide films contain amorphous Al_2O_3 and crystalline Al_2O_3 in amounts of varying percentage. The compounds γ-Al_2O_3 and α-Al_2O_3 exist in the barrier layers. The former is formed in a boric acid solution and the latter is formed in a bisulfate solution.

Anhydrous Al_2O_3 is so hygroscopic that the part of the anodic oxide film that contacts the electrolyte is hydrated. That is, anhydrous Al_2O_3 is converted to $Al_2O_3 \cdot H_2O$ (boehmite) or $Al_2O_3 \cdot 3H_2O$ (bayerite). Thus, anodic oxide films contain moisture. Hydration is influenced by temperature.

The thickness of the barrier layer is increased with electrolytic voltage and is commonly 0.03 to 0.05 μm. The barrier layer corresponds to 0.5 to 20% of the anodic oxide film and exhibits good insulating properties. The barrier layer contains a stoichiometric excess of aluminum ions. The formation of other compounds, except alumina, depends on the electrolyte. For example, the barrier layer formed in a sulfuric acid solution consists of 13% SO_4 and the barrier layer formed in a chromic acid solution contains less than 1% chromium.

The porous layer is constructed of long hexagonal cells with a pore at the center of the cell. The porosity of the porous layer is $4 \times 10^8/cm^2$, and the diameters of the pores are approximately 1000 Å. The relationships between cell size and other factors are as follows[1,2]:

$$C = 2WE + P$$

where C is the size of the cell (Å), W is the thickness of wall (Å), E is the electrolytic voltage (V), and P is the diameter of the pore (Å).

The porous structure has a strong adsorbing ability; thus, the surface of the oxide film can be dyed, but is also be easily contaminated. Because this property of a porous layer causes the formation of corrosion cells, a sealing process to seal the pores is an important post-treatment.

Sealing is carried out with hot water or steam. This process seals the pores by the formation of boehmite ($Al_2O_3 \cdot H_2O$) or bayerite ($Al_2O_3 \cdot 3H_2O$). The volume expansion of pore walls with the formation of boehmite or bayerite seals the pores. Temperature influences the formation of boehmite and bayerite. Boehmite forms in the temperature range greater than 176°F (80°C), while bayerite forms

when the temperature is less than 176°F (80°C). Sealing is conducted after dyeing, because sealed film does not absorb dye.

As mentioned previously, the durability of a conversion coating is controlled by its continuity, compactness, and stability. An anodic oxide film on aluminum exhibits extremely good continuity compared with other conversion coatings and its compactness is greatly improved by sealing.

To prolong the service life of a coating layer, thicker coatings are usually applied for a severe environment. A thin film of 5 μm is suitable for most indoor atmospheres and a thickness of 15 to 25 μm is preferred for outdoor atmospheres.

PHOSPHATE COATING

When a metal surface is treated with a weak phosphoric acid solution of iron, zinc, or manganese phosphate, phosphate layers form. These phosphate coatings are applied to iron, steel, zinc, aluminum, and their alloys.

Phosphate films form by the dissolution of the base metal and the precipitation of phosphate films. The metal surface must be free of greases, oils, and other carbonaceous material before immersion in the phosphating solution or before spray application. Baths operating at 120°F (50°C) have pH values of approximately 2, while those operating below 120°F (50°C) have pH values of approximately 3.

The zinc phosphate coating is basically the result of a corrosion process. Reactions of iron and steel in a zinc phosphate solution are as follows:

1. The dissolution of the base metal at the anodic sites:

$$Fe + 2H_3PO_4 \rightarrow Fe(H_2PO_4)_2 + H_2$$

Promotion by the activator:

$$2Fe + 2H_2PO_4^- + 2H^+ + 3NO_2 \rightarrow 2FePO_4 + 3H_2O + 3NO$$

$$4Fe + 3Zn^{2+} + 6H_2PO_4^- + 6NO_2 \rightarrow$$

$$4ZnPO_4 + Zn(PO_4)_2 + 6H_2O + 6NO$$

2. Precipitation of phosphate films at the cathodic sites:

$$2Zn(H_2PO_4)_2 + Fe(H_2PO_4)_2 + 4H_2O \rightarrow$$

$$\underset{\text{phosphophyllite}}{Zn_2Fe(PO_4)_2 4H_2O} + 4H_3PO_4$$

$$3Zn(H_2PO_4)_2 + 4H_2O \rightarrow \underset{\text{hopeite}}{Zn_3(PO_4)_2 4H_2O} + 4H_3PO_4$$

In this case, the phosphate films consist of phosphophyllite and hopeite.

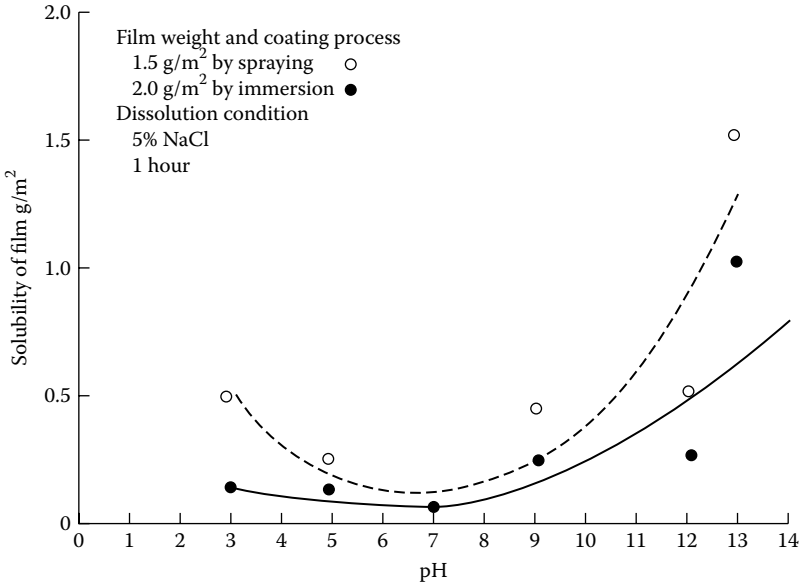


FIGURE 11.1 Solubilities of phosphate film for various pH values.

A zinc phosphate coating typically consists of a dense agglomeration of thin crystals lying both in the plane of the metal surface and at various angles to the surface. The number of crystals per square centimeter is on the order of 10^6 and the total thickness of the phosphate layer is 3 to 5 μm. The phosphate coating is very rough with much open volume. The roughness and open volume provide excellent anchor points for paint and good adhesion between the phosphate layer and paint is achieved.

As has been described, the barrier action of a conversion coating is influenced by its solubility and continuity. The solubilities of phosphates are lowest in the pH range of 6 to 8, as shown in Figure 11.1. Phosphates are stable in neutral environments, and are nonelectric conductive compounds. However, the continuity of phosphate films is not as good as that of anodic oxide and chromate films because phosphate films deposit on cathodic areas and anodic sites remain in the form of pinholes.

Characteristic of phosphate coatings is that they provide a good base for paint, plastics, and rubber coatings. The uniformity of metal surfaces in chemical and physical properties is greatly improved by phosphating treatment. The chemical effects of phosphating on the surface include converting the surface to a nonalkaline condition, protecting the surface against reaction with oils in paint, and protecting against the spread of corrosion from defects. Alkaline residues on the surface of a base metal cause under-film corrosion. The effect of phosphating on the physical properties of the surface is to increase uniformity in the surface

texture and surface area, which affects paint adhesion. These characteristics of phosphating result in the extension of the service life of paint films.

The protective ability of a phosphate coating itself is inferior to that of anodic and chromate conversion coatings. As previously described, phosphate films are formed on the cathodic sites so that small anodic sites remain in the form of pinholes. Phosphates forming the films are mostly crystalline compounds. The type of surface found in phosphate films in which very small defects are distributed uniformly provides excellent adhesion for lacquer films and makes the electrodeposition of primers possible.

The presence of pinholes in phosphate films results in rapid rusting under severely corrosive conditions. Rusting is observed on phosphated steel in 10 to 60 minutes in salt-spray tests. On the other hand, on the painted phosphate coated steel, it takes several hundred hours until rusting occurs under the same conditions. One-year exposure tests at Kure Beach, North Carolina (a marine atmosphere), show that the corrosion rate of bare mild steel is 212 mg/dm^2/day, that of painted steel 55 mg/dm^2/day, and that of painted phosphate coated steel is 26 mg/dm^2/day — showing that phosphate treatment greatly enhances the protective ability of paint coatings.

CHROMATE COATINGS

Chromate conversion coatings are formed on aluminum and its alloys, magnesium, zinc, and cadmium. These coatings provide good corrosion protection and improve adhesion of organic layers. A chromate coating is composed of a continuous layer consisting of insoluble trivalent chromium compounds and soluble hexavalent chromium compounds. The coating structure provides a secondary barrier-inhibiting action, and also good adhesion for lacquer films.

Chromate coatings provide their corrosion resistance based on the following three properties:

1. Cr(III) oxide, which is formed by the reduction of Cr(IV) oxide, has poor solubility in aqueous media and thus provides a barrier layer.
2. Cr(VI) will be included in the conversion coating and will be reduced to Cr (III) to passivate the surface when it is damaged, thereby preventing hydrogen gas from developing.
3. The rate of cathodic oxygen reactions is strongly reduced.

Most chromate conversion coatings are amorphous gel-like precipitates, so they are excellent in continuity. The service life depends on the thickness, the characteristics of the base metal, coating conditions — particularly dry heat — and the environmental conditions under which the chromate products are used.

When a chromated product is exposed to the atmosphere, hexavalent chromium slowly leaches from the film, with the result that the surface appearance changes from iridescent yellow to either a green color or to clear. The structure

of the film consists of more of the insoluble trivalent chromium compounds. Passivation is provided for any of the damaged areas by the leached hexavalent chromium.

The longer the time of wetness, the shorter the coating's service life because chromate coatings absorb moisture and moisture results in the leaching of hexavalent chromium. The leaching behavior of a chromate film is also affected by its aging process, drying process, and long-term storage. Aging of a chromate coating reduces its protective ability.

Chrome baths always contain a source of hexavalent chromium ion (e.g., chromate, dichromate, or chromic acid) and an acid to produce a low pH (usually in the pH range of 0 to 3). A source of fluoride ions is also usually present. These fluoride ions will attack the original (natural) aluminum oxide film, exposing the base metal substrate to the bath solution. Fluoride ion also prevents the aluminum ions (which are released by the dissolution of the oxide layer) from precipitation by forming complex ions. The fluoride concentration is critical. If the concentration is too low, a conversion layer will not form because of the failure of the fluoride to attack the natural oxide layer, while too high a concentration will result in poor adherence of the coating due to reaction of the fluoride with the aluminum substrate.

During the reaction, hexavalent chromium is partially reduced to trivalent chromium, forming a complex mixture consisting largely of hydrated hydroxides of both chromium and aluminum:

$$6H^+ + H_2Cr_2O_7 + 6e^- \rightarrow 2Cr(OH)_3 + H_2O$$

There are two types of processes by which conversion coatings can be produced: the chromic acid process and chromic acid–phosphoric acid process. The overall governing equation in the formation of the chromic acid-based conversion coating is:

$$6H_2Cr_2O_7 + 30HF + 12Al + 8HNO_3 \rightarrow$$

$$3Cr_2O_3 + Al_2O_3 + 10AlF_3 + 6Cr(NO_3)_3 + 30H_2O$$

The oxide Cr_2O_3 is better described as an amorphous chromium hydroxide, $Cr(OH)_3$. The conversion coating is yellow to brown in color.

The governing reaction in the chromic acid–phosphoric acid process is:

$$2H_2Cr_2O_7 + 10H_3PO_4 + 12HF + 4Al \rightarrow$$

$$Cr\,PO_4 + 4AlF + 3Cr(H_2PO_4)_3 + 14H_2O$$

This conversion coating is greenish in color and consists primarily of hydrated chromium phosphate with hydrated chromium oxide concentrated toward the metal.

The barrier action of a chromate coating increases with its thickness. Chromium conversion coatings can be used as a base for paint or alone for corrosion protection. Previously it was described how the leached hexavalent chromium acts as an anodic inhibitor, by forming passive film over defects in the coating. Because films formed on aluminum by the chromic acid–phosphoric acid process contain no hexavalent chromium, they do not provide self-healing from defects.

The service life of a chromate coating depends on coating thickness. Chromate coatings absorb moisture, and moisture results in the leaching of hexavalent chromium. Therefore, the longer the wetness time, the shorter the life of the coating. However, as long as the leaching of hexavalent chromium continues, the base metal is protected.

Environmental conditions — in particular, the time of wetness and the temperature — determine the leaching rate. In natural environments, the leaching rate is commonly low. Pollutants in the atmosphere, particularly chloride ions, increase the rate of deterioration of the film. Chromate conversion coatings provide good corrosion resistance in a mild atmosphere (such as indoor atmospheres) and surface appearance. They also provide a good base for organic films.

Chromate conversion coatings are usually applied to zinc- and its alloy-coated sheets to protect against staining during storage, and to products of zinc die castings, aluminum and its alloys, and magnesium and its alloys.

PHOSPHATE–CHROMATE COATINGS

A chromate film is normally very thin and exhibits poor resistance to abrasion. Phosphate conversion coatings do not provide adequate corrosion protection. Phosphate–chromate coatings were developed to improve the quality of both phosphate and chromate coatings. Combining the two different conversion coatings increases both the corrosion resistance and abrasion resistance.

Phosphate–chromate coatings consist of dense amorphous layers and do not contain hexavalent chromium.

ANODIZED COATINGS

The electrochemical treatment of a metal serving as an anode in an electrolyte is known as *anodizing.* Because aluminum's electrode potential is negative and its oxide film is stable in neutral environments, surface treatments have been developed for the purpose of producing more stable oxide films. The anodic films formed can be either porous or nonporous, depending upon which electrolyte is used.

Porous films result when electrolytes such as sulfuric acid, oxalic acid, chromic acid, and phosphoric acid are used. These films have the advantage of being able to be dyed.

Sulfuric acid is the most widely used electrolyte. A large range of operating conditions can be utilized to produce a coating to meet specific requirements. Hard protective coatings are formed that serve as a good base for dyeing.

To obtain the maximum corrosion resistance, the porous coating must be sealed after dyeing. The anodic coating formed, using sulfuric acid as the electrolyte, is clear and transparent on pure aluminum. Aluminum alloys containing silicon or manganese and the heterogeneous aluminum–magnesium alloy yield coatings that range from gray to brown and may be patchy in some cases. The adsorptive power of these coatings makes them excellent bases for dyes, especially if they are sealed in nickel or cobalt acetate solution.

It is not recommended to use sulfuric acid as the electrolyte for anodizing work containing joints that can retain the sulfuric acid after removal from the bath. The retained electrolyte will provide sites for corrosion.

When chromic acid is used as the electrolyte, the coatings produced are generally opaque, gray, and iridescent, with the quality depending on the concentration and purity of the electrolyte. These are unattractive characteristics as compared to those formed using sulfuric acid as the electrolyte. When 0.03% sulfate is added to the electrolyte, colorless and transparent coatings are formed. These coatings are generally thin, of low porosity, and hence difficult to dye. Black coatings can be obtained in concentrated solution at elevated temperatures. Attractive opaque surfaces can be obtained by adding titanium, zirconium, and thallium compounds to the electrolyte.

The chromic acid anodizing process is the only one that can be used on structures containing blind holes, crevices, or difficult to rinse areas. Chromic acid anodizing generally increases fatigue strength, while sulfuric acid anodizing may produce decreases in fatigue strength.

Boric acid electrolytes produce a film that is iridescent and oxides in the range of 2500 to 7500 Å. The coating is essentially nonporous.

Oxalic and other organic acids are electrolytes used to produce both protective and decorative films. Unsealed coatings are generally yellow in color. These films are harder and more abrasion resistant than the conventional sulfuric acid films. However, the especially hard coatings produced under controlled conditions in sulfuric acid electrolytes are superior.

The anodized film consists of two major components: the nonporous barrier layer adjoining the metal and a porous layer extending from the barrier layer to the outer surface of the film. In the case of thick films especially, there may be an identifiable transition region between the barrier layer and the porous layer. Boric acid electrolytes yield barrier-type films only, whereas both barrier and porous layers are obtained in sulfuric, chromic, and oxalic acids. Electron microscope studies of the barrier layer indicate that it consists of a hexagonal distribution of cells that continue up into the porous layer. The central portion of each cell is amorphous, whereas the outer portion has a partially crystalline nature. In the case of aluminum anodized in boric acid at 68°F (20°C) with an applied voltage of 500 V, the number of cells was $1.4 \times 10^8/cm^2$.

The service life of anodic films is determined by the environmental conditions under which they are used, and on properties of the products into which they are made. The former are SO_x gases and depositions; the latter are their thicknesses,

bath constituents, degrees of sealing, impurities, alloy elements, and other factors such as dyeing.

The corrosion patterns of anodized aluminum and its alloys are pitting and galvanic corrosion.

Galvanic corrosion is caused by contact with other metals such as copper, iron, and steel. When nonmetallic compounds such as mortar and concrete come in contact with anodized aluminum products, corrosion is induced because chloride ions leach from these materials. The corrosion of metals is influenced by pollutants and time-of-wetness. On anodized aluminum and its alloys, the most aggressive factors are SO_x gas and depositions. Deposits of grime, sulfates, and chlorides promote the deterioration of anodic films because they tend to absorb aggressive gases and moisture, thereby increasing the time-of-wetness and decreasing the pH of the electrolyte at the interface between the deposits and the surface.

Although rainfall increases the time-of-wetness, it also has the effect of cleaning the surface, thus removing some of the deposits. Therefore, cleaning with water is one of the methods used to protect anodized aluminum and its alloys from corrosion. The deposits in marine atmospheres can be removed from surfaces by cleaning with water because the deposits are mostly soluble chlorides, but cleaning with detergents to remove deposits in industrial atmospheres is necessary because the deposits tend to be greasy. Purer aluminum substrates form more durable films, and thicker films provide better corrosion protection for the base metal.[3]

SO_x gas is the most aggressive pollutant for anodic films. Figure 11.2 shows changes in appearance with time on well-sealed anodized specimens exposed to

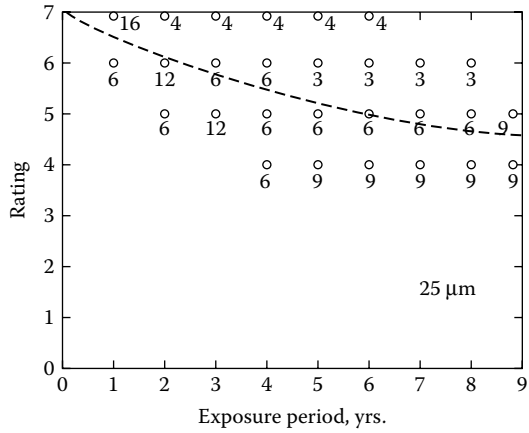


FIGURE 11.2 Corrosion behavior of well-sealed anodized specimens in a severe industrial atmosphere.

a severe industrial atmosphere. Film thickness was 25 μm. Ratings shown in Figure 11.2 were obtained from the "weighted percentage area affected" as follows[4]:

Rating	Weighted Percentage Area Affected
7	0–<0.03
6	0.03–<0.1
5	0.1–<0.3
4	0.3–<1.0
3	1.0–<3.0
2	3.0–<10
1	10–<30
0	>30

The median rating attained a 4.4 rating (0.6%) after 9 years of exposure in a severe industrial atmosphere, 5.3 (0.2%) in an industrial atmosphere, and 6.0 (0.09%) in a marine atmosphere. This data shows that the corrosion behavior of anodized aluminum is strongly affected by the $S0_x$ concentration in the atmosphere. From exposure test results by Carter[4] (and shown in Figure 11.2), the relationship between weighted percentage area affected and SO_x concentration is shown in Figure 11.3. In Figure 11.2, the SO_x concentrations in various areas were extracted from data by Hudson and Stanners[5,6] and by Schikoor.[7] The corrosion area increases linearly with increasing SO_x concentration. In Figure 11.3,

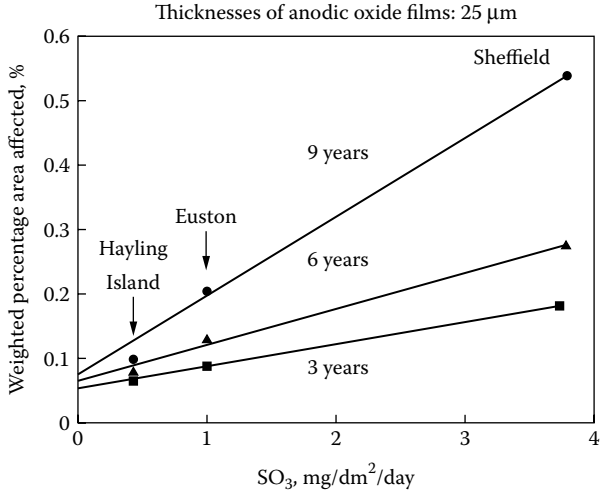


FIGURE 11.3 Relationship between weighted percentage area affected and SO_x concentration. (*Source:* From References 4 through 7.)

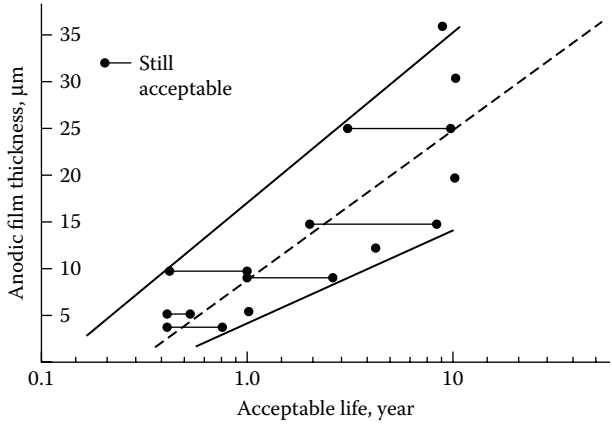


FIGURE 11.4 Relation between anodic film thickness and acceptable life for well-sealed anodized aluminum exposed to a severe industrial atmosphere.

Sheffield represents a severe industrial area, Euston represents an average industrial area, and Hayling Island represents a severe marine atmosphere.

As described above, one of the important factors in the effectiveness of anodic film is its thickness. Figure 11.4 shows the relationship between anodic film thickness and acceptable life for a well-sealed anodized aluminum exposed to a severe industrial atmosphere. The logarithm of an acceptable life in years is approximately proportional to the anodic film thickness; a minimum anodic film thickness of 35 μm for exposure in severe industrial atmospheres, 16 μm for exposure in moderately industrial atmospheres, and 12 μm for exposure in severe marine atmospheres are required for a service life in excess of 10 years.[4]

The durability of anodic films depends upon the degree of sealing. On well-sealed specimens, light blooming developed after 3 years; while on nonsealed specimens, severe blooming developed in less than 1 year of exposure.[4] The degree of opacity of anodic oxide films tends to increase on low-sealed specimens in marine atmospheres. Sealing with city water or at low temperature decreases the durability of anodic films.

Anodic films formed at 80°F (27°C) provide less corrosion protection in industrial atmospheres than those formed at 68°F (20°C); and mixed baths with sulfuric and oxalic acids, or organic sulfonic acid baths, improve the durability of the film. This indicates that the durability of the film is determined by the surface treatment.

Types of aluminum alloys that are anodized include 10% Cu-Al, 10% Mg-Al, 13% Si-Al, 5% Fe-Al, 2% Cr-Al, 1% Ti-Al, 4% Fe-8% Si-Al, 6.4% Mg-3.7% Si-Al, and 9% Zn-3% Mg-Al, plus others. The corrosion resistance of

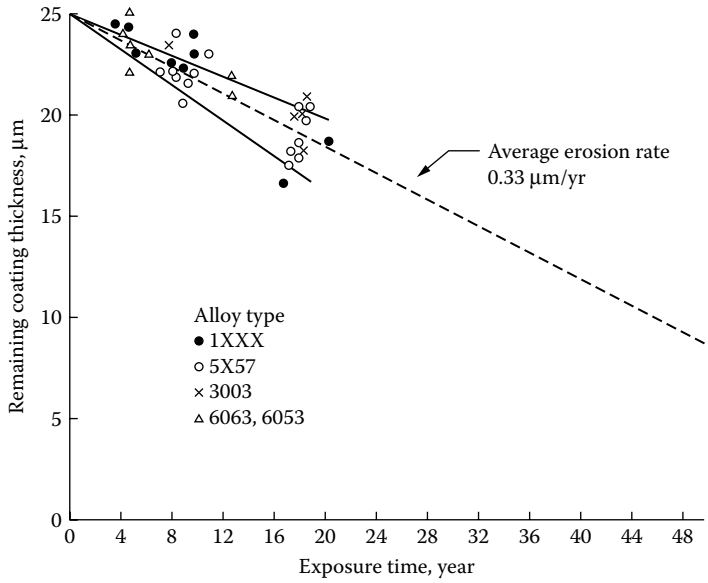


FIGURE 11.5 Relationship between remaining coating thickness and exposure time in an industrial atmosphere.

these materials varies with the type of alloy and is influenced by the environment the same as anodized aluminum. The order of pitting resistance of anodized aluminum alloys exposed in moderately industrial atmospheres is 5052 > 6063 > 1100 > 3003 > 4043 > 6351 > 2014. Anodic films on commercial aluminum alloys erode uniformly at the slow rate of about 0.33 μm per year.[8] Figure 11.5 shows the relationship between the remaining coating thickness and the exposure time in an industrial atmosphere (New Kensington, Pennsylvania). The density of pits decreases exponentially with increasing anodic film thickness.

Decorative appearance is required for architectural materials, such as for building curtain walls, and for window frames. Anodic film is colored by the action of its alloy elements, by electrolyte, or by dyeing. For example, the anodic films on Al-Si alloys 4043 exhibit a gray color, and a gold color anodic film is formed in an oxalic acid bath. The oxalic acid film is superior to a sulfuric acid film in corrosion resistance. Weathering causes color changes. Figure 11.6 shows the relationship between color changes of various anodic films and exposure times in industrial atmospheres. Gold and bronze anodic films tend to fade in 2 years of exposure, but an equivalent degree of color change in most anodic films colored by dye takes 5 years of exposure. Anodic films also provide a superior base for paint adhesion compared to bare aluminum and its alloys.

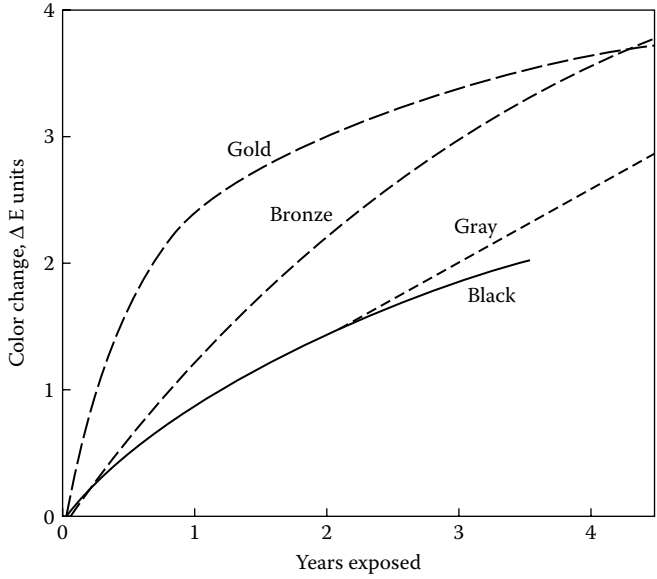


FIGURE 11.6 Relationship between color change of anodic films and exposure time in an industrial atmosphere.

OXIDE COATINGS

Iron or steel articles to be coated are heated in a closed retort to a temperature of 1600°F (871°C), after which superheated steam is admitted. This results in the formation of red oxide (Fe_2O_3) and magnetic oxide (Fe_3O_4). Carbon monoxide is then admitted to the retort, reducing the red oxide to magnetic oxide, which is resistant to corrosion. Each operation takes approximately 20 minutes.

Iron and steel can also be oxide coated by electrolytic means. The article to be coated is made the anode in an alkaline solution (anodic oxidation). These coatings are primarily for appearance, such as for cast iron stove parts.

Oxide coatings can also be produced on steel by controlled high-temperature oxidation in air or by treatment in hot alkali solutions containing some oxidizing additives such as nitrate, chlorates, or persulfates. Black, brown, or blue coatings are developed, depending on film thickness. The oxide coatings are not protective but are made so by rubbing with inhibitor-containing oils or waxes. Gun barrels provide examples for oxide-coated utility.

REFERENCES

1. Keller, F., Hunter, M.S., and Robinson, D.L., *J. Electrochem. Soc.,* 100, 411, 1953.
2. Keller, F., Hunter, M.S., and Robinson, D.L., *J. Electrochem Soc.,* 101, 335, 1954.
3. Wittacker, J.A. and Kape, J.M., *Trans. Inst. Metal Finishing,* 38, 66, 1961.

4. Carter, V.E., *J. Inst. Metals,* 100, 208, 1972.
5. Hudson, J.D. and Stanners, J.F., *J. Appl. Chem.,* 3, 86, 1953.
6. Hudson, J.C., *Sixth Report of the Corrosion Committee,* Iron and Steel Institute, London, 1957, p. 176.
7. G. Schikoor, *Corrosion Behavior of Zinc in the Atmosphere.,* Iron and Steel Inst., London, 1957, p. 176.
8. Mader, O.M., *Metals and Materials,* 6, 303, 1972.

12 Cementitious Coatings

INTRODUCTION

Cementitious coatings provide corrosion resistance to substrates such as steel by maintaining the pH above 4 at the metal/coating interface, a pH range in which steel corrodes at a low rate. The proper selection of materials and their application is necessary if the coating is to be effective. To select the proper material, it is necessary to define the problems:

1. Identify all chemicals that will be present and their concentrations. Knowing pH alone is not sufficient. All the pH tells you is whether the environment is acid, neutral, or alkaline; it does not identify whether the environment is oxidizing, organic, inorganic, or alternately acid or alkaline.
2. Is the application fumes, splash, or total immersion?
3. What are the minimum and maximum temperatures to which the coating will be subjected?
4. Is the installation indoors or outdoors? Thermal shock and ultraviolet exposure can be deleterious to many resins.
5. How long is the coating expected to last? This can have an effect on the cost.

Surface preparation prior to application of the coating is essential. The surface must be free of mill scale, oil, grease, and other chemical contaminants. The surface must be roughened by sandblasting and the coating applied immediately after preparation. An intermediate bonding coating is used when adhesion between the substrate and the coating is poor, or where thermal expansion characteristics are incompatible. Coatings are installed in thicknesses of 1/16 to 1/2 in. (1.5 to 13 mm). They can be applied by casting, troweling, or spraying. The spraying process, known as Gunite or Shotcrete, is particularly useful in systems with unusual geometry or with many sharp bends or corners. It has the advantage that there are no seams, which are often weak points as far as corrosion resistance is concerned.

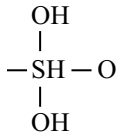
SILICATES

Silicates are noted for their resistance to concentrated acids, except hydrofluoric and similar fluorinated chemicals at elevated temperatures. They are also resistant to many aliphatic and aromatic solvents. They are not intended for use in

alkaline or alternately acid and alkaline atmospheres. This category of coatings includes:

1. Sodium silicate
2. Potassium silicate
3. Silica (silica sol)

The alkali silicates form a hard coating by a polymerization reaction involving repeating units of the structure:



The sodium and potassium silicates are available as two-component systems: filler and binder, with the setting agent in the filler. Sodium and potassium silicates are referred to as *soluble* silicates because of their solubility in water. This prevents their use in many dilute acid services while they are not affected by strong concentrated acids. This disadvantage becomes an advantage for formulating single-component powder systems. All that is required is the addition of water at the time of use. The fillers of these materials are pure silica.

The original sodium silicate acid-resisting coating uses an inorganic silicate base consisting of two components: a powder and a liquid. The powder is basically quartzite of selected gradation and a setting agent. The liquid is a special sodium silicate solution. When the coating is used, the two components are mixed together and hardening occurs via chemical reaction.

This coating can be cast, poured, or applied by guniting. It has excellent acid resistance and is suitable for use over a pH range of 0.0 to 7.0.

The sodium silicates can be produced over a wide range of liquid binder compositions. These properties and new hardening systems have significantly improved the water resistance of some sodium silicate coatings. These formulations are capable of resisting dilute as well as concentrated acids without compromising physical properties.

The potassium silicate materials are less versatile in terms of formulation flexibility than the sodium silicate materials. However, they are less susceptible to crystallization in high concentrations of sulfuric acid as long as metal ion contamination remains minimal. Potassium silicate materials are available with halogen-free hardening systems, thereby removing the remote possibility of catalyst poisoning in certain chemical processes.

Chemical-setting potassium materials are supplied as two-component systems that comprise the silicate solution and the filler powder and setting agent. Setting agents may be inorganic, organic, or a combination of both. The properties of

TABLE 12.1
Comparative Chemical Resistance: Silicate Coatings

	Sodium		Potassium	
Medium, R.T.	**Normal**	**Water Resistant**	**Normal**	**Halogen-Free**
Acetic acid, glacial	G	G	R	R
Chlorine dioxide, water sol.	N	N	R	R
Hydrogen peroxide	N	R	N	N
Nitric acid, 5%	C	R	R	R
Nitric acid, 20%	C	R	R	R
Nitric acid, over 20%	R	R	R	R
Sodium bicarbonate	N	N	N	N
Sodium sulfite	R	R	N	N
Sulfates, aluminum	R	R	R	R
Sulfates, copper	G	G	R	R
Sulfates, iron	G	G	R	R
Sulfates, magnesium	G	G	R	R
Sulfates, nickel	G	G	R	R
Sulfates, zinc	G	G	R	R
Sulfuric acid, to 93%	G	G	R	R
Sulfuric acid, over 93%	G	G	R	R

Note: R.T. = room temperature; R = recommended; N = not recommended; G = potential failure, crystalline growth; C = conditional.

the coating are determined by the setting agent and the alkali-to-silica ratio of the silicate used. Properties such as absorption, porosity, strength, and water resistance are affected by the choice of setting agent. Organic setting agents will burn out at low temperatures, thereby increasing porosity and absorption. Organic setting agents are water soluble and can be leached out if the coating is exposed to steam or moisture. Coatings that use inorganic setting agents are water and moisture resistant.

Silicate formulations will fail when exposed to mild alkaline media (e.g., bicarbonate of soda). Dilute acid solutions, such as nitric acid, will have a deleterious effect on sodium silicates unless the water-resistant type is used. Table 12.1 points out the differences between the various silicate coatings.

Silica, or silica sol, types of coatings are the newest of this class of material. They consist of a colloidal silica binding instead of the sodium or potassium silicates, with a quartz filler. These materials are two-component systems that comprise a powder composed of high-quality crushed quartz and a hardening agent, which are mixed with colloidal silica solution to form the coating. These coatings are recommended for use in the presence of hot concentrated sulfuric acid. They are also used for weak acid conditions up to pH 7.

CALCIUM ALUMINATE

Coatings of this type consist of a calcium aluminate-based cement and various inert ingredients and are supplied in powder form to be mixed with water when used. This can be applied by casting, pouring, or guniting. Calcium aluminate-based coatings are hydraulic and consume water in their reaction mechanism to form hydrated phases. This is similar to Portland cement compositions; however, their rates of hardening are very rapid. Essentially full strength is reached within 24 hr at 73°F (23°C).

Calcium aluminate-based cements have better mild acid resistance than Portland cement, but they are not useful in acids below pH 4.5 to 5.0. They are not recommended for alkali service above pH 10, nor are they recommended for halogen service. Refer to Table 12.2 for the chemical resistance of calcium aluminate and Portland cement.

PORTLAND CEMENT

Portland cement is made from limestone or other natural sources of calcium carbonate, clay (a source of silica), alumina, ferric oxide, and minor impurities. After grinding, the mixture is fired in a kiln at approximately 2500°F (1137°C). The final product is ground to a fineness of about 10 μm and mixed with gypsum to control setting. When mixed with water, the Portland cement forms a hydrated phase and hardens. As the cement hardens, chemical reactions take

TABLE 12.2
Chemical Resistance of Calcium Aluminate and Portland Cements

Cement Type	Calcium Aluminate	Portland Cement
pH Range	4.5–0	7–12
Water Resistance	E	E
Sulfuric Acid	X	X
Hydrochloric Acid	X	X
Phosphoric Acid	P	X
Nitric Acid	X	X
Organic Acids	F	F
Solvents	G	G
Ammonium Hydroxide	F	G
Sodium Hydroxide	F	F
Calcium Hydroxide	F	G
Amines	F	G

Note: E = excellent; G = good; F = fair; P = poor; X = not recommended.

place. The two most important reactions are the generation of calcium hydroxide and tricalcium silicate hydrate. The calcium hydroxide generated could theoretically be as high as 20% of the weight of the cement, producing an alkalinity that at the solubility of lime results in an equilibrium of pH of 12.5. Steel that has been coated with the cement is passivated as a result of the hardened materials. The alkalinity of the coating is provided by the presence of calcium oxide (lime). Any material that will cause the calcium oxide or hydride to be renewed, lowering the pH, will prove detrimental and cause solution of the cement hydrates. Contact with inorganic or organic acids can cause this to happen. Organic acids can be generated when organic materials ferment.

When carbon dioxide dissolves in water that may be present on the cement, a weak carbonic acid is formed. The weak carbonic acid lowers the pH of the cement solution, allowing the steel to corrode. This is sometimes referred to as the *carbonation of cement*.

Sulfates will also cause the Portland cement to deteriorate. In addition to being able to produce sulfuric acid, which is highly corrosive to Portland cement, sulfates are also reactive with some additives used in the formulations (see Table 12.2).

COMPARATIVE CORROSION RESISTANCE

Following is a series of tables that show the compatibility of the cementitious coatings with selected corrodents. It must be remembered that the silicate coatings are subject to formulation and use of various setting agents. Consequently, all formulations do not exhibit the same corrosion resistance. When compatibility in the table is recommended, it an indication that at least one formulation is compatible. Before using, the manufacturer should be consulted to ensure that the correct formulation will be provided.

The following notation is used in the tables:

R = recommended
X = not recommended
A blank space indicates no data available

Recommendations are based on ambient temperature.

Acetic Acid, 10%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Acetic Acid, 50%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Acetic Acid, 80%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Acetic Acid, Glacial

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Acetic Acid, Vapor

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Aluminum Chloride, Aqueous

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	
Silica	R		

Aluminum Fluoride

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	
Silica	X		

Aluminum Sulfate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Ammonium Bifluoride

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	X
Silica	X		

Ammonium Carbonate

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Ammonium Chloride, 10%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Ammonium Fluoride, 10%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	X
Silica	X		

Ammonium Fluoride, 25%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	X
Silica	X		

Ammonium Hydroxide, 10%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Ammonium Hydroxide, 25%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Ammonium Hydroxide, Sat.

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Ammonium Nitrate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Ammonium Persulfate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Ammonium Sulfate, 10–40%

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Ammonium Sulfate, Sat.

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Ammonium Sulfide

Sodium silicate	X	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Aniline Hydrochloride

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	
Silica	R		

Aqua Regia, 3:1

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Bromine, Liquid

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Bromine Water, Dilute

Sodium silicate, 5%	R	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Bromine Water, Sat.

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	
Silica	R		

Butyric Acid

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Calcium Chloride, Dilute

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	R	Portland cement	
Silica	R		

Calcium Chloride, Sat.

Sodium silicate	X	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Calcium Hydroxide, 10%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Calcium Hydroxide, 20%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Calcium Hydroxide, 30%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Calcium Hydroxide, Sat.

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	R
Silica	X		

Calcium Nitrate

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Calcium Sulfate

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Chlorine, Liquid

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Chlorine Water, Sat.

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Chloroacetic Acid

Sodium silicate, 80%	R	Calcium aluminate	
Potassium silicate, 10%	R	Portland cement	X
Silica, 10%	R		

Chromic Acid, 10%

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Chromic Acid, 50%

Sodium silicate		Calcium aluminate	X
Potassium silicate		Portland cement	X
Silica	R		

Citric Acid, All Concentrations

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Copper Acetate

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Copper Chloride

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Copper Nitrate

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Dichloroacetic Acid

Sodium silicate, 20%	R	Calcium aluminate	X
Potassium silicate		Portland cement	X
Silica			

Ethyl Acetate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Fatty Acids

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Ferric Chloride

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	R	Portland cement	
Silica	R		

Formic Acid, 5–85%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Formic Acid, Anhydrous

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Hydrobromic Acid, Dilute

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Hydrobromic Acid, 20%

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Hydrobromic Acid, 50%

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Hydrochloric Acid, Dilute

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Hydrochloric Acid, 20–50%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Hydrofluoric Acid, All Concentrations

Sodium silicate	X	Calcium aluminate	
Potassium silicate	X	Portland cement	X
Silica	X		

Hydrogen Peroxide, Dilute

Sodium silicate	R	Calcium aluminate
Potassium silicate	R	Portland cement
Silica	R	

Hydrogen Peroxide, 30%

Sodium silicate	R	Calcium aluminate
Potassium silicate	X	Portland cement
Silica	X	

Hydrogen Peroxide, 50%

Sodium silicate	X	Calcium aluminate
Potassium silicate	X	Portland cement
Silica	X	

Hydrogen Peroxide, 90%

Sodium silicate	X	Calcium aluminate
Potassium silicate	X	Portland cement
Silica	X	

Iodine

Sodium silicate	R	Calcium aluminate
Potassium silicate	R	Portland cement
Silica	R	

Isopropyl Acetate

Sodium silicate	R	Calcium aluminate	
Potassium silicate		Portland cement	X
Silica			

Lactic Acid, All Concentrations

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Magnesium Chloride

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	
Silica	R		

Magnesium Sulfate

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Maleic Acid

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Methyl Acetate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Methyl Ethyl Ketone

Sodium silicate	R	Calcium aluminate	R
Potassium silicate		Portland cement	
Silica			

Methyl Isobutyl Ketone

Sodium silicate	R	Calcium aluminate	R
Potassium silicate		Portland cement	
Silica			

Methyl Sulfate

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Muriatic Acid

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Nitric Acid, 5%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Nitric Acid, 10–70%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica			

Nitric Acid, Anhydrous

Sodium silicate	R	Calcium aluminate	X
Potassium silicate		Portland cement	X
Silica			

Oleic Acid

Sodium silicate	R	Calcium aluminate	R
Potassium silicate	R	Portland cement	X
Silica	R		

Oleum

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica			

Oxalic Acid, to 50%

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Oxalic Acid, Sat.

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Perchloric Acid, 10%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Phenol

Sodium silicate	R	Calcium aluminate	
Potassium silicate		Portland cement	
Silica			

Phenol, 10%

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Phosphoric Acid, 5–20%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Phosphoric Acid, 25–50%

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Phosphoric Acid, 50–85%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Phosphorous Oxychloride

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Picric Acid, 10%

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Picric Acid, 50%

Sodium silicate		Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Potassium Hydroxide, 5–27%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate		Portland cement	X
Silica	X		

Potassium Hydroxide, 50–90%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate		Portland cement	X
Silica	X		

Potassium Nitrate, 90%

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Propionic Acid

Sodium silicate	R	Calcium aluminate	X
Potassium silicate		Portland cement	X
Silica			

Sodium Acetate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Sodium Carbonate

Sodium silicate	X	Calcium aluminate	
Potassium silicate	X	Portland cement	X
Silica	X		

Sodium Chloride

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Sodium Chromate

Sodium silicate	R	Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Sodium Hydroxide, All Concentrations

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	X
Silica	X		

Sodium Hypochlorite

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	X	Portland cement	X
Silica	X		

Sulfuric Acid, 10–98%

Sodium silicate, to 70%	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica			

Sulfuric Acid, 100%

Sodium silicate	X	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica			

Sulfurous Acid

Sodium silicate	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Trichloroacetic Acid, 2N

Sodium silicate, 20%	R	Calcium aluminate	X
Potassium silicate	R	Portland cement	X
Silica	R		

Uric Acid

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	X
Silica	R		

Vinegar

Sodium silicate	R	Calcium aluminate	R
Potassium silicate		Portland cement	X
Silica			

Zinc Chloride

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

Zinc Nitrate

Sodium silicate		Calcium aluminate	
Potassium silicate	R	Portland cement	
Silica	R		

13 Monolithic Surfacings

INTRODUCTION

Although concrete and cement-based products are all inherently weak in tension, they are strong in compression. To overcome the weakness in tension, steel rods (reinforcing rods) are placed in the uncured mix. The reinforcing steel can be plain or pre-and/or post-stressed. Stressed steel places the concrete in compression (its strong point). Any tensile load placed on the structure must overcome the compressive load due to the stressed steel before the concrete is placed in the tensile load mode. Micro- and macrocracking of the concrete results due to a weakness of tensile loading ability, which reduces the life expectancy in a corrosive environment. Corrosives gain access to the interior of the concrete through these cracks. If this results in the rusting of the embedded steel, then the volume of the excess iron oxide cannot be accommodated. Because of the poor tensile strength of the concrete, spalling of the cement mass will take place.

The resistance of concrete to corrosion is the result of its nonoxidizable structure (resistance to water and oxygen). Steel that has been embedded in the mix is passivated as a result of the hardened materials at pH 12.5. Concrete will resist degradation as long as nothing in the environment dissolves the cement matrix or reduces its ability to passivate the embedded steel.

The alkalinity of the concrete is provided by the presence of calcium oxide (lime). Any material that causes removal of the calcium oxide or hydroxide, lowering the pH, will prove detrimental and cause solution of the cement hydrates. Contact with inorganic or organic acids can cause this to happen. Organic acids can be generated when organic materials ferment.

When carbon dioxide dissolves in water that may be present on the concrete, weak carbonic acid is produced. The weak carbonic acid lowers the pH of the cement solution, allowing the embedded steel to corrode. This is sometimes referred to as carbonation of cement.

Sulfates will also cause concrete to deteriorate. In addition to being able to produce sulfuric acid, which is highly corrosive to concrete, sulfates are also reactive with some aggregates used in concrete mixes. Sulfate ions react with tricalcium aluminate to form sulfoaluminate hydrate with a large crystallized water content.

Typical compounds that can cause problems include sour milk, industrial wastes, fruit juices, some ultrapure waters and organic materials that ferment and produce organic acids. Typical chemical families found in various types of chemical processing industry plants and their effect on concrete are shown in Table 13.1.

TABLE 13.1
Effects of Various Chemicals on Concrete

Chemical	Effect on Concrete
	Chemical Plants
Acid waters, pH 6.5 or less	Disintegrates slowly
Ammonium nitrate	Disintegrates
Benzene	Liquid loss by penetration
Sodium hypochlorite	Disintegrates slowly
Ethylene	Disintegrates slowly
Phosphoric acid	Disintegrates slowly
Sodium hydroxide, 20% and above	Disintegrates slowly
	Food and Beverage Plants
Almond oil	Disintegrates slowly
Beef fat	Solid fat disintegrates slowly, melted fat more readily
Beer	May contain, as fermentation products, acetic, carbonic, lactic, or tannic acids, which disintegrate slowly
Buttermilk	Disintegrates slowly
Carbonic acid (soda water)	Disintegrates slowly
Cider	Disintegrates slowly
Coconut oil	Disintegrates slowly
Corn syrup	Disintegrates slowly
Fish oil	Disintegrates slowly
Fruit juices	Disintegrates
Lard or lard oil	Lard disintegrates slowly, lard oil more quickly
Milk	No effect
Molasses	Disintegrates slowly above 120°F (49°C)
Peanut oil	Disintegrates slowly
Poppyseed oil	Disintegrates slowly
Soybean oil	Disintegrates slowly
Sugar	Disintegrates slowly
	Electric Generating Utilities
Ammonium salts	Disintegrates
Coal	Sulfides leaching from damp coal may oxidize to sulfurous or sulfuric acid, disintegrates
Hydrogen sulfide	Dry, no effect; in moist oxidizing environments concerts to sulfurous acid and disintegrates slowly
Sulfuric acid, 10–80%	Disintegrates rapidly
Sulfur dioxide	With moisture forms sulfurous acid, which disintegrates rapidly

(*continued*)

TABLE 13.1 (Continued)
Effects of Various Chemicals on Concrete

Chemical	Effect on Concrete
	Pulp and Paper Mills
Chlorine	Slowly disintegrates moist concrete
Sodium hypochlorite	Disintegrates slowly
Sodium hydroxide	Disintegrates concrete
Sodium sulfide	Disintegrates slowly
Sodium sulfide	Disintegrates concrete of inadequate sulfate resistance
Tanning liquor	Disintegrates if acid

It is essential that water from subslab ground sources be eliminated or minimized because migration through the concrete can create pressures at the bond line of water-resistant barriers.

The life of the concrete can be prolonged by providing a coating that will be resistant to the pollutants present. These coatings are referred to as monolithic surfacings.

Chemical monolithic surfacings or toppings are a mixture of a liquid synthetic resin binder, selected fillers, and a setting agent for application to concrete in thicknesses ranging from approximately 1/16 in. (1.5 mm) to 1/2 in. (13 mm). Materials applied in thicknesses greater than 1/2 in. (13 mm) are usually referred to as polymer concretes. Polymer concretes are defined as a composition of low-viscosity binders and properly graded inert aggregates, which when combined and thoroughly mixed yield a chemical-resistant synthetic concrete that can be precast or poured in place. Polymer concretes can also be used as a concrete surfacing, with the exception of sulfur cement polymer concrete. By definition, monolithic surfacings are also polymer concretes.

Monolithic corrosion-resistant coatings and linings have been used successfully for more than 40 years, for both new and existing installations.

Monolithic surfaces have limitations that must be considered. For example, like all cementitious materials, they are inflexible and tend toward brittleness. The modulus of elasticity ranges from 10^5 to 10^6 psi; the flexural strength ranges from 500 to 2000 psi; and the tensile strengths range from 1800 to 5000 psi. They also have porosity ranging from 5 to 35%.

The thermal properties of monolithics vary considerably. In general, the coefficient of thermal expansion of monolithics should be matched as closely as possible to that of the substrate over which they will be applied. If it cannot be matched, a bond-breaker or membrane should be considered. The thermal conductivity of monolithic surfaces is lower than either steel or concrete. This is usually advantageous because the lower temperature on the substrate reduces corrosion rates exponentially and also reduces thermal movement and stresses in the substrate.

Care must be exercised in placing monolithic surfaces over substrates that are still experiencing curing shrinkage in excess of 1%. They can be expected to develop shrinkage cracks if placed directly on such substrates. Here it is necessary to provide expansion joints and to place the monolithic over a bond-breaker such as an impervious membrane.

As a rule, inorganic monolithic materials must be placed over a suitable membrane material because of the previously described tendency toward porosity and cracking. This is especially true in those applications in which the exposure is to liquid media or to halogens, and where these corrodents can condense from a hot-gas stream.

Before selecting an appropriate coating, consideration must be given to the condition of the concrete and the environment to which the concrete will be exposed. Proper surface preparation is essential. Surface preparation can be different for freshly placed concrete and for old concrete.

When concrete is poured, it is usually held in place by means of steel or wood forms that are removed when the concrete is still in its tender state. To facilitate their removal, release agents are applied to the forms prior to pouring. Oils, greases, and proprietary release agents are left on the surface of the concrete. These must be removed if they will interfere with the adhesion of subsequent coatings.

Quite often, curing compounds are applied to fresh concrete as soon as practical after the forms have been removed. These are liquid membranes based on waxes, resins, chlorinated rubber, or other film formers, usually in a solvent. Pretesting is necessary to determine whether or not they will interfere with the coating that will be applied.

In general, admixtures that are added to concrete mixtures to speed up or slow down the cure, add air to the mix, or obtain special effects will not interfere with surface treatments to improve durability. The concrete supplier can furnish specific data regarding these admixtures. If in doubt, try a test patch of the coating material to be used.

SURFACE PREPARATION

It is essential to properly prepare the concrete surface prior to application of the coating. The surfaces of cement-containing materials may contain defects that require repair before application of the coating. In general, the surface must be thoroughly cleaned and all cracks repaired.

Unlike specifications for the preparation of steel prior to coating, there are no detailed standard specifications for the preparation of concrete surfaces. In most instances, it is necessary to follow the instructions supplied by the coating manufacturer. Specifications can range from simple surface cleaning that provides a clean surface without removing concrete from the substrate, to surface abrading that provides a clean, roughened surface, to acid etching that also provides a clean, roughened surface.

Surface Cleaning

Surface cleaning is accomplished by one of the following means:

1. Broom sweeping
2. Vacuum cleaning
3. Air blast
4. Water cleaning
5. Detergent cleaning
6. Steam cleaning

Water cleaning and detergent cleaning will not remove deeply embedded soils in the pores of concrete surfaces. In addition, these methods saturate the concrete, which then requires a drying period (which is not always practical).

Surface Abrading

Surface abrading can be accomplished by:

1. Mechanical abrading
2. Water blasting
3. Abrasive blasting

Of the three methods to produce a roughened surface, the most technically effective is abrasive blasting by means of sandblasting or shot blasting, followed by broom sweeping, vacuum cleaning, or an air blast to remove the abrasive. However, in some instances, this may not be a practical approach.

Acid Etching

Acid etching is a popular procedure for both new and aged concrete. It must be remembered that during this process, acid fumes will evolve and may be objectionable. Also, thorough rinsing is required, which saturates the concrete. This may necessitate a long drying period, depending on the coating used.

COATING SELECTION

Before selecting a monolithic surfacing material, the physical properties and conditions of the concrete, as well as environmental conditions, must be known. Factors such as alkalinity, porosity, water adsorption and permeability, and weak tensile strength must be considered. The tendency of concrete to crack, particularly on floors, must also enter into the decision. Floor cracks can develop as a result of periodic overloading or from drying shrinkage. Drying shrinkage is not considered a working moment, while periodic overloading is. In the former, a rigid flooring system could be used, while in the latter an elastomeric caulking of the moving cracks would be considered.

Selection can be influenced by the presence of substrate water during coating. If the concrete cannot be dried, one of the varieties of water-based or water-tolerant systems should be considered.

When aggressive environments are present, the surface profile and surface porosity of the concrete must be taken into account. If complete coverage of the substrate is required, specification of film thickness or number of coats may require modification. Block fillers may be required. In a nonaggressive atmosphere, an acrylic latex coating may suffice.

Specific environmental conditions will dictate the type of coating required. Not only must atmospheric pollutants be considered, but any local pollutants must also be taken into account. Also to be considered are the local weather conditions, which will result in minimum and maximum temperatures as seasons change. The possibilities of chemical spillage on the surface must also be considered. Coatings can be applied in various thicknesses, depending on the environment and contaminants.

Thin film coatings are applied at less than 20 mil dry film thickness. Commonly used are epoxies that may be formulations of polyamides, polyamines, polyesters, or phenolics. These coatings will protect against spills of hydrocarbon fuels, some weak solutions of acids and alkalies, and many agricultural chemicals. Epoxies can also be formulated to resist spills of aromatic solvents such as xylol or toluol.

Most epoxies will lose some of their gloss and develop a "chalk face" when exposed to weather. However, this does not affect their chemical resistance.

Medium film coatings are applied at approximately 20 to 40 mil dry film thickness. Epoxies used in this category are often flake filled to give them rigidity, impact strength, and increased chemical resistance. The flakes can be mica, glass, or other inorganic platelets.

Vinyl esters are also used in this medium film category. These coatings exhibit excellent resistance to many acids, alkalies, hypochlorites, and solvents. Vinyl esters can also be flake filled to improve their resistance.

Some vinyl esters require the application of a low-viscosity penetrating primer to properly cleaned and profiled concrete before application, while others can be applied directly.

Thick film coatings are installed by two means. The specialty epoxy types are mixed with inorganic aggregates and trowel applied. The vinyl esters are applied with a reinforcing glass mat.

Table 13.2 provides a guideline for specifying film thickness.

The success or failure of a chemical-resistant monolithic surfacing is based on proper selection of materials and their application. Unless the problem is defined, the proper material cannot be selected. To define the problem, the following information is required:

1. Identify all chemicals that will be present, as well as their concentrations. It is not sufficient to say that the pH will be 4, 7, or 11. This tells you only that it is acid, neutral, or alkaline. It does not indicate whether the environment is oxidizing or nonoxidizing, organic or inorganic, alternately acid or alkaline, etc.

TABLE 13.2
Guidelines for Specifying Film Thickness

	Film Thickness		
Contaminant	**Thin**	**Medium**	**Thick**
Aliphatic hydrocarbons	x	x	x
Aromatic hydrocarbons	x	x	
Organic acids:			
Weak	x		
Moderate	x	x	
Strong			x
Inorganic acids:			
Weak	x		
Moderate		x	
Strong			x
Alkalies:			
Weak	x		
Moderate		x	x
Strong			x
Bleach liquors	x		
Oxygenated fuels	x	x	
Fuel additives	x	x	
Deionized water			x
Methyl ethyl ketone	x	x	
Fermented beverages	x	x	
Seawater	x		
Hydraulic/brake fluids	x	x	x

2. Is the application fumes, splash, or total immersion? Floors can have integral trenches and sumps, curbs, pump pads, etc.
3. What are the minimum and maximum temperatures to which the installation will be subjected?
4. Is the installation indoors or outdoors? Thermal shock and ultraviolet exposure can be detrimental to many resin systems.
5. What are the physical conditions? Foot traffic vs. vehicular traffic, impact from dropping steel plates vs. paper boxes, etc. must be defined.
6. Longevity — how long must it last? Is process obsolescence imminent? This could have a major effect on cost.
7. Must it satisfy standards organizations such as the U.S.D.A. or FDA? Some systems do not meet these standards.
8. Some resin systems are odoriferous, which could eliminate their use in many processing plants, such as food, beverage, and pharmaceutical.

Answering these questions will permit a selection of a suitable monolithic surfacing material.

To select a coating material to meet the conditions of the problem, the following properties of any potential coating system must be considered:

1. Chemical resistance
2. Physical strength (compressive, tensile, flexural, bond, and shear)
3. Flexibility
4. Thermal limits, upper and lower
5. Effect of thermal shock
6. K factor of the material (what will be the thermal insulation effect of the coating?)
7. Coefficient of thermal expansion
8. Cure shrinkage of the material
9. Absorption of water or specific chemicals in the anticipated service

The most popular monolithic surfacings are formulated from the following resins:

1. Epoxy, including epoxy novolac
2. Polyester
3. Vinyl ester, including vinyl ester novolac
4. Acrylic
5. Urethane, rigid and flexible
6. Phenolic novolacs
7. Silicates
8. Sodium silicate
9. Potassium silicate
10. Silica
11. Furan

The major advantages observed from the use of chemical-resistant monolithic surfacings include:

1. These formulations provide flexibility, giving aesthetically attractive materials with a wide range of chemical resistance, physical properties, and methods of application.
2. These formulations provide high early development of physical properties. Compressive values with some systems reach 5000 psi (35 MPa) in 2 hours and 19,000 psi (133 MPa) as an ultimate compressive value.
3. Most systems are equally appropriate for applications to new and existing concrete, including pour-in-place.
4. Systems offer ease of installation by in-house maintenance personnel.
5. Systems offer economy when compared to many types of brick and tile installations.
6. Systems are available for horizontal, vertical, and overhead installations.

Furan polymer concretes are inherently brittle and in large masses have a tendency to shrink. They are used when resistance to acids, alkalies, and solvents such as aromatic and aliphatic solvents is required. They have been successfully

used in small areas in the chemical, electronic, pharmaceutical, steel, and metal working industries.

Polyester, vinyl ester, and acrylic polymer concretes have strong aromatic odors that can be offensive to installation and in-plant personnel. Fire codes, particularly for acrylics, must be studied to ensure compliance.

Polymer concretes are not to be confused with polymer-modified Portland cement concrete. Polymer concretes are totally chemical-resistant compounds with outstanding physical properties. Polymer concretes pass the immersion test, at varying temperatures, for sustained time periods. Polymer-modified Portland cement can use some of the same generic resins as used in polymer concrete, but with different results.

The success of monolithic surfacing installations depends on the qualifications of the design, engineering, and installation personnel, be they in-house or outside contractors.

The following basic rules are important to the success of any monolithic surfacing installation:

1. Substrate must be properly engineered to be structurally sound, free of cracks, and properly sloped to drains.
2. New as well as existing slabs must be clean and dry, free of laitance and contaminants, with a coarse surface profile.
3. Ambient slab and materials to be installed should be 65° to 85°F (18 to 29°C). Special catalyst and hardening systems are available to accommodate higher or lower temperatures, if required.
4. Thoroughly prime substrate before applying any monolithic surfacing. Follow the manufacturer's directions.
5. Thoroughly mix individual and combined components at a maximum speed of 500 rpm to minimize air entrainment during installation.
6. Uncured materials must be protected from moisture and contamination.

INSTALLATION OF COATINGS

Monolithic surfacings can be installed by a variety of methods, many of which are the same methods used in the Portland cement concrete industry. The primary methods are:

1. Hand troweled
2. Power troweled
3. Spray
4. Pour-in-place/self-level
5. Broadcast

Hand Troweled

Hand-troweled applications are approximately 1/4 in. (6 mm) thick, and are suggested for small areas or areas with multiple obstructions such as piers, curbs, column

foundations, trenches, and sumps. The finished application is tight, dense, and with a high-friction finish. Topcoat sealers are recommended to provide increased density and imperviousness with a smooth, easy-to-clean finish. High- and low-friction finishes are easily accomplished predicated on end-use requirements.

Power Troweling

Large areas with minimal obstructions are best handled with power troweling. The minimum thickness would be 1/4 in. (6. mm). The density of the finish can be improved by the use of appropriate sealers.

Spray

Spray applications are also ideal for areas where corrosion is aggressive. Spray applications are applied, minimum 1/8 in. (3 mm) thick in one pass on horizontal surfaces. On vertical and overhead areas, including structural components, the material can be spray-applied 1/16 to 1/32 in. thick (1.5 to 2.4 mm) in one pass and without slump. The mortar-like consistency of the material can be varied to control slump and the type of finish. Floors installed in this manner are dense, smooth, safe finishes for people and vehicular traffic.

Pour-in-Place/Self-Level

Pour-in-place and self-level materials are intended for flat areas where the pitch to floor drains and trenches is minimal. They are intended for light-duty areas with minimal process spills. The completed installation is 1/8 to 1/16 in. (3 to 5 mm) thick with a very smooth, high gloss, easy-to-clean, aesthetically attractive finish.

Broadcast

Economical and aesthetically attractive floors can be applied by the broadcast system, in which the resins are "squeegee" applied to the concrete slab. Filler or colored quartz aggregates of varying color and size are sprinkled or broadcast into the resin. Excess filler and quartz are vacuumed or swept from the floor after the resin has set. This results in a floor thickness of 3/32 to 1/8 in. (2 to 3 mm). This type of floor is outstanding for light industrial and interior floors.

CHEMICAL RESISTANCE

Reinforced concrete and carbon steel are outstanding general construction materials, and have a record of success in a wide range of industries and applications. However, when oxygen and water are present, these materials will corrode. This corrosion process is accelerated by weather and chemicals.

Chemical-resistant monolithic surfacings are used to protect concrete and steel in a variety of applications across a wide range of industries, including

recycling and waste treatment plants and the agricultural industry, producers of fertilizers and agricultural chemicals.

The pharmaceutical, food, and beverage industries are faced with corrosion from chemicals and food acids, as well as from acid and alkaline cleaning and sanitizing chemicals.

Chemical-resistant monolithic surfacings are proven solutions to a wide range of these types of corrosion problems.

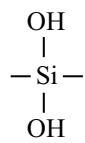
Table 13.3 shows the comparative chemical resistance for the most popular resins and polymer concretes used as monolithic surfacings. Additional data can be found as each resin or polymer concrete is discussed and in the tables found at the end of this chapter. Table 13.4 provides the atmospheric corrosion resistance of monolithic concrete surfacings.

Silicates

These materials are noted for their resistance to concentrated acids, except hydrofluoric acid and similar fluorinated chemicals at elevated temperatures. They are also resistant to many aliphatic and aromatic solvents. They are not intended for use in alkaline or alternately acid and alkaline environments. This category of surfacings includes:

1. Sodium silicate mortar
2. Potassium silicate mortar
3. Silica (silica sol) mortar

The alkali silicates form a hard coating by a polymerization reaction involving repeating units of the structure:



The sodium and potassium silicate mortars are available as two-component systems: filler and binder, with a setting agent in the filler. Sodium and potassium silicates are referred to as soluble silicates because of their solubility in water. This prevents their use in many dilute acid services, while they are not affected by strong concentrated acids. This disadvantage becomes an advantage for formulating single-component powder systems. All that is required is the addition of water at the time of use. The fillers of these materials are pure silica.

The original sodium silicate acid resisting mortar uses an inorganic silicate base consisting of two components, a powder and a liquid. The powder is basically quartzite of selected gradation and a setting agent. The liquid is a special sodium silicate solution. When the mortar is used, the two components are mixed together and hardening occurs via chemical reaction.

TABLE 13.3
Comparative Chemical Resistance

1-A = bisphenol A epoxy—aliphatic amine hardener
1-B = bisphenol A epoxy—aromatic amine hardener
1-C = bisphenol F epoxy (epoxy novolac)
2-D = polyester resin—chlorendic acid type
2-E = polyester resin—bisphenol A fumarate type
3-F = vinyl ester resin
3-G = vinyl ester novolac resin

	1			2		3	
Medium, R.T.	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Acetic acid, to 10%	R	R	R	R	R	R	R
Acetic acid, 10–15%	C	R	C	R	R	C	R
Benzene	C	R	R	R	N	R	R
Butyl alcohol	R	C	R	R	R	N	R
Chlorine, wet, dry	C	C	C	R	R	R	R
Ethyl alcohol	R	C	R	R	R	R	R
Fatty acids	C	R	C	R	R	R	R
Formaldehyde, to 37%	R	R	R	R	R	R	R
Hydrochloric acid, to 36%	C	R	R	R	R	R	R
Kerosene	R	R	R	R	R	R	R
Methyl ethyl ketone, 100%	N	N	N	N	N	N	N
Nitric acid, to 20%	N	N	R	R	R	R	R
Nitric acid, 20–40%	N	N	R	R	N	N	C
Phosphoric acid	R	R	R	R	R	R	R
Sodium hydroxide, to 25%	R	R	R	N	R	R	R
Sodium hydroxide, 25–50%	R	C	R	N	R	C	R
Sodium hypochlorite, to 6%	C	R	R	R	R	R	R
Sulfuric acid, to 50%	R	R	R	R	R	R	R
Sulfuric acid, 50–75%	C	R	R	R	C	R	R
Xylene	N	R	R	R	R	N	R

Note: R.T. = room temperature; R = recommended; N = not recommended, C = conditional.

Source: From Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings, in *Corrosion Engineering Handbook,* P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.

This mortar may be cast, poured, or applied by guniting. It has excellent acid resistance and is suitable for use over a pH range of 0.0 to 7.0.

The sodium silicates can be produced over a wide range of compositions of the liquid binder. These properties and new hardening systems have improved the water resistance of some sodium silicate mortars. These formulations are capable of resisting dilute as well as concentrated acids without compromising physical properties.

TABLE 13.4
Atmospheric Corrosion Resistance of Monolithic Concrete Surfacings

	Atmospheric Pollutant							
Surfacing	**NO_x**	**H_2O**	**SO_2**	**CO_2**	**UV**	**Chloride Salt**	**Weather**	**Ozone**
Epoxy-bisphenol A								
Aromatic amine hardener	R	X	X	R	R	R	R	R
Epoxy novolac	R	X	X	R	R	R	R	R
Polyesters:								
Isophthalic	R	R	X	R	RS	R	R	R
Chlorendic	R	R	X	R	RS	R	R	R
Bisphenol A fumarate	R	R	X	R	RS	R	R	R
Vinyl esters	R	R	R	R	R	R	R	R
Acrylics	R		R	R	R	R	R	R
Urethanes	R		X		R	R		

Note: R = resistant; X = not resistant; RS = resistant when stabilized.

Source: From Schweitzer, Philip A., *Atmospheric Degradation and Corrosion Control,* Marcel Dekker, New York, 1999.

The original potassium silicate mortars first appeared in 1981. The potassium silicate materials are less versatile in terms of formulation flexibility than sodium silicate materials. However, they are less susceptible to crystallization in high concentrations of sulfuric acid as long as metal ion contamination is minimal. Potassium silicate materials are available with halogen-free hardening systems, thereby removing the remote possibility of catalyst poisoning in certain chemical processes.

Chemical-setting potassium silicate materials are supplied as two-component systems that comprise the silicate solution and the filler powder and setting agent. Setting agents may be inorganic, organic, or a combination of both. The properties of the mortar are determined by the setting agent and the alkali–silica ratio of the silicate used. Properties such as absorption, porosity, strength, and water resistance are affected by the choice of setting agent. Organic setting agents will burn out at low temperatures, thereby increasing porosity and absorption. Organic setting agents are water soluble and can be leached out if the surfacing is exposed to steam or moisture. Mortars that use inorganic setting agents are water and moisture resistant.

Silicate formulations will fail when exposed to mild alkaline media, such as bicarbonate of soda. Dilute acid solutions, such as nitric acid, will have a deleterious effect on sodium silicates unless the water-resistant type is used.

TABLE 13.5
Minimum Physical and Thermal Properties of Various Silicate Mortars

Property	Sodium	Potassium		Silica
		Normal	Halogen-Free	
Tensile, psi (MPa) ASTM Test Method C-307	400 (3)	700 (5)	700 (5)	400 (3)
Flexural, psi (MPa) ASTM Test Method C-580	500 (3)	1400 (10)	1800 (12)	900 (6)
Compressive, psi (MPa)	2000 (14)	3000 (21)	5000 (34)	3500 (24)
ASTM Test Method	C-579	C-396	C-396	C-396
Bond, psi (MPa) ASTM Test Method C-321	150 (1)	150 (1)	200 (1)	150 (1)
Max. temp., °F (°C)	2100 (1149)	1700 (927)	1650 (900)	1500 (816)

Silica and silica sol types of mortars are the newest of this class of material. They consist of colloidal silica binding instead of sodium or potassium silicates, with a quartz filler. These materials are two-component systems that comprise a powder composed of high-quality crushed quartz and a hardening agent, which are mixed with a colloidal silica solution to form the mortar. These mortars are recommended for use in the presence of hot concentrated sulfuric acid. They are also used for weak acid conditions up to a pH of 7.

The workability and storage stability are comparable for the sodium and potassium silicates. The silica materials are harder to use, less forgiving as to mix ratio, and highly susceptible to irreversible damage due to freezing in storage.

Table 13.5 provides thermal and physical properties for the three types of silicate mortars. The chemical resistance of the various silicate mortars are very similar. Table 13.6 points out the subtle differences between the respective mortars. The compatibility of silicate mortars with selected corrodents can be fond in the table at the end of this chapter.

Epoxy and Epoxy Novolac Coatings

The three most often used epoxy resins for monolithic surfacings are the bisphenol A, bisphenol F (epoxy novolac), and epoxy phenol novolac. These base components react with epichlorhydrin to form resins of varying viscosity and molecular weight. The hardening systems employed to effect the cure or solidification will determine the following properties of the cured system:

1. Chemical and thermal resistance
2. Physical properties
3. Moisture tolerance
4. Workability
5. Safety during use

TABLE 13.6
Comparative Chemical Resistance: Silicate Mortars

	Sodium		Potassium	
Medium, R.T.	**Normal**	**Water Resistant**	**Normal**	**Halogen-free**
Acetic acid, glacial	G	G	R	R
Chlorine dioxide, water sol.	N	N	R	R
Hydrogen peroxide	N	R	N	N
Nitric acid, 5%	C	R	R	R
Nitric acid, 20%	C	R	R	R
Nitric acid, over 20%	R	R	R	R
Sodium bicarbonate	N	N	N	N
Sodium sulfite	R	R	N	N
Sulfates, aluminum	R	R	R	R
Sulfates, copper	G	G	R	R
Sulfates, iron	G	G	R	R
Sulfates, magnesium	G	G	R	R
Sulfates, nickel	G	G	R	R
Sulfates, zinc	G	G	R	R
Sulfuric acid, to 93%	G	G	R	R
Sulfuric acid, over 93%	G	G	R	R

Note: R.T. = room temperature; R = recommended; N = not recommended; G = potential failure, crystalline growth; C = conditional.

Bisphenol A epoxy is the most popular, followed by bisphenol F, which is sometimes referred to as an epoxy novolac. The epoxy phenol novolac is a higher viscosity resin that requires various types of diluents or resin blends for formulating coatings.

The bisphenol A resin uses the following types of hardeners:

1. Aliphatic amines
2. Modified aliphatic amines
3. Aromatic amines
4. Others

Table 13.7 shows effects of hardeners on the chemical resistance of the finished coating of bisphenol A systems for typical compounds. Table 13.8 provides a comparison of the general chemical resistance of optimum chemical-resistant bisphenol A, aromatic amine cured, with bisphenol F resin systems.

Amine hardening systems are the most popular for ambient temperature curing epoxy coatings. These systems are hygroscopic and can cause allergenic responses to sensitive skin. These responses can be minimized or virtually eliminated by attention to personal hygiene and the use of protective creams on

TABLE 13.7
Types of Epoxy Hardeners and Their Effect on Chemical Resistance

	Hardeners		
Medium	**Aliphatic Amines**	**Modified Aliphatic Amines**	**Aromatic Amines**
Acetic acid, 5–10%	C	N	R
Benzene	N	N	R
Chromic acid, <5%	C	N	R
Sulfuric acid, 25%	R	C	R
Sulfuric acid, 50%	C	N	R
Sulfuric acid, 75%	N	N	R

Note: R = recommended; N = not recommended; C = conditional.

Source: From Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings, in Corrosion Engineering Handbook, P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.

TABLE 13.8
Comparative Chemical and Thermal Resistance of Bisphenol A Aromatic Amine Cured vs. Bisphenol F (Epoxy Novolac)

Medium, R.T.	**Bisphenol A**	**Bisphenol F**
Acetone	N	N
Butyl acetate	C	E
Butyl alcohol	C	E
Chromic acid, 10%	C	E
Formaldehyde, 35%	E	G
Gasoline	E	E
Hydrochloric acid, to 36%	E	E
Nitric acid, 30%	N	C
Phosphoric acid, 50%	E	E
Sulfuric acid, to 50%	E	E
Trichloroethylene	N	G
Max. temp., °F (°C)	160 (71)	160 (71)

Note: R.T. = room temperature; C = conditional; N = not recommended; E = excellent; G = good.

Source: Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings, in *Corrosion Engineering Handbook,* P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.

exposed areas of the skin (i.e., face, neck, arms, and hands). Protective garments, including gloves, are recommended when using epoxy materials.

Epoxies are economical, available in a wide range of formulations and properties, and offered by many manufacturers. Formulations are available for interior as well as exterior applications. However, when installed outside, moisture from beneath the slab can affect adhesion and cause blistering.

The typical epoxy system is installed in layers of primer, base, and finish coats. Overall, the installation can take several days. Epoxies should not be applied to new concrete before it has reached full strength (approximately 28 days).

The bisphenol F (epoxy novolac) systems are essentially premium-grade epoxy resins providing an increased chemical resistance. They are also available in a wide range of formulations and from many manufacturers. The primary advantage in the use of epoxy novolacs lies in their improved resistance to higher concentrations of oxidizing and nonoxidizing acids, and aliphatic and aromatic solvents. Refer to Table 13.9.

TABLE 13.9
Corrosion Resistance of Bisphenol A and Bisphenol F Epoxies

	Hardeners			
			Aromatic Amines Bisphenol	
Corrodent at R.T.	**Aliphatic Amines**	**Modified Aliphatic Amines**	**A**	**F**
Acetic acid, 5–10%	C	U	R	
Acetone	U	U	U	U
Benzene	U	U	R	R
Butyl acetate	U	U	U	R
Butyl alcohol	R	R	R	R
Chromic acid, 5%	U	U	R	R
Chromic acid, 10%	U	U	U	R
Formaldehyde, 35%	R	R	R	R
Gasoline	R	R	R	R
Hydrochloric acid, to 36%	U	U	R	R
Nitric acid, 30%	U	U	U	U
Phosphoric acid, 50%	U	U	R	R
Sulfuric acid, 25%	R	U	R	R
Sulfuric acid, 50%	U	U	R	R
Sulfuric acid, 75%	U	U	U	U
Trichloroethylene	U	U	U	R

Note: R = recommended; U = unsatisfactory; R.T. = room temperature

Source: Schweitzer, Philip, A., *Encyclopedia of Corrosion Technology,* Marcel Dekker, New York, 1998.

Disadvantages of these systems are that they involve:

1. Less plastic with slightly more shrinkage
2. Slightly less resistance to alkaline media

The thermal resistance and physical properties are otherwise very similar to the bisphenol A systems.

The novolacs are more expensive than the bisphenol A epoxies and can discolor from contact with sulfuric and nitric acids. For exposure to normal atmospheric pollutants, the bisphenol A epoxies are satisfactory. However, if the surface is to be exposed to other more aggressive contaminants, then the novolacs should be considered.

Additional data regarding the compatibility of the epoxy resin systems with selected corrodents will be found in the table at the end of this chapter and in Reference 4.

Furan Resins

The polyfurfural alcohol or furan resins are the most versatile of all the resins used to formulate corrosion-resistant mortars. They are used for monolithic surfacings; however, they are not a popular choice due to their brittleness and their propensity to shrink. The furan mortars are resistant to most nonoxidizing organic and inorganic acids, alkalies, salts, oils, greases, and solvents to temperatures of 360°F (182°C). Fillers are either 100% carbon, 100% silica, or part carbon/part silica. The 100% carbon-filled mortar provides the widest range of corrosion resistance. Table 13.10 provides comparative chemical resistances for furan resin mortars with 100% carbon and part carbon/silica fillers.

Of all the room-temperature curing resins, furans are one of the highest in thermal resistance with excellent physical properties. Most synthetic resins are petrochemical based but the furan resins are unique because they are agriculturally based. Agricultural byproducts such as corn cob, bagasse, rice, and oat hull are used to produce furfural alcohol.

The furan resin mortars are two-component, convenient-to-use systems consisting of resin and filler. The filler contains an acid that acts as the catalyst or hardener system. Because of the inherent chemical resistance of the resin combined with a 100% carbon filler, this formulation provides chemical resistance to all concentrations of alkalies as well as hydrofluoric acid and other fluorine chemicals. The advantages of mortars with part carbon/part silica fillers are slightly improved workability, physical properties, and cost.

Because of the acidic catalysts used in furan systems, they cannot be applied directly to concrete, steel, or any substrate that would react with the acid. Consequently, various membranes, primers, or mortar bedding systems that are compatible with the substrate are applied first.

TABLE 13.10
Typical Compatibilities of Furan Mortars

Corrodent at R.T.	100% Carbon Filler[a]	Part Carbon/Part Silica Filler[a]
Acetic acid, glacial	R	R
Benzene	R	R
Cadmium salts	R	R
Chlorine dioxide	U	U
Chromic acid	U	U
Copper salts	R	R
Ethyl acetate	R	R
Ethyl alcohol	R	R
Formaldehyde	R	R
Fatty acids	R	R
Gasoline	R	R
Hydrochloric acid	R	R
Hydrofluoric acid	R	U
Iron salts	R	R
Lactic acid	R	R
Methyl ethyl ketone	R	R
Nitric acid	U	U
Phosphoric acid	R	R
Sodium chloride	R	R
Sodium hydroxide, to 20%	R	U
Sodium hydroxide, 40%	R	U
Sulfuric acid, 50%	R	R
Sulfuric acid, 80%	U	U
Trichloroethylene	R	R

[a] R = recommended; N = unsatisfactory; R.T. = room temperature

The versatility of the furan resins is illustrated by these available formulations:

1. High bond strength materials for optimum physical properties
2. Normal bond strength materials for economy and less demanding physical applications
3. 100% carbon filled for improved corrosion resistance
4. Different ratios of carbon and silica for applications requiring varying degrees of conductivity or electrical resistance

Table 13.11 provides physical and thermal properties for normal and high bond strength, 100% carbon-filled mortars.

Part carbon/part silica-filled furan mortars have physical properties equal to or slightly better than the normal bond, 100% carbon-filled furan mortar.

TABLE 13.11
Minimum Physical and Thermal Properties: 100% Carbon-Filled Furan Mortars

	Mortar	
Property	**Normal Bond**	**High Bond**
Tensile, psi (MPa) ASTM Test Method C-307	800 (6)	800 (6)
Flexural, psi (MPa) ASTM Test Method C-580	1600 (11)	1600 (11)
Compressive, psi (MPa) ASTM Test Method C-579	5000 (34)	5000 (34)
Bond, psi (MPa) ASTM Test Method C-321	150 (1)	800 (6)
Max. temp., °F (°C)	350 (177)	350 (177)

Polyester Mortars

At the request of the pulp and paper industry, chemical-resistant polyester mortars were developed and introduced in the early 1950s. The request was for a mortar to resist chlorine dioxide, which was being used in a new bleach process. Polyester mortars became the primary mortar for use where resistance to oxidizing media is required.

Depending on the application, polyester mortars can be formulated to incorporate carbon and silica fillers. Carbon (100%) fillers are used for applications requiring resistance to hydrofluoric acid, fluorine chemicals, and strong alkalies such as sodium and potassium hydroxide. These mortars are excellent in most acids but lack resistance to some solvents. Their temperature limit is 250°F (120°C), and they have an effective pH range of 0.9 to 14.0.

Several types of polyester resins are available, the most popular of which are:

1. Isophthalic
2. Chlorendic acid
3. Bisphenol A fumarate

The original polyester mortars were based on the isophthalic polyester. Although it performed satisfactorily in many oxidizing media, it did have certain physical, thermal, and chemical resistance limitations. Improved chemical resistance, higher thermal capabilities, and improved ductility with less shrinkage were achieved by formulations containing chlorendic and bisphenol A fumarate resins. The bisphenol A fumarate resins provide improved resistance to alkalies and essentially equivalent resistance to oxidizing media.

Table 13.12 provides the chemical resistance of chlorendic and bisphenol A fumarate resins in the presence of selected corrodents.

TABLE 13.12
Chemical Resistance of Chlorendic and Bisphenol A Fumarate Resins

	Polyester	
Corrodent at R.T.	**Chlorendic**	**Bisphenol A Fumarate**
Acetic acid, glacial	U	U
Benzene	U	U
Chlorine dioxide	R	R
Ethyl alcohol	R	R
Hydrochloric acid, 36%	R	R
Hydrogen peroxide	R	U
Methanol	R	R
Methyl ethyl ketone	U	U
Motor oil and gasoline	R	R
Nitric acid, 40%	R	U
Phenol, 5%	R	R
Sodium hydroxide, 50%	U	R
Sulfuric acid, 75%	R	U
Toluene	U	U
Triethanolamine	U	R
Vinyl toluene	U	U

Note: R = recommended; U = unsatisfactory; R.T. = room temperature

Source: Schweitzer, Philip, A., *Encyclopedia of Corrosion Technology,* Marcel Dekker, New York, 1998.

Polyester resins have provided outstanding chemical resistance in a wide variety of applications throughout the pulp and paper, textile, steel and metalworking, pharmaceutical, and chemical process industries. All the resins are able to accommodate carbon and silica as fillers, which are easily mixed and handled for various types of installations. Aesthetic consideration can be met because they are easily pigmented. The polyester mortars can be applied to many substrates, including concrete, steel, etc. These resin systems can be formulated to be compatible with a wide range of temperatures, humidities, and corrodents.

Polyester mortars have certain limitations, including:

1. A strong aromatic odor that can be offensive for certain indoor and confined space applications
2. Shelf-life limitations that can be controlled by low-temperature storage (below 60°F (15°C)) of the resin component.

Table 13.13 provides comparative chemical resistances of the three most popular types of polyester resins. Table 13.14 lists the minimum physical properties for polyester resin mortars having 100% carbon and 100% silica fillers.

TABLE 13.13
Comparative Chemical Resistance of Various Polyester Resins

Medium, R.T.	Isophthalic	Chlorendic	Bisphenol A Fumarate
Acids, oxidizing	R	R	R
Acids, nonoxidizing	R	R	R
Alkalies	N	N	R
Salts	R	R	R
Bleaches	R	R	R
Max. temp., °F (°C)	225 (107)	260 (127)	250 (121)

Note: R.T. = room temperature; R = recommended; N = not recommended.

Source: Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings, in *Corrosion Engineering Handbook,* P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.

Phenolic Mortars

Phenolic resins were originally developed in Europe in the late 1880s. At the turn of the century, the only chemical-resistant mortar available was based on the inorganic silicates. These materials have exceptional acid resistance but little or no resistance to many other chemicals. Physical limitations also pose problems.

Further investigation of the phenolics was prompted after World War I to overcome the limitations of the silicates. Eventually, the phenolic resins found a wide variety of applications because of their excellent physical properties.

By the 1930s, the chemical process and the steel and metalworking industries required more functional and chemical resistant mortars. Chemical resistance and excellent physical properties were required.

TABLE 13.14
Minimum Physical Properties: Polyester Resin Mortars

	Filler	
Property	Carbon	Silica
Tensile, psi (MPa) ASTM Test Method C-307	1500 (10)	1800 (12)
Flexural, psi (MPa) ASTM Test Method C-580	3000 (21)	4000 (28)
Compressive, psi (MPa) ASTM Test Method C-579	9000 (62)	10,000 (69)
Bond to Brick or Tile, psi (MPa) ASTM Test Method C-321	200 (1)	350 (2)

TABLE 13.15
Typical Capabilities of Phenolic Mortars

	Filler	
Corrodent at R.T.	**Carbon**	**Silica**
Amyl alcohol	R	R
Chromic acid, 10%	U	U
Gasoline	R	R
Hydrofluoric acid, to 50%	R	U
Hydrofluoric acid, 93%	R	U
Methyl ethyl ketone	R	R
Nitric acid, 10%	U	U
Sodium hydroxide, to 5%	U	U
Sodium hydroxide, 30%	U	U
Sodium hypochlorite, 5%	U	U
Sulfuric acid, to 50%	R	R
Sulfuric acid, 93%	R	R
Xylene	R	R

Note: R = recommended; U = unsatisfactory; R.T. = room temperature

The first phenolic resin mortar was introduced in the United States in the mid-1930s. It met the two important requirements of the chemical, steel, and metalworking industries:

1. Provide chemical resistance to high concentrations of acids, particularly sulfuric acid, at elevated temperatures.
2. Provide good bond strength while possessing excellent tensile, flexural, and compressive properties.

Phenolic resins permit the use of 100% carbon, 100% silica, or part carbon/part silica as fillers in phenolic mortars. Silica fillers are used in the presence of high concentrations of sulfuric acid and where electrical resistance is required. Carbon fillers are used in the presence of high concentrations of hydrofluoric acid. Table 13.15 provides a comparison of the chemical resistance of carbon-filled and silica-filled phenolic mortars.

They have good resistance to most mineral acids and solutions of inorganic salts and to mildly oxidizing solutions, but are rapidly attacked by strong oxidizing agents such as nitric, chromic, and concentrated sulfuric acids. They are resistant to mild alkaline solutions and many solvents but have poor resistance to strong alkalies. The temperature limit is 350°F (175°C), and they are effective in the pH range from 0.7 to 9.0. Table 13.16 provides the compatibility of phenolic with selected corrodents. Remember that the correct filler must be used.

TABLE 13.16
Compatibility of Phenolic with Selected Corrodents[a]

Chemical	Maximum Temp. °F	°C	Chemical	Maximum Temp. °F	°C
Acetic acid, 10%	212	100	Hydrobromic acid, to 50%	200	93
Acetic acid, glacial	70	21	Hydrochloric acid, to 38%	300	149
Acetic anhydride	70	21	Hydrofluoric acid	x	x
Acetone	x	x	Lactic acid, 25%	160	71
Aluminum sulfate	300	149	Methyl isobutyl ketone	160	71
Ammonium carbonate	90	32	Muriatic acid	300	149
Ammonium chloride, to sat.	80	27	Nitric acid	x	x
Ammonium hydroxide, 25%	x	x	Phenol	x	x
Ammonium nitrate	160	71	Phosphoric acid, 50–80%	212	100
Ammonium sulfate	300	149	Sodium chloride	300	149
Aniline	x	x	Sodium hydroxide	x	x
Benzene	160	71	Sodium hypochlorite	x	x
Butyl acetate	x	x	Sulfuric acid, 10%	250	121
Calcium chloride	300	149	Sulfuric acid, 50%	250	121
Calcium hypochlorite	x	x	Sulfuric acid, 70%	200	93
Carbonic acid	200	93	Sulfuric acid, 90%	70	21
Chromic acid	x	x	Sulfuric acid, 98%	x	x
Citric acid, conc.	160	71	Sulfurous acid	80	27
Copper sulfate	300	149			

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an "x".

Phenolic mortars are similar to the furans in that they are two-component, easy-to-use mortars, with the acid catalyst or curing agent incorporated in the powder. Phenolic resins are not often used to formulate monolithic surfacings.

Phenolic resins have a limited shelf life and must be stored at 45°F (7°C). Phenolic resin mortars can be allergenic to sensitive skin, just as the epoxies. The use of protective creams, and the practice of good personal hygiene, can minimize or prevent any problems.

Table 13.17 provides the minimum physical and thermal properties of 100% carbon vs. 100% silica-filled phenolic mortars. Table 13.18 provides comparative chemical resistances for phenolic mortars, compared to furan mortars, carbon vs. silica filled.

To satisfy the need to provide a coating system that has the ability to bridge cracks and provide improved corrosion resistance, medium build coating systems have been developed. The phenolic/epoxy novolac system is capable of bridging cracks and providing outstanding corrosion resistance.

TABLE 13.17
Minimum Physical and Thermal Properties: 100% Carbon– vs. 100% Silica-Filled Phenolic Mortar

	Filler	
Property	**100% Carbon**	**100% Silica**
Tensile, psi (MPa) ASTM Test Method C-307	800 (6)	400 (3)
Flexural, psi (MPa) ASTM Test Method C-580	1800 (13)	1800 (13)
Compressive, psi (MPa) ASTM Test Method C-579	4500 (31)	6000 (41)
Bond, psi (MPa) ASTM Test Method C-321	150 (1)	150 (1)
Absorption, % ASTM Test Method C-413	1.0	1.0
Maximum temp., °F (°C)	350 (177)	350 (177)

TABLE 13.18
Comparative Chemical Resistance: Phenolic Mortars vs. Furan Mortars

	Furan		Phenolic	
Medium, R.T.	**Carbon**	**Silica**	**Carbon**	**Silica**
Amyl alcohol	R	R	R	R
Chromic acid, 10%	N	N	N	N
Gasoline	R	R	R	R
Hydrofluoric acid, to 50%	R	N	R	N
Hydrofluoric acid, 93%	N	N	R	N
Methyl ethyl ketone	R	R	R	R
Nitric acid, 10%	N	N	N	N
Sodium hydroxide, to 5%	R	R	N	N
Sodium hydroxide, 30%	R	N	N	N
Sodium hypochlorite, 5%	N	N	N	N
Sulfuric acid, to 50%	R	R	R	R
Sulfuric acid, 93%	N	N	R	R
Xylene	R	R	R	R

Note: R.T. = room temperature; R = recommended; N = not recommended.

One such system uses a low-viscosity penetrating epoxy primer. Low viscosity allows use of the primer in areas that need a fast turnaround by quickly "wetting out" the substrate. If surface deterioration or preparation presents an unacceptably high solid/high build an epoxy polyamide filler/sealer is used.

For deep pits, the crack filler used is a two-component epoxy paste developed specifically for sealing and smoothing out applications on concrete. The crack filler can be used to fill small hairline cracks, big holes, gouges, or divots when minimum movement of the substrate is expected.

Vinyl Ester Resin

Vinyl ester resins are addition reactions of methacrylic acid and epoxy resin. These resins have the same properties as the epoxy, acrylic, and bisphenol A fumarate resins.

The vinyl ester resins are the most corrosion resistant of any monolithic surfacing systems, and they are also the most expensive and difficult to install. They are used where extremely corrosive conditions are present. The finished flooring is vulnerable to hydrostatic pressure and vapor moisture transmission. Refer to Table 13.19 for their resistance to selected corrodents.

The major advantage of these resins is their resistance to most oxidizing mediums and high concentrations of sulfuric acid, sodium hydroxide, and many solvents.

Vinyl esters have the disadvantages of having:

1. A strong aromatic odor for indoor or outdoor confined space applications
2. A shelf-life limitation of the resins that require refrigerated storage below 60°F (15°C) to extend its useful life

These mortars are excellent in most acids and are recommended for use in bleach areas and mild oxidizing agents. They lack resistance to strong caustics and some solvents. Their temperature limit is 250°F (120°C) and they have an effective pH range of 0.9 to 14.0. Table 13.20 provides a comparison of the chemical and thermal resistances of polyester vs. vinyl ester mortars.

Acrylic Resins

Acrylic monolithic surfacing and polymer concretes are installed in thicknesses of 1/8 to 1/2 in. (3 to 13 mm) and 1/2 in. and greater, respectively. They are intended to protect against moderate corrosion environments. They excel at water and weather resistance and are best at "breathing" in the presence of a moisture transmission problem in the slab. Acrylic polymer concrete is particularly suitable in areas subject to normal atmospheric corrosion. It exhibits resistance to airborne SO_2, SO_3, and NO_x.

The primary advantages of acrylic resins include:

1. They are the easiest of the resin systems to mix and apply using pour-in-place and self-leveling techniques.
2. They are equally suitable for indoor and outdoors applications due to their outstanding weather resistance.

TABLE 13.19
Resistance of Vinvl Ester and Vinyl Ester Novolac to Selected Corrodents

	Vinyl Ester	
Corrodent	**Vinyl Ester**	**Novolac**
Acetic acid, glacial	U	R
Benzene	R	R
Chlorine dioxide	R	R
Ethyl alcohol	R	R
Hydrochloric acid, 36%	R	R
Hydrogen peroxide	R	R
Methanol	U	R
Methyl ethyl ketone	U	U
Motor oil and gasoline	R	R
Nitric acid, 40%	U	R
Phenol, 5%	R	R
Sodium hydroxide, 50%	R	R
Sulfuric acid, 75%	R	R
Toluene	U	R
Triethanolamine	R	R
Vinyl toluene	U	R
Max. temp., °F (°C)	220 (104)	230 (110)

Note: R = recommended; U = unsatisfactory.

Source: Schweitzer, Philip A., *Encyclopedia of Corrosion Technology,* Marcel Dekker, New York, 1998.

3. They are the only system that can be installed at below freezing temperatures, 25°F (–4°C), without having to use special hardening or catalyst systems.
4. They are the fastest set and cure of all resin systems. The monolithics will support foot and light-wheeled traffic in 1 hour, whereas the thicker cross-section polymer concrete will also support foot and light-wheeled traffic in 1 hour while developing 90% of its ultimate strength in 4 hours.
5. They are the easiest to pigment. Various types of aggregates can be added to make the surface aesthetically attractive.
6. They bond well to concrete and can be used for maintenance or new construction. They are ideal for rehabilitating manufacturing, warehouse, and loading dock floors to impart wear resistance and ease of cleaning.

Acrylic systems have the inherent disadvantage of an aromatic odor that may be objectionable for interior or confined space applications.

TABLE 13.20
Comparative Chemical and Thermal Resistance of Polyester vs. Vinyl Ester Mortars

	Polyester		Vinyl Ester	
Medium, R.T.	**Chlorendic**	**Bisphenol A Fumarate**	**Vinyl Ester**	**Novolac**
Acetic acid, glacial	C	N	N	R
Benzene	C	N	R	R
Chlorine dioxide	R	R	R	R
Ethyl alcohol	R	R	R	R
Hydrochloric acid, 36%	R	R	R	R
Hydrogen peroxide	R	N	R	R
Methanol	R	R	N	R
Methyl ethyl ketone	N	N	N	N
Motor oil and gasoline	R	R	R	R
Nitric acid, 40%	R	N	N	R
Phenol, 5%	R	R	R	R
Sodium hydroxide, 50%	N	R	R	R
Sulfuric acid, 75%	R	C	R	R
Toluene	C	N	N	R
Triethanolamine	N	R	R	R
Vinyl toluene	C	N	C	R
Max. temp., °F (°C)	260 (127)	250 (121)	220 (104)	230 (110)

Note: R.T. = room temperature; R = recommended; N = not recommended; C = conditional.

Urethane Resins

Urethane systems are similar to acrylic systems insofar as being intended for protection against moderate to light corrosion environments. The urethane systems are intended to be monolithic floors with elastomeric properties installed in thicknesses of 1/8 to 1/4 in. (3 to 6 mm). Standard systems are effective at temperatures of 10 to 140°F (–24 to 60°C). High-temperature systems are available for exposure to temperatures of 10 to 180°F (–24 to 82°C). Many urethane systems are capable of bridging cracks up to 1/16 in. (1.6 mm).

Monolithic urethane flooring systems have the following advantages:

1. They are easy to mix and apply using the pour-in-place, self-leveling application technique.
2. Systems are available for indoor and outdoor applications.
3. The elastomeric quality of the systems provides under-floor comfort for production line flooring applications.
4. Because of their elastomeric quality, they have excellent sound-deadening properties.

5. They have outstanding resistance to impact and abrasion.
6. They are excellent waterproof flooring systems for above-grade light- and heavy-duty floors and can be used for maintenance and new-construction applications.
7. They are capable of bridging gaps in concrete up to 1/16 in. (1.6 mm) wide.

The urethanes will retain their appearance (gloss retention, nonchalking, and fading) for extended periods of time. Care must be taken during storage and application of the urethanes because they are moisture sensitive prior to full cure. Contamination will cause foaming, blistering, and loss of the glossy appearance of a coated substrate.

Urethane materials are demanding systems during installation. The mix ratio of components, temperature, and humidity controls are necessary for successful installations.

The comparative chemical resistance of acrylic and urethane systems are shown in Table 13.21.

TABLE 13.21
Comparative Chemical Resistance: Urethane vs. Acrylic Systems

		Urethane	
Medium, R.T.	**Acrylic**	**Standard**	**High Temperature**
Acetic acid, 10%	G	G	C
Animal oils	G	G	N
Boric acid	E	E	E
Butter	G	F	N
Chromic acid, 5–10%	C	C	C
Ethyl alcohol	N	N	N
Fatty acids	F	F	N
Gasoline	E	N	N
Hydrochloric acid, 20–36%	F	C	C
Lactic acid, above 10%	F	C	C
Methyl ethyl ketone, 100%	N	N	N
Nitric acid, 5–10%	G	C	F
Sulfuric acid, 20–50%	G	C	C
Water, fresh	E	E	E
Wine	G	G	F

Note: R.T. = room temperature; E = excellent, G = good; F = fair; C = conditional; N = not recommended.

Source: Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings, in *Corrosion Engineering Handbook,* P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.

TABLE 13.22
Minimum Physical and Thermal Properties of Acrylic Monolithic Surfacings and Urethane Monolithic Surfacings

	Acrylics	Urethanes	
Property	**Monolithic**	**Standard**	**High Temperature**
Tensile, psi (MPa) ASTM Test Method C-307	1000 (7)	650 (5)	550 (5)
Flexural, psi (MPa) ASTM Test Method C-580	2500 (17)	1100 (8)	860 (6)
Compressive, psi (MPa) ASTM Test Method C-579	8000 (55)	2500 (17)	1500 (10)
Bond to concrete	Concrete fails	Concrete fails	Concrete fails
Max. temp., °F (°C)	150(66)	140 (60)	180 (82)

Source: Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings," in *Corrosion Engineering Handbook,* P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.

The physical properties of acrylic systems are different from those of urethane systems. The acrylic flooring systems are extremely hard and too brittle to be considered for applications subjected to excessive physical abuse such as impact from steel plate or heavy castings. Conversely, the inherent flexibility of the urethanes and their impact resistance are suitable for those applications.

Table 13.22 provides physical and thermal properties for the various acrylic and urethane flooring systems.

Precast and poured-in-place polymer concrete has been successfully used in many indoor and outdoor applications in a variety of industries, particularly the chemical, automotive, and pharmaceutical industries.

COMPARATIVE CHEMICAL RESISTANCE

The charts on the following pages provide the compatibility of the various monolithic coatings and surfacings with selected corrodents. The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data is available. Incompatibility is shown by an "X". A blank indicates that data is unavailable. Source is Reference 4.

Remember that the various coatings and surfacing materials are subject to compounding and in some instances alternative hardeners and fillers are available. Therefore, in the following charts when compatibility is shown, it indicates that at least one formulation is satisfactory. The manufacturer must be queried to determine that the correct formulation is being supplied.

Refer to Table 13.4 for the compatibility of coatings and surfacings with atmospheric pollutants.

Acetaldehyde

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	110 (43)
Sodium silicate	400 (204)	Epoxy	150 (66)
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	
		Urethane	X

Acetic Acid, 10%

Coating	MaxTemp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	220 (104)
Sodium silicate	400 (204)	Epoxy	180 (82)
Potassium silicate	400 (204)	Phenolic	210 (99)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	260 (127)	Acrylic	X
		Urethane	90 (32)

Acetic Acid, 20%

Coating	MaxTemp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	200 (93)
Sodium silicate	400 (204)	Epoxy	240 (116)
Potassium silicate	400 (204)	Phenolic	210 (99)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	X
		Urethane	80 (27)

Acetic Acid, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	160 (71)
Sodium silicate	400 (204)	Epoxy	110 (43)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Acetic Acid, 80%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	110 (43)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	150 (66)
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Acetic Acid, Glacial

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	120 (49)
Silica	400 (204)	Vinyl ester	150 (66)
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Acetone

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate		Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	X
		Urethane	90 (32)

Acrylic Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate		Phenolic	X
Silica		Vinyl ester	100 (38)
Furan resin	370 (188)	Acrylic	
		Urethane	

Adipic Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	100 (38)
Sodium silicate	100 (38)	Epoxy	250 (121)
Potassium silicate		Phenolic	
Silica		Vinyl ester	180 (32)
Furan resin	100 (38)	Acrylic	
		Urethane	

Alum

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	X	Epoxy	140 (60)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	240 (116)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	

Aluminum Chloride, Aq.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	260 (127)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	90 (32)

Ammonia, Anhydrous

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	140 (60)
Sodium silicate	X	Epoxy	260 (127)
Potassium silicate		Phenolic	
Silica		Vinyl ester	220 (104)
Furan resin	380 (193)	Acrylic	90 (32)
		Urethane	90 (32)

Ammonium Carbonate

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate		Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	90 (32)
Silica	400 (204)	Vinyl ester	150 (66)
Furan resin	310 (154)	Acrylic	90 (32)
		Urethane	90 (32)

Ammonium Hydroxide, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	250 (121)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	150 (66)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	90 (32)

Ammonium Hydroxide, 25%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	250 (121)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	80 (27)
Silica	X	Vinyl ester	150 (66)
Furan resin	390 (199)	Acrylic	80 (27)
		Urethane	90 (32)

Ammonium Hydroxide, Sat.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	100 (38)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	130 (54)
Furan resin	330 (166)	Acrylic	80 (27)
		Urethane	90 (32)

Ammonium Nitrate

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	200 (93)
Silica	400 (204)	Vinyl ester	250 (121)
Furan resin	350 (177)	Acrylic	
		Urethane	90 (32)

Ammonium Sulfate, 10–40%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	220 (104)
Silica	400 (204)	Vinyl ester	220 (104)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Ammonium Sulfate, Sat.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	300 (149)
Silica	400 (204)	Vinyl ester	220 (104)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	

Ammonium Sulfide

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	120 (49)
Furan resin	370 (188)	Acrylic	
		Urethane	

Aniline

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Aqua Regia, 3:1

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Benzene

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	100 (38)
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Boric Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	120 (49)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	90 (32)

Bromine, Liquid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate		Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Bromine Water, Dilute

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester, 5%	100 (38)
Sodium silicate, 5%	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester, 5%	180 (82)
Furan resin	X	Acrylic	
		Urethane	X

Bromine Water, Sat.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate		Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	
Furan resin	330 (166)	Acrylic	
		Urethane	X

Calcium Chloride, Dilute

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	200 (93)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	80 (27)

Calcium Chloride, Sat.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	200 (93)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	80 (27)

Calcium Hydroxide, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Calcium Hydroxide, 20%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Calcium Hydroxide, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Calcium Hypochlorite

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester, 20%	80 (27)
Sodium silicate	X	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	X	Acrylic	80 (27)
		Urethane	X

Calcium Bisulfite

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	180 (82)
Sodium silicate	400 (204)	Epoxy	140 (60)
Potassium silicate		Phenolic	
Silica		Vinyl ester	260 (127)
Furan resin	360 (182)	Acrylic	90 (32)
		Urethane	90 (32)

Carbon Tetrachloride

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	140 (60)
Potassium silicate	400 (204)	Phenolic	110 (43)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	X
		Urethane	90 (32)

Carbonic Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	90 (32)
Sodium silicate		Epoxy	200 (93)
Potassium silicate		Phenolic	200 (93)
Silica		Vinyl ester	120 (49)
Furan resin		Acrylic	90 (32)
		Urethane	80 (27)

Chlorine, Liquid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate		Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	

Chlorine Water

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	X	Acrylic	80 (27)
		Urethane	X

Chromic Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	150 (66)
Furan resin	X	Acrylic	X
		Urethane	90 (32)

Chromic Acid, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate		Epoxy	X
Potassium silicate		Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Chromic Acid, 40%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate		Epoxy	X
Potassium silicate		Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Chromic Acid, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate		Epoxy	X
Potassium silicate		Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Citric Acid, 5%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Citric Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	210 (99)
Furan resin	360 (182)	Acrylic	80 (27)
		Urethane	90 (32)

Citric Acid, 15%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	

Citric Acid, Conc.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	

Coconut Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	160 (71)
Sodium silicate		Epoxy	110 (43)
Potassium silicate		Phenolic	160 (71)
Silica		Vinyl ester	200 (93)
Furan resin		Acrylic	
		Urethane	

Copper Chloride

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	220 (104)
Sodium silicate		Epoxy	210 (99)
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	220 (104)
Furan resin	330 (166)	Acrylic	80 (27)
		Urethane	80 (27)

Copper Sulfate

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	220 (104)
Sodium silicate		Epoxy	210 (99)
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	210 (99)
Furan resin	330 (166)	Acrylic	X
		Urethane	90 (32)

Corn Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	250 (121)
Sodium silicate		Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	
Silica		Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	
		Urethane	

Cottonseed Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate		Phenolic	100 (38)
Silica		Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	110 (43)

Ethers (General)

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate		Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	330 (166)	Acrylic	X
		Urethane	X

Ethyl Acetate

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	X
		Urethane	90 (32)

Ethylene Glycol

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate		Phenolic	160 (71)
Silica		Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	90 (32)

Fatty Acids

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate		Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	250 (121)
Furan resin	330 (166)	Acrylic	90 (32)
		Urethane	

Formic Acid, 5%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	
		Urethane	X

Formic Acid, 10–85%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	200 (93)
Silica	400 (204)	Vinyl ester	100 (38)
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Formic Acid, Anhydrous

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic, 90%	200 (93)
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Hydrobromic Acid, Dilute

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate		Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	90 (32)
Silica	400 (204)	Vinyl ester	180 (32)
Furan resin	330 (166)	Acrylic	
		Urethane	

Hydrobromic Acid, 20%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	90 (32)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	100 (38)	Acrylic	
		Urethane	

Hydrobromic Acid, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	100 (38)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	100 (38)	Acrylic	
		Urethane	

Hydrochloric Acid, Dilute

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	100 (38)
Silica	400 (204)	Vinyl ester	230 (104)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Hydrochloric Acid, 20%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	100 (38)
Silica	400 (204)	Vinyl ester	220 (104)
Furan resin	370 (188)	Acrylic	
		Urethane	80 (27)

Hydrochloric Acid, 35%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	90 (32)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	80 (27)

Hydrochloric Acid, 38%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	90 (32)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	90 (32)

Hydrochloric Acid, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	110 (43)
Silica	400 (204)	Vinyl ester	140 (60)
Furan resin	330 (166)	Acrylic	90 (32)
		Urethane	X

Hydrofluoric Acid, Dilute

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	100 (38)
Silica	X	Vinyl ester	160 (71)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	

Hydrofluoric Acid, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin	370 (188)	Acrylic	
		Urethane	

Hydrofluoric Acid, 40%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin	370 (188)	Acrylic	
		Urethane	

Hydrofluoric Acid, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin	370 (188)	Acrylic	
		Urethane	

Hydrofluoric Acid, 70%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin	X	Acrylic	
		Urethane	

Hydrofluoric Acid, 100%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin	X	Acrylic	90 (32)
		Urethane	

Hydrogen Peroxide, Dilute

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	140 (60)
Furan resin	X	Acrylic	
		Urethane	

Hydrogen Peroxide, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	X	Phenolic	
Silica	X	Vinyl ester	160 (71)
Furan resin	X	Acrylic	
		Urethane	

Hydrogen Peroxide, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	80 (27)
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	
Silica	X	Vinyl ester	110 (38)
Furan resin	X	Acrylic	80 (27)
		Urethane	

Hydrogen Peroxide, 90%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	80 (27)
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	80 (27)
Silica	X	Vinyl ester	150 (66)
Furan resin	X	Acrylic	80 (27)
		Urethane	

Lactic Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	210 (99)
Furan resin	390 (199)	Acrylic	X
		Urethane	80 (27)

Lactic Acid, Conc.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	X
		Urethane	

Lard Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	
		Urethane	80 (27)

Linseed Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate		Phenolic	
Silica		Vinyl ester	230 (110)
Furan resin	370 (188)	Acrylic	
		Urethane	80 (27)

Methyl Acetate

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	X
Furan resin	370 (188)	Acrylic	
		Urethane	

Methyl Ethyl Ketone

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	X
Silica		Vinyl ester	X
Furan resin	210 (99)	Acrylic	
		Urethane	90 (32)

Methyl Isobutyl Ketone

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	X
Sodium silicate		Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	80 (27)
Silica		Vinyl ester	X
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Methylene Chloride

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	X
Furan resin	100 (38)	Acrylic	X
		Urethane	X

Mineral Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	250 (121)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	90 (32)

Muriatic Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	220 (104)
Sodium silicate		Epoxy	210 (99)
Potassium silicate	400 (204)	Phenolic	110 (43)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	330 (166)	Acrylic	
		Urethane	

Nitric Acid, 5%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	X	Acrylic	X
		Urethane	80 (27)

Nitric Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	140 (60)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	150 (66)
Furan resin	X	Acrylic	X
		Urethane	X

Nitric Acid, 20%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	150 (66)
Furan resin	X	Acrylic	X
		Urethane	X

Nitric Acid, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	100 (38)
Furan resin	X	Acrylic	X
		Urethane	X

Nitric Acid, 40%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	200 (93)
Furan resin	X	Acrylic	X
		Urethane	X

Nitric Acid, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Nitric Acid, 70%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Nitric Acid, 100%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	
Silica		Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Oils, Vegetable

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	190 (88)
Furan resin	370 (188)	Acrylic	
		Urethane	

Peanut Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	140 (60)
Sodium silicate		Epoxy	
Potassium silicate	400 (204)	Phenolic	
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	310 (154)	Acrylic	
		Urethane	

Phenol, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	90 (32)
Silica	400 (204)	Vinyl ester	100 (38)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	X

Phenol

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	X
Silica		Vinyl ester	X
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	X

Phosphoric Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate	400 (204)	Phenolic	210 (99)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	90 (32)

Phosphoric Acid, 25–50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate		Epoxy	X
Potassium silicate	400 (204)	Phenolic	200 (93)
Silica	400 (204)	Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	90 (32)

Phosphoric Acid, 50–85%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	X	Epoxy	X
Potassium silicate	400 (204)	Phenolic	X
Silica	400 (204)	Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	

Potassium Hydroxide, 5%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	150 (66)
Furan resin	100 (38)	Acrylic	100 (38)
		Urethane	

Potassium Hydroxide, 27%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	150 (66)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	

Potassium Hydroxide, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	X
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	

Potassium Hydroxide, 90%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	
Silica	X	Vinyl ester	X
Furan resin		Acrylic	90 (32)
		Urethane	

Sodium Chloride

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	250 (121)
Potassium silicate	400 (204)	Phenolic	160 (71)
Silica	400 (204)	Vinyl ester	180 (82)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	80 (27)

Sodium Hydroxide, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	160 (71)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	80 (27)

Sodium Hydroxide, 15%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	140 (60)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	80 (27)

Sodium Hydroxide, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	150 (66)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	80 (27)

Sodium Hydroxide, 50%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate	X	Phenolic	160 (71)
Silica	X	Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	90 (32)

Sodium Hydroxide, 70%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	
Sodium silicate	X	Epoxy	80 (27)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin		Acrylic	80 (27)
		Urethane	

Sodium Hydroxide, Conc.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	
Sodium silicate	X	Epoxy	80 (27)
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	X
Furan resin		Acrylic	90 (32)
		Urethane	

Sodium Hypochlorite, 20%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester, 15%	180 (82)
Furan resin	X	Acrylic, 15%	100 (38)
		Urethane	X

Sodium Hypochlorite, Conc.

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	X	Epoxy	X
Potassium silicate	X	Phenolic	X
Silica	X	Vinyl ester	100 (38)
Furan resin	X	Acrylic	
		Urethane	X

Soybean Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	210 (99)
Sodium silicate	400 (204)	Epoxy	80 (27)
Potassium silicate		Phenolic	
Silica		Vinyl ester	250 (121)
Furan resin	210 (99)	Acrylic	
		Urethane	

Sulfuric Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate		Phenolic	110 (43)
Silica		Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	80 (27)
		Urethane	100 (38)

Sulfuric Acid, 10%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate		Phenolic	110 (43)
Silica		Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	80 (27)

Sulfuric Acid, 30%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	260 (127)
Sodium silicate	400 (204)	Epoxy	X
Potassium silicate		Phenolic	280 (138)
Silica		Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	90 (32)
		Urethane	80 (27)

Sulfuric Acid, 60%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	120 (49)	Epoxy	X
Potassium silicate		Phenolic	200 (93)
Silica		Vinyl ester	190 (88)
Furan resin	100 (38)	Acrylic	90 (32)
		Urethane	X

Sulfuric Acid, 70%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	140 (60)	Epoxy	X
Potassium silicate	210 (99)	Phenolic	200 (93)
Silica	210 (99)	Vinyl ester	180 (82)
Furan resin	100 (38)	Acrylic	80 (27)
		Urethane	X

Sulfuric Acid, 80%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	100 (38)
Sodium silicate	140 (60)	Epoxy	X
Potassium silicate		Phenolic	90 (32)
Silica		Vinyl ester	X
Furan resin	100 (38)	Acrylic	X
		Urethane	X

Sulfuric Acid, 90%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	100 (38)	Epoxy	X
Potassium silicate		Phenolic	80 (27)
Silica		Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Sulfuric Acid, 95%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	X	Polyester	X
Sodium silicate	100 (38)	Epoxy	X
Potassium silicate		Phenolic	X
Silica		Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Sulfuric Acid, 100%

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	X
Sodium silicate		Epoxy	X
Potassium silicate		Phenolic	X
Silica		Vinyl ester	X
Furan resin	X	Acrylic	X
		Urethane	X

Tall Oil

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	180 (82)
Potassium silicate		Phenolic	110 (43)
Silica		Vinyl ester	200 (93)
Furan resin	370 (188)	Acrylic	
		Urethane	

Tannic Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	220 (104)
Sodium silicate		Epoxy	210 (99)
Potassium silicate		Phenolic	90 (32)
Silica		Vinyl ester	200 (93)
Furan resin	380 (193)	Acrylic	80 (27)
		Urethane	80 (27)

Tartaric Acid

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	250 (121)
Sodium silicate	400 (204)	Epoxy	210 (99)
Potassium silicate		Phenolic, 10%	170 (77)
Silica		Vinyl ester	210 (99)
Furan resin	370 (188)	Acrylic	
		Urethane	90 (32)

Thionyl Chloride

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	X
Sodium silicate	X	Epoxy	X
Potassium silicate		Phenolic	80 (27)
Silica		Vinyl ester	X
Furan resin	X	Acrylic	
		Urethane	

Wines

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate		Polyester	250 (121)
Sodium silicate	X	Epoxy	250 (121)
Potassium silicate		Phenolic	
Silica		Vinyl ester	160 (71)
Furan resin	370 (188)	Acrylic	X
		Urethane	X

Xylene

Coating	Max Temp., °F (°C)	Coating	Max Temp., °F (°C)
Silicate	400 (204)	Polyester	100 (38)
Sodium silicate	400 (204)	Epoxy	100 (38)
Potassium silicate	400 (204)	Phenolic	130 (54)
Silica	400 (204)	Vinyl ester	130 (54)
Furan resin	370 (188)	Acrylic	
		Urethane	X

REFERENCES

1. Schweitzer, Philip A., *Atmospheric Degradation and Corrosion Control,* Marcel Dekker, New York, 1999.
2. Boova, Augustas A., Chemical Resistant Mortars, Grouts, and Monolithic Surfacings, in *Corrosion Engineering Handbook,* P.A. Schweitzer, Ed., Marcel Dekker, New York, 1996, pp. 459–487.
3. Schweitzer, Philip, A., *Encyclopedia of Corrosion Technology,* Marcel Dekker, New York, 1998.
4. Schweitzer, Philip, A., *Corrosion Resistance Tables, fifth edition,* Marcel Dekker, New York, 2004.

14 Comparative Resistance of Coatings and Paints

The following tables provide the compatibility of coatings for immersion service, mortars, and paints with selected corrodents. The information was obtained from Philip A. Schweitzer, P.E., *Corrosion Resistance Tables*, Vol. 1–4, Fifth Edition, Marcel Dekker, New York, 2004.

CORROSION RESISTANCE TABLES

All chemicals are either in the pure state or a saturated solution unless otherwise indicated. Coatings for immersion service and mortars are shown at the maximum allowable temperature for which they are compatible. Incompatibility is indicated by an X. A blank space indicates data is not available. Compatibility for paints is indicated by an R and incompatibility by an X. A blank space indicates data is not available.

It is important to remember that most of the coatings are subject to formulation; therefore, when compatibility is indicated, it means that at least one formulation is suitable. Consequently, it is necessary to verify with the manufacturer that his formulation is suitable for the application. This also applies to many of the paints.

Acetic Acid, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	210/100	Acrylics	R, S
Epoxy	190/88	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R, W
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, S, W
Neoprene	160/71	Epoxies:	R
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	100/38	Polyamine	R, S
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R, S
PTFE	450/232	Polyvinyl butyral	R
ETFE	250/121	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	R
Fluoroelastomers	190/88	Urethanes:	R
PVDF	300/149	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R
Halogenated PE	140/60	Zinc rich	R
Silicone (methyl)	90/32		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	160/71		
Epoxy	140/60		
Vinyl ester	200/93		
Acrylic	90/32		
Urethane	90/32		

Acetic Acid, 80%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	110/43	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	150/66	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R, W
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	160/71	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R, S
PTFE	450/232	Polyvinyl butyral	R
ETFE	230/110	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	R
Fluoroelastomers	180/82	Urethanes:	
PVDF	190/88	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	160/71	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	100/38	Zinc rich	
Silicone (methyl)	90/32		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	X		
Epoxy	X		
Vinyl ester	150/66		
Acrylic	X		
Urethane	X		

Acetic Acid, Glacial

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	70/21	Acrylics	X
Epoxy	X	Alkyds:	
Furans	80/27	Long oil	
Vinyl ester	150/66	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	200/93	Silicone (methyl)	
Fluoroelastomers	X	Urethanes:	
PVDF	190/88	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	110/43	Zinc rich	
Silicone (methyl)	90/32		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	X		
Epoxy	X		
Vinyl ester	140/60		
Acrylic	X		
Urethane	X		

Acetic Acid, Vapors

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	110/43	Acrylics	X
Epoxy	X	Alkyds:	
Furans		Long oil	
Vinyl ester	90/32	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R
Neoprene	90/32	Epoxies:	
Polysulfides	90/32	Aliphatic polyamine	
Hypalon	90/32	Polyamide	X
Plastisols	X	Polyamine	
PFA	200/93	Phenolic	R
FEP	400/232	Polyesters	R
PTFE	400/232	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	200/93	Silicone (methyl)	R
Fluoroelastomers	90/32	Urethanes:	
PVDF	180/82	Aliphatic	R
Isophthalic PE, 50%	110/43	Aromatic	R
Bis. A fum. PE		Vinyls	X
Hydrogenated PE		Vinyl ester	R
Halogenated PE, 25%	180/82	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	160/71
Epoxy	140/38
Vinyl ester	90/32
Acrylic	X
Urethane	90/32

Acetic Anhydride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	200/93	Long oil	X
Vinyl ester	100/38	Short oil	X
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	200/93	Polyamide	R
Plastisols	X	Polyamine	
PFA	200/93	Phenolic	X
FEP	400/232	Polyesters	X
PTFE	400/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	100/38	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	100/38	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	100/38	Vinyls	
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	100/38	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	100/38		
Acrylic	X		
Urethane	X		

Acetone

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	110/43	Alkyds:	
Furans	80/27	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	90/32	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	X
ETFE	150/66	Polyvinyl formal	X
ECTFE	150/66	Silicone (methyl)	R
Fluoroelastomers	X	Urethanes:	
PVDF	X	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	X	Vinyls	R, W
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	100/43		

Mortars	
Sodium silicate	
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	90/32

Ammonium Bicarbonate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	90/32	Alkyds:	
Furans	250/121	Long oil	
Vinyl ester	160/71	Short oil	
Epoxy polyamide	250/121	Asphalt	
Coal tar epoxy	90/32	Chlorinated rubber	
Coal tar	90/32	Coal tar	R
Urethanes		Coal tar epoxy	R, W
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon, 25%	160/71	Polyamide	R
Plastisols		Polyamine	R
PFA	400/204	Phenolic	
FEP	450/232	Polyesters	R
PTFE		Polyvinyl butyral	R
ETFE		Polyvinyl formal	R
ECTFE		Silicone (methyl)	
Fluoroelastomers		Urethanes:	
PVDF		Aliphatic	
Isophthalic PE	120/149	Aromatic	
Bis. A fum. PE	150/66	Vinyls	R, W
Hydrogenated PE		Vinyl ester	
Halogenated PE, 15%	130/54	Zinc rich (Dilute)	R
Silicone (methyl)			
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan			
Polyester	150/66		
Epoxy			
Vinyl ester	160/71		
Acrylic			
Urethane			

Ammonium Carbonate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	90/32	Acrylics	R, S
Epoxy	140/60	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	150/66	Short oil	
Epoxy polyamide	160/71	Asphalt	R
Coal tar epoxy, 50%	110/43	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy, 50%	R, W
Neoprene	200/93	Epoxies: 50%	R, S
Polysulfides		Aliphatic polyamine	
Hypalon	140/60	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	
Fluoroelastomers	190/888	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	90/32	Vinyls	R
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	140/60	Zinc rich (Dilute)	R
Silicone (methyl)			

Mortars	
Sodium silicate	
Potassium silicate	450/232
Silica	450/232
Furan	310/154
Polyester	100/38
Epoxy	100/38
Vinyl ester	150/66
Acrylic	90/32
Urethane	

Ammonium Chloride, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	90/32	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	220/104	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	R, W
Polysulfides	150/66	Aliphatic polyamine	
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	R, S
PFA	400/204	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	290/143	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	200/93	Zinc rich	R
Silicone (methyl)	80/27		
	Mortars		
Sodium silicate	100/38		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic	80/27		
Urethane	90/32		

Ammonium Chloride, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	220/104	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	200/93	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	190/88	Epoxies:	R, W
Polysulfides	150/66	Aliphatic polyamine	
Hypalon	200/93	Polyamide	
Plastisols		Polyamine	
PFA	430/221	Phenolic	
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE		Silicone	R, S
Fluoroelastomers	300/149	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE		Vinyl ester	R, S
Halogenated PE	200/93	Zinc rich (Dilute)	R
Silicone (methyl)			

Mortars	
Sodium silicate	100/38
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	200/93
Acrylic	90/32
Urethane	90/32

Ammonium Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	80/27	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	R
Vinyl ester	200/93	Short oil	R
Epoxy polyamide	100/38	Asphalt, up to 30%	R
Coal tar epoxy (dry)		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy (dry)	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	150/66	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	R
PFA	400/204	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	300/149	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R
Halogenated PE	200/93	Zinc rich (dilute)	R
Silicone (methyl)			

Mortars	
Sodium silicate	100/38
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	200/93
Acrylic	90/32
Urethane	90/32

Ammonium Hydroxide, 25%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R, S
Epoxy	140/60	Alkyds:	
Furans	250/121	Long oil	R
Vinyl ester	100/38	Short oil	R
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	110/43	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/38	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	190/88	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE, 20%	140/60	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	90/32	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	390/199
Polyester	250/121
Epoxy	250/121
Vinyl ester	100/38
Acrylic	80/27
Urethane	90/32

Ammonium Hydroxide, Saturated

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	150/66	Alkyds:	
Furans	200/93	Long oil	X
Vinyl ester	130/54	Short oil	X
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	80/27	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE	300/149	Silicone	R
Fluoroelastomers	190/88	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE		Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	90/32	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	330/166		
Polyester	100/38		
Epoxy	100/38		
Vinyl ester	130/54		
Acrylic	X		
Urethane			

Ammonium Nitrate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy, 25%	250/121	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	250/121	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R, S
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	200/93	Polyamide	E
Plastisols	140/60	Polyamine	R
PFA	350/177	Phenolic	
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	300/149	Silicone	R
Fluoroelastomers	X	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	200/93	Vinyl ester	R, W, S
Halogenated PE	200/93	Zinc rich	X
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	350/177
Polyester	250/121
Epoxy	250/121
Vinyl ester	250/121
Acrylic	X
Urethane	X

Aniline

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	150/66	Alkyds:	
Furans	80/27	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	140/60	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	X
ETFE	230/110	Polyvinyl formal	X
ECTFE	90/32	Silicone (methyl)	X
Fluoroelastomers	230/110	Urethanes:	
PVDF	200/93	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	120/149	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	X

Benzene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	X
Epoxy	180/82	Alkyds:	
Furans	260/127	Long oil	R
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	X
ETFE	210/99	Polyvinyl formal	X
ECTFE	140/60	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	140/60	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	R, W
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	90/32	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	100/38
Vinyl ester	X
Acrylic	X
Urethane	X

Benzoic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics, 10%	100/38	Acrylics	X
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R
Neoprene	150/66	Epoxies:	
Polysulfides	150/66	Aliphatic polyamine	
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic 10%	R
FEP	400/204	Polyesters	R, S, W
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	250/121	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	250/121	Aliphatic	X
Isophthalic PE	180/82	Aromatic	X
Bis. A fum. PE	180/82	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	250/121	Zinc rich	
Silicone (methyl)	80/27		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	140/60		
Epoxy	140/60		
Vinyl ester	180/82		
Acrylic	X		
Urethane	X		

Boric Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	120/149	Acrylics	R, S
Epoxy	220/104	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	140/60	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar	100/38	Coal tar	R, W
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	280/138	Polyamide	R, S
Plastisols	140/60	Polyamine	R
PFA	300/149	Phenolic	R
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	390/199	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	180/82	Zinc rich	
Silicone (methyl)	180/82		

Mortars

Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	100/38
Vinyl ester	200/93
Acrylic	
Urethane	

Bromine Gas, Dry

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar	X	Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	60/16	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	
FEP	200/93	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	150/66	Polyvinyl formal	
ECTFE	X	Silicone (methyl)	
Fluoroelastomers, 25%	180/82	Urethanes:	
PVDF	210/99	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	90/32	Vinyls	X
Hydrogenated PE		Vinyl ester	R
Halogenated PE	100/38	Zinc rich	
Silicone (methyl)			
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	100/38		
Acrylic			
Urethane			

Bromine Gas, Moist

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	60/16	Polyamide	X
Plastisols	X	Polyamine	
PFA	200/93	Phenolic	
FEP	200/93	Polyesters	R
PTFE	250/121	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE		Silicone (methyl)	
Fluoroelastomers, 25%	180/82	Urethanes:	
PVDF	210/99	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	100/38	Vinyls	X
Hydrogenated PE		Vinyl ester	R
Halogenated PE	100/38	Zinc rich	
Silicone (methyl)			
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Bromine, Liquid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	X	Alkyds:	
Furans, 3% Max	300/149	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	60/16	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	140/60	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate	450/232		
Silica	450/232		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Butyl Alcohol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy	140/60	Alkyds:	
Furans	210/99	Long oil	
Vinyl ester	120/49	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon		Polyamide	X
Plastisols	X	Polyamine	R
PFA	380/193	Phenolic	
FEP	400/204	Polyesters	R, S
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE		Silicone (methyl)	R
Fluoroelastomers		Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	80/27	Aromatic	X
Bis. A fum. PE	80/27	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	100/38	Zinc rich	R
Silicone (methyl)			

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	140/60
Vinyl ester	
Acrylic	
Urethane	X

Calcium Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics (dilute)	R, S
Epoxy, 37.5%	180/82	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	110/43	Asphalt, up to 30%	R
Coal tar epoxy	110/43	Chlorinated rubber	R
Coal tar	80/27	Coal tar	R
Urethanes	80/27	Coal tar epoxy	R
Neoprene	200/93	Epoxies:	
Polysulfides	150/66	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	R
PFA	400/204	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	300/149	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	210/99	Vinyl ester	R, W, S
Halogenated PE	250/121	Zinc rich	X
Silicone (methyl)	300/149		

Mortars	
Sodium silicate	X
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	180/82
Acrylic	X
Urethane	X

Calcium Hydroxide

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics (dilute)	R, S
Epoxy	180/32	Alkyds:	
Furans	260/170	Long oil	X
Vinyl ester	180/82	Short oil	X
Epoxy polyamide	140/60	Asphalt (dilute)	R
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar	X	Coal tar (dilute)	R
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	230/110	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R, S
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	X	Zinc rich (dilute)	R
Silicone (methyl)	400/201		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	370/188
Polyester	100/38
Epoxy	250/121
Vinyl ester	180/82
Acrylic	X
Urethane	X

Carbon Dioxide, Dry

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	90/32	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	80/27	Coal tar epoxy	
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	400/204	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R
Fluoroelastomers	80/27	Urethanes:	
PVDF	280/128	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	350/177	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	250/121	Zinc rich	R
Silicone (methyl)	110/43		
	Mortars		
Sodium silicate			
Potassium silicate	450/232		
Silica	450/232		
Furan	330/166		
Polyester	100/38		
Epoxy	100/38		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Carbon Tetrachloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	X
Epoxy	170/77	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	212/100	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	200/93	Polyamide	X
Plastisols	X	Polyamine	R
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	110/43	Vinyls	X
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	120/49	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	140/60
Epoxy	140/60
Vinyl ester	180/82
Acrylic	X
Urethane	X

Carbonic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans		Long oil	
Vinyl ester	120/49	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes	90/27	Coal tar epoxy	
Neoprene	160/71	Epoxies:	
Polysulfides	150/66	Aliphatic polyamine	
Hypalon	90/32	Polyamide	
Plastisols	140/60	Polyamine	R, S
PFA	380/193	Phenolic 10%	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	90/32	Vinyls	R, S
Hydrogenated PE		Vinyl ester	R, S
Halogenated PE	160/71	Zinc rich	
Silicone (methyl)	400/204		

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

Chlorine Gas, Wet

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	250/121	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	90/23	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R, S
PTFE	450/232	Polyvinyl butyral	
ETFE	250/121	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF, 10%	210/99	Aliphatic	X
Isophthalic PE	160/71	Aromatic	X
Bis. A fum. PE	200/93	Vinyls	X
Hydrogenated PE	210/99	Vinyl ester	R, S
Halogenated PE	220/104	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Chlorine, Liquid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy		Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon		Polyamide	
Plastisols	X	Polyamine	
PFA	X	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	X	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF	210/99	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate	450/232		
Silica	450/232		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic			
Urethane			

Chlorobenzene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	260/127	Acrylics	X
Epoxy	150/66	Alkyds:	
Furans	260/127	Long oil	X
Vinyl ester	110/43	Short oil	X
Epoxy polyamide	100/38	Asphalt	X
Coal tar epoxy	100/38	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	R
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	R, S
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	R, W
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	210/99	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	400/104	Urethanes:	
PVDF	220/104	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	R
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	140/60
Epoxy	140/60
Vinyl ester	
Acrylic	X
Urethane	X

Chloroform

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	X
Epoxy	110/43	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	250/121	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	X

Chlorosulfonic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	140/60	Acrylics	X
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	80/27	Polyvinyl formal	
ECTFE	80/27	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	110/43	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	X	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Chromic Acid, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics (dilute)	R, S
Epoxy	110/38	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	140/60	Short oil	
Epoxy polyamide	X	Asphalt (dilute)	R
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar		Coal tar (dilute)	R, W
Urethanes	X	Coal tar epoxy	X
Neoprene	140/60	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	150/66	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	380/193	Phenolic	X
FEP		Polyesters	R
PTFE	450/232	Polyvinyl butyral	R, S
ETFE		Polyvinyl formal	
ECTFE		Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	220/104	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	X	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	180/82	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	X		
Polyester	100/38		
Epoxy	X		
Vinyl ester	140/60		
Acrylic	X		
Urethane	X		

Chromic Acid, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics (conc.)	160/71	Acrylics	X
Epoxy	X	Alkyds:	
Furans (conc.)	250/121	Long oil	
Vinyl ester (conc.)	210/99	Short oil	
Epoxy polyamide	100/38	Asphalt	X
Coal tar epoxy	100/38	Chlorinated rubber	R, S
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene (conc.)	150/66	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon (conc.)	200/93	Polyamide	X
Plastisols (conc.)	140/60	Polyamine	X
PFA (conc.)	450/232	Phenolic	X
FEP (conc.)	400/204	Polyesters	R
PTFE (conc.)	450/232	Polyvinyl butyral	R
ETFE		Polyvinyl formal	R
ECTFE (conc.)	300/149	Silicone (methyl)	X
Fluoroelastomers (conc.)	400/204	Urethanes:	
PVDF (conc.)	250/121	Aliphatic	X
Isophthalic PE (conc.)	200/93	Aromatic	X
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	X	Vinyl ester	R, S
Halogenated PE	250/121	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica	450/232		
Furan	X		
Polyester, 30%	100/38		
Epoxy	X		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Citric Acid, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R, S
Epoxy	190/88	Alkyds:	
Furans	250/121	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar		Coal tar	R
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	150/66	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	R
ETFE	120/49	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	300/149	Urethanes:	
PVDF	250/121	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R
Halogenated PE	250/121	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	250/121		
Epoxy	X		
Vinyl ester	210/99		
Acrylic	X		
Urethane			

Citric Acid, Concentrated

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R
Epoxy	X	Alkyds:	
Furans	250/121	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	250/121	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	370/188	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	R
ETFE		Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	250/121	Aliphatic	
Isophthalic PE	200/93	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R, W
Halogenated PE	250/121	Zinc rich	R
Silicone (methyl)	390/199		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	250/121
Epoxy	X
Vinyl ester	210/99
Acrylic	X
Urethane	

Copper Sulfate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	X
Epoxy, 17%	210/99	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	240/116	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar		Coal tar, dry	R
Urethanes	90/32	Coal tar epoxy, dry	R
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	250/121	Polyamide	
Plastisols	140/60	Polyamine	R
PFA	400/204	Phenolic, dry	R
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R, S
Isophthalic PE	200/93	Aromatic	R, S
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	250/121	Zinc rich	
Silicone (methyl)	210/99		
	Mortars		
Sodium silicate			
Potassium silicate	450/232		
Silica	450/232		
Furan	330/166		
Polyester	220/104		
Epoxy	210/99		
Vinyl ester	240/116		
Acrylic	X		
Urethane			

Detergents

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R, S
Epoxy	250/121	Alkyds:	
Furans	100/38	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	R
Coal tar		Coal tar	R
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	220/104	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	390/199	Phenolic	
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	R
ETFE	300/149	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	200/93
Fluoroelastomers	190/88	Urethanes:	
PVDF		Aliphatic	R
Isophthalic PE	90/32	Aromatic	R
Bis. A fum. PE	90/32	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	90/32	Zinc rich	R
Silicone (methyl)	200/93		

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

Dextrose

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy	100/38	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	240/116	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, S
PTFE	400/204	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	240/116	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	180/82	Aromatic	X
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	220/104	Zinc rich	
Silicone (methyl)	170/77		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	250/121		
Acrylic			
Urethane	X		

Dichloroacetic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar		Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon		Polyamide	X
Plastisols, 20%	100/38	Polyamine	X
PFA	400/204	Phenolic	
FEP	400/204	Polyesters, 20%	R, S
PTFE	400/204	Polyvinyl butyral	
ETFE	150/66	Polyvinyl formal	
ECTFE		Silicone (methyl)	
Fluoroelastomers		Urethanes:	
PVDF	120/149	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	100/38	Vinyls, 20%	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	100/38	Zinc rich	
Silicone (methyl)			
	Mortars		
Sodium silicate, 20%	450/232		
Potassium silicate			
Silica			
Furan, 20%	370/188		
Polyester, 20%	120/49		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Diesel Fuels

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	100/38	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	220/104	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene	80/27	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	80/27	Polyamide	R,S
Plastisols	X	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	180/82	Vinyls	R, S
Hydrogenated PE		Vinyl ester	R, W, S
Halogenated PE	180/82	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan	190/88		
Polyester			
Epoxy	160/71		
Vinyl ester			
Acrylic			
Urethane			

Diethylamine

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy	X	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	120/49	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	R
PFA	200/93	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE	200/93	Polyvinyl formal	
ECTFE	X	Silicone	R
Fluoroelastomers	X	Urethanes:	
PVDF	100/38	Aliphatic	
Isophthalic PE	120/49	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	X	Zinc rich	
Silicone	X		
	Mortars		
Sodium silicate			
Potassium silicate	450/232		
Silica	450/232		
Furan	330/166		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic			
Urethane			

Dimethyl Formamide

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	160/71	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	250/121	Polyvinyl formal	
ECTFE	100/38	Silicone	R, W
Fluoroelastomers	X	Urethanes:	
PVDF	X	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	R
Silicone	300/149		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane			

Ethyl Acetate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	X	Alkyds:	
Furans	200/93	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	90/32	Coal tar epoxy	X
Neoprene	X	Epoxies:	X
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	140/60	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE	150/66	Polyvinyl formal	
ECTFE	150/66	Silicone	R
Fluoroelastomers	X	Urethanes:	
PVDF	160/71	Aliphatic	R, S
Isophthalic PE	X	Aromatic	R, S
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	R
Silicone	170/77		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	X

Ethyl Alcohol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	110/43	Acrylics	X
Epoxy	140/60	Alkyds:	
Furans	140/60	Long oil	R
Vinyl ester	100/38	Short oil	R
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	150/66	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, S
FEP	200/93	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R
Fluoroelastomers	300/149	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	80/27	Aromatic	R
Bis. A fum. PE	90/32	Vinyls	R, W
Hydrogenated PE	90/32	Vinyl ester	R
Halogenated PE	140/60	Zinc rich	R
Silicone	400/204		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	140/60
Epoxy	140/60
Vinyl ester	100/38
Acrylic	X
Urethane	X

Ethylene Glycol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	80/27	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	X
Vinyl ester	210/99	Short oil	R
Epoxy polyamide	100/38	Asphalt	R
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	160/71	Epoxies:	
Polysulfides	150/66	Aliphatic polyamine	R, W
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	R, S
PFA	390/199	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	X
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R, S
Isophthalic PE	250/121	Aromatic	R, S
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	250/121	Zinc rich	R
Silicone (methyl)	400/204		

Mortars

Sodium silicate	450/232
Potassium silicate	
Silica	
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	210/99
Acrylic	X
Urethane	X

Fatty Acids

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	80/27	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	250/121	Short oil	
Epoxy polyamide		Asphalt	X
Coal tar epoxy		Chlorinated rubber	X
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	140/60	Epoxies:	
Polysulfides	X	Aliphatic polyamine	
Hypalon	250/121	Polyamide	
Plastisols	140/60	Polyamine	R, S
PFA	400/204	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE	180/82	Aromatic	
Bis. A fum. PE	200/93	Vinyls	R, W
Hydrogenated PE	220/104	Vinyl ester	R
Halogenated PE	250/121	Zinc rich	R
Silicone (methyl)	X		

Mortars

Sodium silicate	
Potassium silicate	450/232
Silica	450/232
Furan	330/166
Polyester	100/38
Epoxy	100/38
Vinyl ester	250/121
Acrylic	X
Urethane	

Formaldehyde, up to 37% Solution

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy	150/66	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R
Neoprene	140/60	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	140/60	Polyamide	R, S
Plastisols	100/38	Polyamine	R, W
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	230/104	Polyvinyl formal	
ECTFE	150/66	Silicone	R
Fluoroelastomers	350/177	Urethanes:	
PVDF	120/49	Aliphatic	X
Isophthalic PE	140/60	Aromatic	X
Bis. A fum. PE	80/27	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	150/66	Zinc rich	
Silicone	200/93		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	100/38
Vinyl ester	200/93
Acrylic	X
Urethane	X

Formaldehyde, 50% solution

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy		Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	140/60	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R
Neoprene	140/60	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	X	Polyamide	R
Plastisols	120/49	Polyamine	R
PFA		Phenolic	
FEP	400/204	Polyesters	R, S
PTFE	450/232	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	80/27	Silicone (methyl)	R
Fluoroelastomers	X	Urethanes:	
PVDF	280/128	Aliphatic	X
Isophthalic PE	180/82	Aromatic	X
Bis. A fum. PE	80/27	Vinyls	R
Hydrogenated PE		Vinyl ester	R, S
Halogenated PE	120/49	Zinc rich	
Silicone (methyl)	200/93		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	110/43		
Epoxy	110/43		
Vinyl ester	140/60		
Acrylic	X		
Urethane	X		

Formic Acid, 10–85%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics, dilute	R, S
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	160/71	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	90/32	Polyamine	X
PFA	400/204	Phenolic	R, S
FEP	400/204	Polyesters	R, S
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	250/121	Silicone	R
Fluoroelastomers	190/88	Urethanes:	
PVDF	250/121	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	150/66	Vinyls	R, W
Hydrogenated PE	90/32	Vinyl ester	R, S
Halogenated PE	150/66	Zinc rich, dilute	R
Silicone	80/27		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	X

Gasoline, Unleaded

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy	250/121	Alkyds:	
Furans	280/138	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide	100/38	Asphalt	X
Coal tar epoxy	100/38	Chlorinated rubber	X
Coal tar		Coal tar	
Urethanes	80/27	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	250/121	Polyamide	R, S
Plastisols	X	Polyamine	R, W
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	100/38	Aromatic	R
Bis. A fum. PE	90/32	Vinyls	X
Hydrogenated PE	90/32	Vinyl ester	R
Halogenated PE	200/93	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan	380/193		
Polyester	220/104		
Epoxy	80/27		
Vinyl ester	100/38		
Acrylic	X		
Urethane	X		

Glycerine

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R
Epoxy	280/138	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	300/149	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	X
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R, S
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R, W
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	210/99	Vinyl ester	R, S
Halogenated PE, 75%	250/121	Zinc rich	R
Silicone	400/204		

Mortars	
Sodium silicate	450/232
Potassium silicate	
Silica	
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	300/149
Acrylic	X
Urethane	X

Heptane

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	X
Epoxy	150/66	Alkyds:	
Furans	210/99	Long oil	R
Vinyl ester	210/99	Short oil	X
Epoxy polyamide	100/38	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	90/32	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	X
ECTFE	300/149	Silicone (methyl)	
Fluoroelastomers	350/177	Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	200/93	Aromatic	X
Bis. A fum. PE	200/93	Vinyls	R, W
Hydrogenated PE	80/27	Vinyl ester	R
Halogenated PE	200/93	Zinc rich	R
Silicone (methyl)			
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	140/60		
Epoxy	250/121		
Vinyl ester			
Acrylic	X		
Urethane	X		

Hydrobromic Acid, Dilute

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R, S
Epoxy	180/82	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	90/32	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	126/49	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate	450/232		
Silica	450/232		
Furan	330/166		
Polyester	100/38		
Epoxy	100/38		
Vinyl ester	180/82		
Acrylic			
Urethane			

Hydrobromic Acid, 20%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	
Epoxy	180/82	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	100/38	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE	140/60	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	90/32	Vinyl ester	R
Halogenated PE	160/71	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	100/38		
Polyester	100/38		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Hydrobromic Acid, 30%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	X
Epoxy	150/66	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	100/38	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE	140/60	Aromatic	
Bis. A fum. PE	190/88	Vinyls	R, W
Hydrogenated PE	90/32	Vinyl ester	R
Halogenated PE	190/88	Zinc rich	X
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	100/38
Polyester	100/38
Epoxy	X
Vinyl ester	
Acrylic	X
Urethane	

Hydrobromic Acid, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	X
Epoxy	110/43	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	100/38	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE	140/60	Aromatic	
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE	90/32	Vinyl ester	R
Halogenated PE	200/93	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/32		
Potassium silicate	450/32		
Silica	450/32		
Furan	100/38		
Polyester	140/60		
Epoxy	X		
Vinyl ester	200/93		
Acrylic	X		
Urethane			

Hydrochloric Acid, Dilute

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	R, S
Epoxy	200/93	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	220/104	Short oil	
Epoxy polyamide	100/38	Asphalt	R
Coal tar epoxy	100/38	Chlorinated rubber	R, W
Coal tar	X	Coal tar	R, S
Urethanes	X	Coal tar epoxy	R, W
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	160/71	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	350/177	Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	160/71	Aromatic	X
Bis. A fum. PE	190/88	Vinyls	R, W
Hydrogenated PE	180/82	Vinyl ester	R
Halogenated PE	230/110	Zinc rich	R
Silicone (methyl)	90/32		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	250/121
Epoxy	100/38
Vinyl ester	
Acrylic	
Urethane	

Hydrochloric Acid, 20%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	R, S
Epoxy	200/93	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	220/104	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	160/71	Polyamide	X
Plastisols	140/60	Polyamine	R, S
PFA	450/232	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	350/177	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	190/88	Vinyls	R
Hydrogenated PE	180/82	Vinyl ester	R, S
Halogenated PE	230/110	Zinc rich	
Silicone (methyl)	90/32		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	140/60		
Epoxy	X		
Vinyl ester			
Acrylic	X		
Urethane	X		

Hydrochloric Acid, 35%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	R, S
Epoxy	140/60	Alkyds:	
Furans	80/27	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	140/60	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	X	Vinyls	R
Hydrogenated PE	190/88	Vinyl ester	R
Halogenated PE	180/82	Zinc rich	X
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	X
Vinyl ester	
Acrylic	X
Urethane	X

Hydrochloric Acid, 38%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	X
Epoxy	140/60	Alkyds:	
Furans	250/121	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	90/32	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	140/60	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	X	Vinyls	R, W
Hydrogenated PE	170/77	Vinyl ester	R, S
Halogenated PE	180/82	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	100/38		
Epoxy	X		
Vinyl ester			
Acrylic	X		
Urethane	X		

Hydrofluoric Acid, 30%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	X	Alkyds:	
Furans	230/110	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	90/32	Polyamide	X
Plastisols	120/149	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	210/99	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	120/49	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	370/188		
Polyester	100/38		
Epoxy	X		
Vinyl ester	X		
Acrylic			
Urethane			

Hydrofluoric Acid, 70%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	X	Alkyds:	
Furans	140/60	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	90/32	Polyamide	X
Plastisols	68/20	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	250/121	Polyvinyl formal	
ECTFE	240/116	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	200/93	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE		Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Hydrofluoric Acid, 100%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	X	Alkyds:	
Furans	140/60	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	90/32	Polyamide	X
Plastisols		Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	240/116	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	200/93	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE		Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane			

Hydrogen Chloride Gas, Moist

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy (dry)	140/60	Alkyds:	
Furans (dry)	250/121	Long oil	
Vinyl ester	350/177	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	
Neoprene (dry)	90/32	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon (dry)	90/32	Polyamide	
Plastisols (dry)	80/27	Polyamine (dry)	R
PFA (dry)	200/93	Phenolic	
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE (dry)	300/149	Polyvinyl formal	
ECTFE (dry)	300/149	Silicone (methyl)	
Fluoroelastomers (dry)	90/32	Urethanes:	
PVDF	270/132	Aliphatic	
Isophthalic PE	120/49	Aromatic	
Bis. A fum. PE	210/99	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	210/99	Zinc rich	
Silicone (methyl)			
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan			
Polyester			
Epoxy			
Vinyl ester			
Acrylic			
Urethane			

Hypochlorous Acid, 100%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	200/93	Alkyds:	
Furans	X	Long oil	
Vinyl ester	150/66	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE	90/32	Aromatic	
Bis. A fum. PE, 20%	90/32	Vinyls	X
Hydrogenated PE, 50%	210/99	Vinyl ester	R
Halogenated PE, 10%	100/38	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	X
Polyester	X
Epoxy	X
Vinyl ester	
Acrylic	
Urethane	

Isopropyl Alcohol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	80/27	Acrylics	
Epoxy	180/82	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	120/49	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	250/121	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA		Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	300/149	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	80/27	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	100/38	Zinc rich	R
Silicone	400/204		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	100/38		
Epoxy	140/60		
Vinyl ester			
Acrylic			
Urethane	X		

Lactic Acid, 25%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	
Epoxy	220/104	Alkyds:	
Furans	212/100	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	140/60	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	140/60	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	250/121	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	300/149	Urethanes:	
PVDF	130/54	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	210/99	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R, S, W
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	140/60
Epoxy	X
Vinyl ester	210/99
Acrylic	
Urethane	

Lactic Acid, Concentrated

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	200/93	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	90/32	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	80/27	Polyamide	X
Plastisols	80/27	Polyamine	X
PFA	450/232	Phenolic	
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	250/121	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	110/43	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	100/38		
Epoxy	X		
Vinyl ester	200/93		
Acrylic	X		
Urethane			

Methyl Acetate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	140/60	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA		Phenolic	X
FEP	200/93	Polyesters	X
PTFE	450/232	Polyvinyl butyral	X
ETFE		Polyvinyl formal	X
ECTFE		Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	140/60	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	

Methyl Alcohol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	140/60	Acrylics	
Epoxy	X	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	90/32	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	140/60	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	X	Urethanes:	
PVDF	200/93	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	140/60	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	140/60	Zinc rich	R
Silicone (methyl)	410/210		
	Mortars		
Sodium silicate	450/232		
Potassium silicate	450/232		
Silica	450/232		
Furan	370/188		
Polyester	220/104		
Epoxy	210/99		
Vinyl ester			
Acrylic			
Urethane			

Methyl Cellosolve

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	100/38	Acrylics	
Epoxy	80/27	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	X	Polyamide	
Plastisols	X	Polyamine	R
PFA	190/88	Phenolic	R
FEP	400/204	Polyesters	
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	280/138	Aliphatic	
Isophthalic PE		Aromatic	
Bis. A fum. PE		Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE		Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan	X		
Polyester			
Epoxy	170/77		
Vinyl ester			
Acrylic			
Urethane			

Methyl Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	X
Epoxy	X	Alkyds:	
Furans	120/49	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	140/60	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF	300/149	Aliphatic	X
Isophthalic PE		Aromatic	X
Bis. A fum. PE		Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	80/27	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Methyl Ethyl Ketone

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	X
Epoxy	90/32	Alkyds:	
Furans	80/27	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy		Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	X
ETFE	230/110	Polyvinyl formal	X
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	X	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	210/99		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane			

Methyl Isobutyl Ketone

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	140/60	Alkyds:	
Furans	160/71	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	X
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	110/43	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	R, W
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	80/27	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	X		
Epoxy	100/38		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Methylene Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	X	Alkyds:	
Furans	280/138	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	X
ETFE	210/99	Polyvinyl formal	X
ECTFE	X	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	120/49	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	R
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	100/38
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	X

Mineral Oil

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R
Epoxy	220/99	Alkyds:	
Furans		Long oil	
Vinyl ester	250/121	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	250/121	Aliphatic	R
Isophthalic PE	200/93	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	90/32	Zinc rich	R
Silicone	300/149		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	250/121
Acrylic	
Urethane	X

Motor Oil

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	
Epoxy	100/38	Alkyds:	
Furans		Long oil	
Vinyl ester	250/121	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy	110/43	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene		Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon		Polyamide	
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	
PTFE	400/204	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	
Fluoroelastomers	190/88	Urethanes:	
PVDF	250/121	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE		Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE		Zinc rich	R
Silicone (methyl)			

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

Naphtha

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	110/43	Acrylics	R
Epoxy	100/38	Alkyds:	
Furans	200/93	Long oil	R
Vinyl ester	200/93	Short oil	X
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	R
Neoprene	X	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	X	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	4000/204	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	200/93	Aromatic	R
Bis. A fum. PE	180/66	Vinyls	R
Hydrogenated PE	200/93	Vinyl ester	R
Halogenated PE	200/93	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	140/60		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Nitric Acid, 5%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	100/38	Polyamide	X
Plastisols	100/38	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	150/66	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	
Fluoroelastomers	400/204	Urethanes:	
PVDF	200/93	Aliphatic	R
Isophthalic PE	120/49	Aromatic	R
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE	90/32	Vinyl ester	R
Halogenated PE	210/99	Zinc rich	
Silicone (methyl)	80/27		
	Mortars		
Sodium silicate	450/32		
Potassium silicate	450/32		
Silica	450/32		
Furan	X		
Polyester	140/60		
Epoxy	X		
Vinyl ester	180/82		
Acrylic	X		
Urethane	X		

Nitric Acid, 20%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	100/38	Alkyds:	
Furans	X	Long oil	
Vinyl ester	150/66	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	100/38	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	150/66	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	180/82	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	100/38	Vinyls	R
Hydrogenated PE		Vinyl ester	R, S
Halogenated PE	80/27	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	X		
Polyester	100/38		
Epoxy	X		
Vinyl ester			
Acrylic	X		
Urethane	X		

Nitric Acid, 70%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	70/23	Polyamine	X
PFA	450/232	Phenolic	
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	80/27	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF	120/49	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	80/27	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	450/232		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Nitric Acid, Concentrated

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA		Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	X	Polyvinyl formal	
ECTFE	140/60	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF	150/66	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE		Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE		Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	400/232		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Nitrobenzene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	140/60	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	140/60	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	
Hydrogenated PE		Vinyl ester	R
Halogenated PE	X	Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	450/232
Potassium silicate	450/232
Silica	450/232
Furan	370/188
Polyester	100/38
Epoxy	100/38
Vinyl ester	
Acrylic	
Urethane	

Oil, Vegetable

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	90/32	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	100/38	Asphalt	X
Coal tar epoxy	100/38	Chlorinated rubber	X
Coal tar	X	Coal tar	R
Urethanes		Coal tar epoxy	R, W
Neoprene	240/116	Epoxies:	
Polysulfides	X	Aliphatic polyamine	
Hypalon		Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	R
ETFE	290/143	Polyvinyl formal	R
ECTFE	300/149	Silicone	R, W
Fluoroelastomers	200/93	Urethanes:	
PVDF	220/104	Aliphatic	
Isophthalic PE	150/66	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	220/104	Zinc rich	R, W
Silicone	400/204		

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	180/82
Acrylic	
Urethane	

Oleum

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	X	Alkyds:	
Furans	180/82	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	400/204	Phenolic	
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE	150/66	Polyvinyl formal	
ECTFE	X	Silicone (methyl)	X
Fluoroelastomers	190/88	Urethanes:	
PVDF	X	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	100/38		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Oxalic Acid, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy	100/38	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R ,W
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	R, W
Plastisols	140/60	Polyamine	X
PFA		Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	200/93	Polyvinyl formal	
ECTFE	140/60	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	140/60	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	200/93	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R, W
Halogenated PE	200/93	Zinc rich	
Silicone	X		

Mortars

Sodium silicate	
Potassium silicate	460/238
Silica	460/238
Furan	330/166
Polyester	220/43
Epoxy	110/43
Vinyl ester	200/93
Acrylic	
Urethane	

Oxalic Acid, Saturated

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics (dry)	110/43	Acrylics	X
Epoxy	100/38	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R, W
Coal tar	X	Coal tar	R
Urethanes		Coal tar epoxy	R, S
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	R, S
Plastisols	140/60	Polyamine	X
PFA		Phenolic (dry)	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	200/93	Polyvinyl formal	
ECTFE	140/60	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	120/49	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	200/93	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R, W
Halogenated PE	200/93	Zinc rich	X
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	140/60
Epoxy	X
Vinyl ester	200/93
Acrylic	X
Urethane	

Perchloric Acid, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	140/60	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	90/32	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	X
ETFE	200/93	Polyvinyl formal	X
ECTFE	140/60	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	X	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	90/32	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic			
Urethane	X		

Perchloric Acid, 70%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	X	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	90/32	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE	140/60	Polyvinyl formal	
ECTFE	140/60	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	100/38	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	90/32	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica	460/238		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic			
Urethane	X		

Phenol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	210/99	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	210/99	Urethanes:	
PVDF	200/93	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE, 50%	90/32	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Phosphoric Acid, 5%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	210/99	Acrylics	R, S
Epoxy	X	Alkyds:	
Furans		Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R, W
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	X	Polyamine	R
PFA	210/99	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	460/238	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	250/121	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE		Vinyls	X
Hydrogenated PE		Vinyl ester	R
Halogenated PE		Zinc rich	R
Silicone (methyl)	X		

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	X
Vinyl ester	210/99
Acrylic	
Urethane	

Phosphoric Acid, 50–85%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	110/93	Alkyds:	
Furans, 50%	212/100	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	150/66	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	300/149	Urethanes:	
PVDF	220/104	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	250/121	Zinc rich	R
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	250/121		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Phthalic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics (dry)	100/38	Acrylics	
Epoxy	X	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	150/66	Asphalt	
Coal tar epoxy		Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	140/60	Polyamide	R, W
Plastisols	X	Polyamine	X
PFA		Phenolic (dry)	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	200/93	Polyvinyl formal	
ECTFE	200/93	Silicone (methyl)	
Fluoroelastomers	90/32	Urethanes:	
PVDF	200/93	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	200/93	Vinyls	X
Hydrogenated PE	200/93	Vinyl ester	
Halogenated PE	80/27	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	
Potassium silicate	460/238
Silica	
Furan	330/166
Polyester	220/104
Epoxy	210/99
Vinyl ester	200/93
Acrylic	
Urethane	

Potassium Acetate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	160/171	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon		Polyamide	R, S
Plastisols		Polyamine	
PFA	250/121	Phenolic	
FEP	200/93	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE		Silicone (methyl)	X
Fluoroelastomers	80/27	Urethanes:	
PVDF	200/93	Aliphatic	
Isophthalic PE	160/71	Aromatic	
Bis. A fum. PE	200/93	Vinyls	
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic			
Urethane			

Potasium Bromide, 30%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics, 10%	160/71	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	200/93	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R
Neoprene	160/71	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	240/116	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	X
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	
Fluoroelastomers	190/88	Urethanes:	
PVDF	200/93	Aliphatic	R, S
Isophthalic PE	160/71	Aromatic	R, S
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	X
Polyester	250/121
Epoxy	X
Vinyl ester	
Acrylic	X
Urethane	

Potassium Carbonate, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	120/49	Short oil	
Epoxy polyamide, 25%	100/38	Asphalt	
Coal tar epoxy, 25%	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy, 25%	R
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	200/93	Polyamide, 25%	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters, 25%	R, S
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl)	
Fluoroelastomers	180/82	Urethanes:	
PVDF	200/93	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE, 10%	180/82	Vinyls	R
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE	110/43	Zinc rich	
Silicone (methyl)			

	Mortars
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	330/166
Polyester	110/43
Epoxy	210/99
Vinyl ester	120/49
Acrylic	
Urethane	

Potassium Chloride, 30%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics (dilute)	R, S
Epoxy	200/38	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt (dilute)	R
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	R
Urethanes	110/43	Coal tar epoxy	R, W
Neoprene	160/71	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	R
Isophthalic PE	160/71	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R, W
Hydrogenated PE	190/88	Vinyl ester	R, W
Halogenated PE	190/88	Zinc rich	X
Silicone	400/204		
	Mortars		
Sodium silicate	140/60		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Potassium Cyanide, 30%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	140/60	Asphalt	
Coal tar epoxy	140/60	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	240/116	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE	200/93	Vinyl ester	X
Halogenated PE	140/60	Zinc rich	
Silicone	400/204		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	X
Acrylic	X
Urethane	

Potassium Hydroxide, Dilute

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R, S
Epoxy	200/93	Alkyds:	
Furans	250/121	Long oil	X
Vinyl ester	150/66	Short oil	X
Epoxy polyamide	110/43	Asphalt	R
Coal tar epoxy	100/38	Chlorinated rubber	R, W
Coal tar	100/38	Coal tar	R
Urethanes		Coal tar epoxy	R
Neoprene	200/93	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	250/121	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	X
PTFE	460/238	Polyvinyl butyral	
ETFE	210/99	Polyvinyl formal	
ECTFE	150/66	Silicone	R
Fluoroelastomers	320/160	Urethanes:	
PVDF	210/99	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	140/60	Vinyls	R
Hydrogenated PE	X	Vinyl ester	R
Halogenated PE		Zinc rich	R
Silicone	210/99		

Mortars

Sodium silicate	X
Potassium silicate	
Silica	X
Furan	100/38
Polyester	100/38
Epoxy	250/121
Vinyl ester	150/66
Acrylic	X
Urethane	

Potassium Hydroxide, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R
Epoxy	100/38	Alkyds:	
Furans	200/93	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, S
Neoprene	200/93	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	X
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, S
PTFE	400/204	Polyvinyl butyral	
ETFE	200/93	Polyvinyl formal	
ECTFE	140/60	Silicone	R, W
Fluoroelastomers	X	Urethanes:	
PVDF	200/93	Aliphatic	R, S
Isophthalic PE	X	Aromatic	R, S
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	
Silicone	210/99		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	370/188
Polyester	100/38
Epoxy	250/121
Vinyl ester	X
Acrylic	X
Urethane	X

Potassium Hydroxide, 90%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy		Alkyds:	
Furans	200/93	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	90/32	Coal tar epoxy	X
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	X
PTFE	400/204	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	140/60	Silicone	R
Fluoroelastomers	X	Urethanes:	
PVDF	200/93	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE		Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	X
Silicone	X		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	170/77
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	X
Urethane	X

Potassium Nitrate, 80%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE	180/82	Vinyl ester	R, W
Halogenated PE	180/82	Zinc rich	X
Silicone	400/204		
	Mortars		
Sodium silicate	100/38		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Potassium Permanganate, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	80/27	Acrylics	X
Epoxy	140/60	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	100/38	Coal tar epoxy	R
Neoprene	100/38	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R, S
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	460/238	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl)	
Fluoroelastomers	160/71	Urethanes:	
PVDF	260/127	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R, W
Halogenated PE	150/66	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	X
Vinyl ester	200/93
Acrylic	X
Urethane	X

Potassium Permanganate, 20%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	90/32	Acrylics	X
Epoxy	140/60	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene	100/38	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	240/160	Polyamide	R
Plastisols	90/32	Polyamine	X
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone	
Fluoroelastomers	160/71	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	100/38	Aromatic	
Bis. A fum. PE	200/93	Vinyls	
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	140/60	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	
Silica	460/238
Furan	390/199
Polyester	250/121
Epoxy	X
Vinyl ester	
Acrylic	X
Urethane	

Potassium Sulfate, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R, S
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R
Neoprene	200/93	Epoxies:	
Polysulfides	90/32	Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	R
Isophthalic PE	100/38	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE	200/93	Vinyl ester	R, W
Halogenated PE	190/58	Zinc rich	X
Silicone	400/204		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic	X		
Urethane			

Propyl Alcohol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	90/32	Alkyds:	
Furans		Long oil	
Vinyl ester		Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	250/121	Polyamide	
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R
PTFE	460/238	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	250/121	Aliphatic	
Isophthalic PE		Aromatic	
Bis. A fum. PE		Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE		Zinc rich	R
Silicone (methyl)	400/204		

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

Propylene Glycol

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	X
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	90/32	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon		Polyamide	R, W
Plastisols	X	Polyamine	R
PFA		Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE		Silicone (methyl)	
Fluoroelastomers	300/149	Urethanes:	
PVDF	240/116	Aliphatic	
Isophthalic PE	180/82	Aromatic	
Bis. A fum. PE	200/93	Vinyls	X
Hydrogenated PE	200/93	Vinyl ester	R, W
Halogenated PE	100/38	Zinc rich	R
Silicone (methyl)			
	Mortars		
Sodium silicate	460/238		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	100/38		
Epoxy	100/38		
Vinyl ester	200/93		
Acrylic			
Urethane			

Pyridine

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	460/238	Polyvinyl butyral	X
ETFE	140/60	Polyvinyl formal	X
ECTFE	X	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	X	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic			
Urethane			

Salicylic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	140/60	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	X	Polyamide	R
Plastisols	X	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	240/116	Polyvinyl formal	
ECTFE	240/116	Silicone	
Fluoroelastomers	280/138	Urethanes:	
PVDF	200/93	Aliphatic	
Isophthalic PE	100/38	Aromatic	
Bis. A fum. PE	140/60	Vinyls	X
Hydrogenated PE		Vinyl ester	R, S
Halogenated PE	120/49	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	210/99
Vinyl ester	140/60
Acrylic	
Urethane	

Sodium Acetate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	X	Polyamide	R, W
Plastisols	140/60	Polyamine	R, S
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	180/82	Aromatic	
Bis. A fum. PE	180/82	Vinyls	
Hydrogenated PE	200/93	Vinyl ester	R, S
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)	X		

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	210/99
Acrylic	90/32
Urethane	

Sodium Bicarbonate, 20%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl)	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE, 10%	180/82	Aromatic	
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	140/60	Zinc rich	
Silicone (methyl)	400/204		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	250/121		
Epoxy	250/121		
Vinyl ester	200/93		
Acrylic			
Urethane			

Sodium Bisulfate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	260/127	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	100/38	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone	
Fluoroelastomers	180/82	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	180/82	Aromatic	
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	200/93	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	200/93
Acrylic	
Urethane	

Sodium Carbonate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	X
Epoxy	200/93	Alkyds:	
Furans, 50%	240/116	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl)	R, W
Fluoroelastomers	180/82	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE, 20%	90/32	Aromatic	
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE, 10%	100/38	Vinyl ester	R
Halogenated PE, 10%	180/82	Zinc rich	
Silicone (methyl)	300/149		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	370/188
Polyester	100/38
Epoxy	250/121
Vinyl ester	180/82
Acrylic	X
Urethane	

Sodium Chlorate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics, 50%	160/71	Acrylics	R
Epoxy	100/38	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	220/104	Short oil	
Epoxy polyamide, 50%	110/43	Asphalt	
Coal tar epoxy, 50%	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene	80/27	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R
Plastisols	140/60	Polyamine	R, S
PFA	200/93	Phenolic	R, S
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl)	
Fluoroelastomers	180/82	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE	200/93	Vinyl ester	R, W
Halogenated PE, 45%	200/93	Zinc rich	
Silicone (methyl)			

Mortars	
Sodium silicate	X
Potassium silicate	
Silica	
Furan	100/38
Polyester	170/77
Epoxy	160/71
Vinyl ester	220/104
Acrylic	
Urethane	

Sodium Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	110/43	Asphalt	X
Coal tar epoxy	110/43	Chlorinated rubber	R, S
Coal tar	X	Coal tar	R
Urethanes	80/27	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	240/116	Polyamide	R
Plastisols	140/60	Polyamine	R, S
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone (methyl), 10%	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	R
Isophthalic PE	200/93	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R
Halogenated PE	210/99	Zinc rich	X
Silicone (methyl), 10%	400/204		

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	180/82
Acrylic	X
Urethane	X

Sodium Cyanide

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	240/116	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	180/82	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	240/116	Polyamide	R
Plastisols	140/60	Polyamine	R, W
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, S
PTFE	400/204	Polyvinyl butyral	
ETFE	280/138	Polyvinyl formal	
ECTFE	280/138	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	150/66	Aromatic	
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE		Vinyl ester	R, S
Halogenated PE, 50%	140/60	Zinc rich	
Silicone	140/60		

Mortars	
Sodium silicate	X
Potassium silicate	
Silica	
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	200/93
Acrylic	
Urethane	

Sodium Hydroxide, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/140	Acrylics	R
Epoxy	190/88	Alkyds:	
Furans	X	Long oil	X
Vinyl ester	170/77	Short oil	X
Epoxy polyamide	100/38	Asphalt (dilute)	R
Coal tar epoxy	100/38	Chlorinated rubber	R, W
Coal tar	X	Coal tar (dilute)	R
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	230/110	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R, W
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R, W
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R, S
Fluoroelastomers	X	Urethanes:	
PVDF	230/110	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	130/54	Vinyls	X
Hydrogenated PE	100/38	Vinyl ester	X
Halogenated PE	110/43	Zinc rich	R
Silicone (methyl)	90/27		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	370/188
Polyester	100/38
Epoxy	250/121
Vinyl ester	X
Acrylic	X
Urethane	X

Sodium Hydroxide, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	X	Long oil	X
Vinyl ester	220/104	Short oil	X
Epoxy polyamide	100/38	Asphalt	X
Coal tar epoxy	100/38	Chlorinated rubber	R, W
Coal tar	X	Coal tar	R
Urethanes	90/32	Coal tar epoxy	R
Neoprene	230/110	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	R, S
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	R
Fluoroelastomers	X	Urethanes:	
PVDF	220/104	Aliphatic	R
Isophthalic PE	X	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	X	Vinyl ester	R, W
Halogenated PE	X	Zinc rich	
Silicone (methyl)	90/27		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	370/188
Polyester	100/38
Epoxy	250/121
Vinyl ester	220/104
Acrylic	
Urethane	

Sodium Hydroxide, 70%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy	250/121	Alkyds:	
Furans	260/127	Long oil	X
Vinyl ester	X	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	R, W
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon		Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	80/27	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	460/238	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	R
Fluoroelastomers		Urethanes:	
PVDF	X	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	140/60	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE		Zinc rich	X
Silicone (methyl)	X		

Mortars	
Sodium silicate	X
Potassium silicate	X
Silica	X
Furan	
Polyester	X
Epoxy	80/27
Vinyl ester	X
Acrylic	
Urethane	

Sodium Hypochlorite, 20%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics, 15%	R
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester, 15%	180/82	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	R
Hydrogenated PE, 10%	160/71	Vinyl ester, 15%	R, S
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester			
Acrylic	X		
Urethane	X		

Sodium Hypochlorite, Concentrated

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	X	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	140/60	Vinyls	
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane	X		

Sodium Nitrate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	80/27	Acrylics	R
Epoxy	200/93	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy	80/27	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes	90/32	Coal tar epoxy	R, W
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	140/60	Polyamide	
Plastisols	140/60	Polyamine	R, W
PFA	200/93	Phenolic	R
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	X	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	180/32	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	250/121	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate	460/238		
Silica	460/238		
Furan	330/166		
Polyester	220/104		
Epoxy	210/99		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Sodium Peroxide, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	90/32	Alkyds:	
Furans		Long oil	
Vinyl ester	160/71	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	250/121	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	220/104	Vinyls	
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	X		
Potassium silicate	X		
Silica	X		
Furan	X		
Polyester	110/43		
Epoxy	X		
Vinyl ester	160/71		
Acrylic			
Urethane			

Stearic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	210/99	Acrylics	
Epoxy	220/104	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	220/104	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	R, W
Coal tar	X	Coal tar	X
Urethanes:	X	Coal tar epoxy	X
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	140/60	Polyamide	X
Plastisols	140/60	Polyamine	R, W
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R, S
Fluoroelastomers	100/38	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	200/93	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R, W
Halogenated PE	250/121	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	160/71		
Epoxy	X		
Vinyl ester			
Acrylic			
Urethane			

Styrene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	100/38	Alkyds:	
Furans	360/182	Long oil	
Vinyl ester	100/38	Short oil	
Epoxy polyamide		Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	
Urethanes		Coal tar epoxy	
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	
Plastisols	X	Polyamine	X
PFA		Phenolic	
FEP	100/38	Polyesters	
PTFE	350/177	Polyvinyl butyral	
ETFE	210/99	Polyvinyl formal	
ECTFE		Silicone (methyl)	X
Fluoroelastomers	300/149	Urethanes:	
PVDF	190/85	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	100/38	Vinyls	X
Hydrogenated PE	100/38	Vinyl ester	R, W
Halogenated PE	X	Zinc rich	
Silicone (methyl)	X		

Mortars	
Sodium silicate	460/238
Potassium silicate	
Silica	
Furan	350/177
Polyester	100/38
Epoxy	110/43
Vinyl ester	100/38
Acrylic	
Urethane	

Sulfur Dioxide, Wet

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/49	Acrylics	
Epoxy	150/66	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	R, W
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	230/110	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	R, S
Fluoroelastomers	X	Urethanes:	
PVDF	210/99	Aliphatic	
Isophthalic PE	90/32	Aromatic	
Bis. A fum. PE	220/104	Vinyls	
Hydrogenated PE	210/99	Vinyl ester	R, W
Halogenated PE	250/121	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	X		
Epoxy	X		
Vinyl ester	210/99		
Acrylic			
Urethane			

Sulfur Trioxide

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	80/27	Polyvinyl formal	
ECTFE	80/27	Silicone (methyl)	R, S
Fluoroelastomers	190/88	Urethanes:	
PVDF	X	Aliphatic	
Isophthalic PE	90/32	Aromatic	
Bis. A fum. PE	250/121	Vinyls	R
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	120/49	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	160/71		
Polyester	160/71		
Epoxy	X		
Vinyl ester	210/99		
Acrylic			
Urethane			

Sulfuric Acid, 10%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	250/121	Acrylics	X
Epoxy	140/60	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	200/93	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R, W
Coal tar	X	Coal tar	R
Urethanes	X	Coal tar epoxy	X
Neoprene	150/66	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	200/93	Polyamide	X
Plastisols	140/60	Polyamine	R
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	350/149	Urethanes:	
PVDF	250/121	Aliphatic	R, S
Isophthalic PE	180/71	Aromatic	R, S
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	260/127	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	250/121		
Epoxy	100/38		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Sulfuric Acid, 50%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	250/121	Acrylics	R
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	210/99	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R, S
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	100/38	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	200/93	Polyamide	X
Plastisols	140/60	Polyamine	R, S
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	220/104	Aliphatic	X
Isophthalic PE	150/66	Aromatic	X
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R, W
Halogenated PE	200/93	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	260/127		
Epoxy	X		
Vinyl ester	210/99		
Acrylic	X		
Urethane			

Sulfuric Acid, 70%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	R
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	X
Vinyl ester	180/82	Short oil	X
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	160/71	Polyamide	X
Plastisols	140/60	Polyamine	X
PFA	450/232	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	220/104	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	160/71	Vinyls	R
Hydrogenated PE	90/32	Vinyl ester	R, W
Halogenated PE	190/88	Zinc rich	X
Silicone (methyl)	X		

Mortars	
Sodium silicate	140/60
Potassium silicate	210/99
Silica	210/99
Furan	100/38
Polyester	100/38
Epoxy	X
Vinyl ester	180/82
Acrylic	X
Urethane	X

Sulfuric Acid, 90%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	R
Vinyl ester	X	Short oil	R
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	350/177	Urethanes:	
PVDF	210/99	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	100/38		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Sulfuric Acid, 98%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	350/149	Urethanes:	
PVDF	140/66	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate	100/38		
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Sulfuric Acid, 100%

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	X
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	450/232	Phenolic	X
FEP	400/204	Polyesters	X
PTFE	450/232	Polyvinyl butyral	X
ETFE	300/149	Polyvinyl formal	X
ECTFE	80/27	Silicone (methyl)	X
Fluoroelastomers	180/82	Urethanes:	
PVDF	X	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	X	Vinyl ester	X
Halogenated PE	X	Zinc rich	X
Silicone (methyl)	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan	X		
Polyester	X		
Epoxy	X		
Vinyl ester	X		
Acrylic	X		
Urethane	X		

Sulfurous Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	R
Epoxy, 20%	240/160	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester, 10%	120/49	Short oil	
Epoxy polyamide	110/43	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R, W
Neoprene	100/38	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	160/71	Polyamide	R, S
Plastisols	140/60	Polyamine	R, S
PFA	450/232	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	450/232	Polyvinyl butyral	
ETFE	210/99	Polyvinyl formal	
ECTFE	250/121	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	220/104	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	110/43	Vinyls	R
Hydrogenated PE, 25%	210/99	Vinyl ester	R
Halogenated PE, 10%	80/27	Zinc rich	
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/238		
Potassium silicate	460/238		
Silica	460/238		
Furan	370/188		
Polyester	250/121		
Epoxy	210/99		
Vinyl ester	X		
Acrylic	X		
Urethane			

Tannic Acid

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	R
Epoxy	180/82	Alkyds:	
Furans	250/121	Long oil	R
Vinyl ester	200/93	Short oil	R
Epoxy polyamide	100/38	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	R
Neoprene	200/93	Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon	100/38	Polyamide	R
Plastisols	140/60	Polyamine	R, W
PFA	400/204	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	450/232	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	250/121	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	240/116	Aliphatic	R
Isophthalic PE	180/82	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R, W
Halogenated PE	250/121	Zinc rich	
Silicone	X		
	Mortars		
Sodium silicate			
Potassium silicate			
Silica			
Furan	200/93		
Polyester	220/104		
Epoxy	210/99		
Vinyl ester	200/93		
Acrylic	X		
Urethane	X		

Thionyl Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	
Coal tar epoxy	X	Chlorinated rubber	
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides		Aliphatic polyamine	X
Hypalon		Polyamide	X
Plastisols	X	Polyamine	X
PFA[1]	450/232	Phenolic	R, W
FEP[1]	400/204	Polyesters	X
PTFE[1]	450/232	Polyvinyl butyral	X
ETFE	210/99	Polyvinyl formal	X
ECTFE	150/66	Silicone (methyl)	
Fluoroelastomers	X	Urethanes:	
PVDF	X	Aliphatic	
Isophthalic PE	X	Aromatic	
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	
Halogenated PE	X	Zinc rich	
Silicone (methyl)		[1] Corrodent will permeate.	

Mortars	
Sodium silicate	X
Potassium silicate	
Silica	
Furan	X
Polyester	X
Epoxy	X
Vinyl ester	X
Acrylic	
Urethane	

Toluene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	200/93	Acrylics	X
Epoxy	X	Alkyds:	
Furans	212/100	Long oil	X
Vinyl ester	120/149	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	210/99	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	X
ETFE	250/121	Polyvinyl formal	X
ECTFE	140/60	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	210/99	Aliphatic	X
Isophthalic PE	100/38	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE	80/27	Vinyl ester	R, W
Halogenated PE	100/38	Zinc rich	R, W
Silicone (methyl)	X		

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	100/38
Epoxy	X
Vinyl ester	120/149
Acrylic	X
Urethane	X

Trichloroethylene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	X
Epoxy	X	Alkyds:	
Furans	160/71	Long oil	
Vinyl ester	X	Short oil	
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	X	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, S
PTFE	400/204	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	R
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	X	Vinyls	X
Hydrogenated PE		Vinyl ester	X
Halogenated PE	120/149	Zinc rich	R, W
Silicone (methyl)	X		

Mortars	
Sodium silicate	460/232
Potassium silicate	460/232
Silica	460/232
Furan	370/188
Polyester	100/38
Epoxy	100/38
Vinyl ester	X
Acrylic	X
Urethane	X

Turpentine

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	110/43	Acrylics	R
Epoxy	150/66	Alkyds:	
Furans		Long oil	X
Vinyl ester	150/66	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	R
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE	270/132	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	80/27	Aromatic	R
Bis. A fum. PE	80/27	Vinyls	R
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	120/49	Zinc rich	R, W
Silicone (methyl)	X		
	Mortars		
Sodium silicate	460/232		
Potassium silicate			
Silica			
Furan	370/188		
Polyester	100/38		
Epoxy	100/38		
Vinyl ester	150/66		
Acrylic	X		
Urethane	X		

Water, Potable

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	210/99	Alkyds:	
Furans		Long oil	R
Vinyl ester	210/99	Short oil	R
Epoxy polyamide		Asphalt	R
Coal tar epoxy		Chlorinated rubber	R, W
Coal tar		Coal tar	R
Urethanes		Coal tar epoxy	R, W
Neoprene	180/82	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	200/93	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA		Phenolic	
FEP		Polyesters	R
PTFE	400/204	Polyvinyl butyral	R
ETFE		Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R, W
Fluoroelastomers	300/149	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	210/99	Aromatic	R
Bis. A fum. PE	210/99	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R
Halogenated PE	170/77	Zinc rich	R, W
Silicone (methyl)			

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

Water, Salt

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	R
Epoxy, 10%	210/99	Alkyds:	
Furans		Long oil	R
Vinyl ester	160/71	Short oil	R
Epoxy polyamide	130/54	Asphalt	R
Coal tar epoxy	130/54	Chlorinated rubber	R
Coal tar	100/38	Coal tar	R
Urethanes	X	Coal tar epoxy	R
Neoprene	210/99	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	R
Hypalon	250/121	Polyamide	R
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	R
ETFE	250/121	Polyvinyl formal	R
ECTFE	300/149	Silicone (methyl)	R, W
Fluoroelastomers	190/88	Urethanes:	
PVDF	280/138	Aliphatic	X
Isophthalic PE	160/71	Aromatic	X
Bis. A fum. PE	180/82	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE		Zinc rich	R
Silicone (methyl)	210/99		

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

Water, Sea

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	X	Acrylics	
Epoxy	300/149	Alkyds:	
Furans	250/121	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	130/54	Asphalt	R
Coal tar epoxy	90/32	Chlorinated rubber	R, W
Coal tar	90/32	Coal tar	R, W
Urethanes	X	Coal tar epoxy	R, W
Neoprene	210/99	Epoxies:	
Polysulfides	X	Aliphatic polyamine	R
Hypalon	250/121	Polyamide	R, W
Plastisols	140/60	Polyamine	R, W
PFA	400/204	Phenolic	R, S
FEP	400/204	Polyesters	R, W
PTFE	460/238	Polyvinyl butyral	R
ETFE	250/121	Polyvinyl formal	
ECTFE	300/149	Silicone (methyl)	R, W
Fluoroelastomers	190/88	Urethanes:	
PVDF	280/138	Aliphatic	R
Isophthalic PE	120/49	Aromatic	R
Bis. A fum. PE	220/104	Vinyls	R, W
Hydrogenated PE	200/93	Vinyl ester	R, W
Halogenated PE	180/82	Zinc rich	R
Silicone (methyl)	200/93		

Mortars

Sodium silicate
Potassium silicate
Silica
Furan
Polyester
Epoxy
Vinyl ester
Acrylic
Urethane

White Liquor

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	160/71	Acrylics	X
Epoxy	200/93	Alkyds:	
Furans	140/60	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide	150/66	Asphalt	
Coal tar epoxy	100/38	Chlorinated rubber	
Coal tar	X	Coal tar	R
Urethanes	X	Coal tar epoxy	R
Neoprene	140/60	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon		Polyamide	R, W
Plastisols	140/60	Polyamine	R, W
PFA	400/204	Phenolic	R
FEP	400/204	Polyesters	R
PTFE	400/204	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	250/121	Silicone	
Fluoroelastomers	190/88	Urethanes:	
PVDF	200/93	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	180/82	Vinyls	R
Hydrogenated PE		Vinyl ester	R
Halogenated PE	X	Zinc rich	X
Silicone (methyl)			

Mortars	
Sodium silicate	X
Potassium silicate	
Silica	
Furan	370/188
Polyester	160/71
Epoxy	250/121
Vinyl ester	180/82
Acrylic	X
Urethane	X

Wines

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	X
Epoxy	100/38	Alkyds:	
Furans	160/71	Long oil	R
Vinyl ester	160/71	Short oil	R
Epoxy polyamide	100/38	Asphalt	R, S
Coal tar epoxy	X	Chlorinated rubber	R
Coal tar		Coal tar	
Urethanes		Coal tar epoxy	R
Neoprene		Epoxies:	
Polysulfides		Aliphatic polyamine	R
Hypalon		Polyamide	R, W
Plastisols	140/60	Polyamine	R, S
PFA	400/204	Phenolic	
FEP	400/204	Polyesters	R, W
PTFE	460/238	Polyvinyl butyral	
ETFE		Polyvinyl formal	
ECTFE	250/121	Silicone	R, W
Fluoroelastomers		Urethanes:	
PVDF	200/93	Aliphatic	X
Isophthalic PE	140/60	Aromatic	X
Bis. A fum. PE	210/99	Vinyls	R, W
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	210/99	Zinc rich	R
Silicone	170/77		

Mortars	
Sodium silicate	X
Potassium silicate	
Silica	
Furan	370/188
Polyester	250/121
Epoxy	250/121
Vinyl ester	160/71
Acrylic	X
Urethane	X

Xylene

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	150/66	Acrylics	X
Epoxy	X	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	140/60	Short oil	X
Epoxy polyamide	X	Asphalt	X
Coal tar epoxy	X	Chlorinated rubber	X
Coal tar	X	Coal tar	X
Urethanes	X	Coal tar epoxy	X
Neoprene	X	Epoxies:	
Polysulfides	80/27	Aliphatic polyamine	X
Hypalon	X	Polyamide	X
Plastisols	X	Polyamine	X
PFA	200/93	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	400/204	Polyvinyl butyral	
ETFE	250/121	Polyvinyl formal	
ECTFE	150/66	Silicone (methyl)	X
Fluoroelastomers	400/204	Urethanes:	
PVDF	210/99	Aliphatic	X
Isophthalic PE	X	Aromatic	X
Bis. A fum. PE	90/32	Vinyls	X
Hydrogenated PE	90/32	Vinyl ester	R, W
Halogenated PE	150/66	Zinc rich	R, W
Silicone (methyl)	X		

Mortars	
Sodium silicate	460/238
Potassium silicate	460/238
Silica	460/238
Furan	370/188
Polyester	100/38
Epoxy	100/38
Vinyl ester	140/60
Acrylic	X
Urethane	X

Zinc Chloride

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	R
Epoxy	300/149	Alkyds:	
Furans	260/127	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide		Asphalt	R
Coal tar epoxy		Chlorinated rubber	R
Coal tar	X	Coal tar	R
Urethanes		Coal tar epoxy	
Neoprene	160/71	Epoxies:	
Polysulfides	X	Aliphatic polyamine, 40%	R, S
Hypalon	250/121	Polyamide	
Plastisols	140/60	Polyamine	R, W
PFA[a]	380/193	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE[a]	460/238	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R
Fluoroelastomers	400/204	Urethanes:	
PVDF	260/127	Aliphatic	
Isophthalic PE	180/82	Aromatic	
Bis. A fum. PE	250/121	Vinyls	R
Hydrogenated PE	200/93	Vinyl ester	R
Halogenated PE	200/93	Zinc rich	
Silicone	400/204		

Mortars

Sodium silicate	
Potassium silicate	460/238
Silica	460/238
Furan	330/166
Polyester	220/104
Epoxy	210/99
Vinyl ester	180/82
Acrylic	
Urethane	

[a] Corrodent will be absorbed.

Zinc Nitrate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics		Acrylics	
Epoxy	X	Alkyds:	
Furans	X	Long oil	
Vinyl ester	180/82	Short oil	
Epoxy polyamide		Asphalt	R
Coal tar epoxy		Chlorinated rubber	
Coal tar		Coal tar	R
Urethanes		Coal tar epoxy	
Neoprene	100/38	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	200/93	Polyamide	
Plastisols	140/60	Polyamine	R
PFA	200/93	Phenolic	
FEP	400/204	Polyesters	
PTFE	460/238	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	
Fluoroelastomers	190/88	Urethanes:	
PVDF	270/132	Aliphatic	
Isophthalic PE	180/82	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE	210/99	Vinyl ester	R
Halogenated PE	180/82	Zinc rich	
Silicone (methyl)			

Mortars

Sodium silicate	
Potassium silicate	460/238
Silica	460/238
Furan	330/166
Polyester	220/104
Epoxy	210/99
Vinyl ester	
Acrylic	
Urethane	

Zinc Sulfate

Coatings for Immersion Service	Max Temp. (°F/°C)	Paints S = Splash Resistant W = Immersion Resistant	
Phenolics	300/149	Acrylics	
Epoxy	250/121	Alkyds:	
Furans	250/121	Long oil	
Vinyl ester	250/121	Short oil	
Epoxy polyamide		Asphalt	R
Coal tar epoxy		Chlorinated rubber	
Coal tar	X	Coal tar	R
Urethanes		Coal tar epoxy	
Neoprene	180/82	Epoxies:	
Polysulfides		Aliphatic polyamine	
Hypalon	250/121	Polyamide	
Plastisols		Polyamine	R, W
PFA	400/204	Phenolic	R, W
FEP	400/204	Polyesters	R, W
PTFE	460/238	Polyvinyl butyral	
ETFE	300/149	Polyvinyl formal	
ECTFE	300/149	Silicone	R, W
Fluoroelastomers	400/204	Urethanes:	
PVDF	270/132	Aliphatic	
Isophthalic PE	200/93	Aromatic	
Bis. A fum. PE	220/104	Vinyls	R
Hydrogenated PE		Vinyl ester	R, W
Halogenated PE	220/104	Zinc rich	
Silicone	400/204		
	Mortars		
Sodium silicate			
Potassium silicate	460/238		
Silica	460/238		
Furan	330/166		
Polyester	220/104		
Epoxy	210/99		
Vinyl ester	250/121		
Acrylic			
Urethane			

15 Tribological Synergistic Coatings

In the conventional sense of the word, tribological synergistic coatings are not really coatings. These "coatings" are formed during multi-step processes that combine hardplate coating or anodizing with controlled infusion of low-friction polymer and/or dry lubricants. The "coatings" become an integral part of the top layers of the substrate rather than a surface cover. The processes that produce these "coatings" are identified as synergistic because the resulting surfaces are superior in performance to both the base metal and the individual components of the coating.

One such family of "coatings," known as the Tufram process, for use on aluminum alloys, converts the hydrated aluminum oxide $Al_2O_3 \cdot H_2O$ and replaces the H_2O of the newly formed ceramic surface with inert polymeric material that provides a self-lubricating surface. During the process, the aluminum crystals expand and form porous anchors, crystals that remain hygroscopic for a short period of time. Particles of a selected polymer are then introduced under controlled conditions of solution concentrations, time, and temperature. The polymer particles permanently interlock with the newly formed crystals. The result is a harder-than-steel continuous lubricating plastic–ceramic surface of which the polymeric particles become an integral part. Synergistic coatings solve many wear problems as well as provide corrosion resistance.

Synergistic coatings for aluminum (Tufram) have been used successfully for many years. All aluminum alloys can be coated, providing the copper content does not exceed 5% and the silicon content remains below 7%.

The Tufram system produces films having improved wear resistance, better surface release (lower coefficient of friction), good corrosion resistance, and high dielectric strength.

These coatings are used in a wide variety of industries. The improvement in wear resistance to aluminum ranges from 5 to 25 times that without the coating. Some coatings meet the requirements of the U.S. Food and Drug Administration and can be used in food and medical applications.

COATING SYSTEMS

Polymer Coatings

Polymer or organic coatings can produce such properties as dielectric, corrosion resistance, radiation resistance, and by use of special organic coatings applications have been approved for use in the food and pharmaceutical industries.

TABLE 15.1
Polymer Coatings and Their Properties

Coating	Properties
601	Primarily chemical resistance Can withstand strong acids and alkalies up to 2000°F (1098°C)
604	Has similar corrosion resistance to material 601 but can be utilized in food applications
615	This is a tough, durable coating (D-80 durometer) that can also be used in food applications Allowable temperature range is from –400 to 500°F (–240 to 260°C)
611	This coating has good release characteristics, is used in applications in the baking industry, and is available in a variety of colors

These latter coatings are in compliance with regulations of the U.S. Food and Drug Administration.

All coatings are proprietary. Identification of coatings is by a specific nomenclature (601, 604, 611, 615, etc.).

Application of coatings is by means of dipping, spraying, or by an electrostatic process. Maximum surface hardness and minimum porosity will be achieved, in most cases, with a curing temperature in the range of 300 to 750°F (149 to 399°C). Polymer coatings normally range in thickness from 0.001 to 0.015 in.

Salt spray resistance of these coatings is excellent (approximately 6 years in the atmosphere). Specific properties of the various coatings are as in Table 15.1.

Magnesium (Magnadize) and Titanium (Canadize)

Magnesium and titanium are widely used in the fields of aerospace and computers and are often subject to wear applications. An electrochemical process has been developed for each material to produce a hardened surface. However, the synergistic coating system is still the superior answer for a wear application. Special fluoropolymers or dry lubricants are infused into the hard facing. The synergistic coating for magnesium is called Magnadize and for titanium it is called Canadize.

The coating thickness on magnesium can vary from 0.0002 in. to a maximum exceeding 0.0015 in. Normal application thicknesses range from 0.0005 to 0.001 in.

Normal application thickness on titanium ranges from 0.0002 to 0.0005 in. It is more difficult to build up thickness on titanium.

A typical application for Magnadize would be an aircraft magnesium engine mount. The entire engine mount would be hardcoated, and the gear spline would receive dry lubricant to improve the efficiency of that part.

Titanium hardware for aircraft is subject to Canadizing. These components are anodized with an infusion to a thickness of 0.0002 to 0.0004 in. to prevent the titanium from seizing.

TABLE 15.2
Physical Properties of Magnagold Coatings

Hardness	Re 80–85
Chemical resistance to:	
30% nitric and sulfuric acids on copper and steel substrates at ambient temperature	Virtually no attack
Alkali resistance	Virtually no attack
Taber abrasion test, CS 10 wheel, 1000-g load, 10,000 cycles	Average weight loss: >0.5 mg
Coating thickness	1–3μm
Uniformity of thickness	15×10^{-5} in. (max)
Crystal lattice	Body-centered cubic a = 4.249 ô
Density	5.44 g/cm^4
Thermal conductivity, cal/cm/sec/°C	~ 0.162 (at 1500°C) ~ 0.167 (at 1600°C) ~ 0.165 (at 1700°C) ~ 0.136 (at 2300°C)

Titanium Nitride (Magnagold)

One of the unique features of the titanium nitride process is the uniformity of the coating, a critical feature for many applications involving missile, computer, and semiconductor applications. Other applications are found in the plastics extrusion industry, which makes use of the superior release properties in molds and dies, and the medical industry, which coats delicate surgical instruments. Some physical properties of Magnagold coatings are presented in Table 15.2.

A uniform coating, held to within a few millionths of an inch thickness, can be applied to the most critical, closest tolerance parts by means of special cleaning fixture mechanisms and techniques that permit 360° rotation of the part while traveling through the vapor stream.

There are no restrictions on the shapes of parts because the parts are rotated both radially and axially within the unique ion bombardment chamber. All surfaces, except the clamp and fixture areas, are uniform in coating thickness. The thickness normally ranges from 0.00003 to 0.0002 in. Load life and/or edge sharpness determines the final thickness.

As with any physical vapor deposition (PVD) process, preparation of the substrate surface is critical. Consequently, General Magnaplate has developed a proprietary surface treatment consisting of specially designed equipment and chemical cleaning techniques. The cleaned parts are mounted on a specially designed fixture and then placed in the vacuum chamber. A vacuum of 1×10^{-6} torr is drawn, after which the chamber is purged with argon gas as a further cleaning step. Titanium metal (99.9%) is then vaporized by a plasma energy source, after

which nitrogen (the reactive gas) is introduced into the chamber. The parts to be coated are cathodically charged by direct high voltage, thereby attracting ions of titanium. Simultaneously, they combine with nitrogen to produce the tightly adhering, highly wear-resistant titanium nitride PVD coating.

Some alloys are sensitive to temperatures up to 900°F (482°C) and can be reduced in hardness if the substrate material is not heat-compatible with the process. To prevent certain steels from annealing, the processing temperature can be reduced but this might result in a slight reduction in the hardness of the titanium nitride coating.

16 High-Temperature Coatings

INTRODUCTION

Because of the need for high-temperature alloys to operate at higher temperatures in aggressive environments, alloys were developed with increasing strength and with additional favorable mechanical and corrosion resistance properties.

In a manner similar to aqueous corrosion, all forms of attack at elevated temperatures in which the metal is converted to a corrosion product are considered to be oxidation. There is an electron transfer involved and an "electrolyte" (i.e., the semiconductive layer of corrosion products). Between the three phases (metal, corrosion product layer, and environment), there is a definite migration of ions and electrons. In a semiconductor, unlike in a metal, electron transfer increases with temperature.

As in the electromotive series, there is an ordering of metals at high temperature. Gold will remain bright and unoxidized up to its melting point, while less noble metals oxidize more readily. Note that the reaction of metals with oxygen to form oxides is reversible, depending on the specific metal, the temperature, and the nature of the environment.

The rate at which a metal will oxidize depends on how protective the oxide layer is. The rate (usually weight gain) will be linear with time for a completely nonprotective oxide layer. A protective oxide layer that remains in place will have a rate that is parabolic or logarithmic, diminishing with time. The ease with which metal ions can diffuse out, and gaseous species in, depends on the structure of the oxide film.

Cycling temperatures tend to spall off the surface oxidation products, which leads to a paralinear rate. In this case, oxidation proceeds in a stepwise manner. Changes in the environment can also remove or modify the surface products.

An environment of hot air, oxygen, steam, carbon dioxide, etc. will tend to oxidize a metal. Environments of hydrogen, hydrogen-rich gases, or carbon monoxide are reducing and tend to convert oxides back to the metallic state.

The ratio of carbon monoxide to carbon dioxide determines the carburization or decarburization condition. This generalization also applies to other combinations of oxidizing and reducing species (such as hydrogen and water vapor, nitric oxides and ammonia, and sulfurous oxides with hydrogen sulfide). The picture is further complicated by the fact that an atmosphere may be reducing to one component such as nickel, but oxidizing to another such as chromium or silicon.

Catastrophic oxidation may also occur, as when silicon oxide dissolves in nickel or when molybdenum is vaporized as the oxide.

An alloy must meet two essential requirements to be oxidation-resistant at high temperatures. It must form a surface oxide that thickens slowly, and the oxide layer must remain adherent to the alloy substrate under all service conditions. Resistance to high-temperature corrosion of metals or alloys can be achieved by the formation and maintenance of an impervious, inert, adherent protective layer on the substrate. The protective layer can be formed either by direct application of, for example, a ceramic coating, or by the interaction between the environment and the metallic surface.

The role of coatings is to provide a protective barrier layer between the two reactants — the alloy and its environment — with long-term stability and resistance to cracking or spalling under the mechanical and thermal stresses produced during the operation of the component. The motivation for high-temperature coating development was the result of the need to develop alloys for gas turbine components that required increased alloy strength at high temperatures with increased corrosion resistance.

For a high-temperature metallic material to perform satisfactorily under service conditions, it is necessary that an impervious, protective oxide scale be formed and maintained. It is equally important that the mechanical properties of the alloy substrate (e.g., strength, creep, fatigue) remain unchanged by any compositional or structural changes resulting from the degradation process caused by the environment during the service period. However, the alloy compositions and microstructure that provide optimum mechanical properties do not always provide satisfactory high-temperature corrosion resistance. The development of alloy-strengthening mechanisms is such that higher strength can only be achieved at the expense of oxidation resistance.

The situation is even worse for refracting metals such as Mo, W, Nb, and Ta. Although these metals have high melting points, they cannot be used in oxidizing environments without additional protection because of their poor resistance to oxidation. Volatile oxides such as MoO_3 and WO_3 are formed during the oxidation of Mo and W, respectively. Nb and Ta, in addition to developing poor protective scales, have a high affinity for interstitial elements such as oxygen, nitrogen, carbon, and hydrogen. These interstitial elements easily dissolve in the metal and form ordered and sometimes metastable, martensitic phases that have a detrimental effect on the physical and mechanical properties of the alloy as well as the oxidation process. However, with a suitable protective coating, these metals can be used at high temperatures.

At high temperatures, the oxide layer formed by the environment frequently does not provide adequate protection for the underlying alloy substrate. Consequently, it is subject to degradation, either partially or at times catastrophically, within a short period of time. However, the service life of an alloy designed for high-temperature operation can be extended by coating the alloy with a special protective layer. Such a layer should have protective properties characterized by satisfactory adherence, compactness, and low mobility of the reactants (i.e., constituents of the alloy and the aggressive environment as well as the coating

constituents). The basic purpose of a high-temperature coating is to act as an effective solid-state barrier between the oxidants and the alloy. This will decrease the rate of degradation of the metallic component, thereby increasing the service life of the alloy substrate. The most effective way to combat the degradation of structural materials in high-temperature oxidizing environments is to protect them by means of surface layers of high-melting, thermally stable, and chemically resistant oxides.

In an oxidizing environment, a metallic material can be protected from degradation by either alloying with appropriate elements or by coating. The objective in both cases is to form or obtain a layer on the metallic surface that acts as a barrier to separate the metallic substrate from the reacting gas. The high-temperature corrosion resistance of numerous alloys is provided by scales consisting of chromia, alumina, and silica or more complex oxides of these. Such scales are formed by preferential or selective oxidation of chromium, aluminum, or silicon present as constituents of the alloys or coating. The oxide usually preferred for temperatures below 1832°F (1000°C) is Cr_2O_3; above this temperature, volatile CrO_3 forms at or near atmospheric pressure, whereas AlO_3 and SiO_2 are chemically more stable at higher temperatures.

Formation of such oxides can be considered in many ways, as shown in Figure 16.1. Prefabricated oxides can be developed with maximum chemical resistance as shown in Figure 16.1 but they usually exhibit unfavorable mechanical properties. In most cases, they are incompatible with the metal substrate. When chemical inertness of the coating is a factor along with improved mechanical properties of the alloy substrate, then the use of nonoxide ceramic coatings must be considered, keeping in mind that components of the coating material will diffuse into the substrate. As a result of the reactivity of these coating constituents with the substrate metallic elements during long-term application at high temperatures, a sequence of intermetallic phases may be formed. Figure 16.1B illustrates this situation. Solid-state reactions with the coating material and substrate alloy may cause embrittlement of the alloy after a long exposure period. This should be avoided because the composition and microstructure of the substrate alloy is always optimized to provide the desired mechanical properties. The solution to the problem is the combination of a high-strength alloy with a highly alloyed coating of the preferentially oxidizable alloy constituents having the ability to form self-healing layers, as shown in Figure 16.1C.

Because the addition of elements such as Cr, Al, and Si added in sufficient quantity to the substrate alloys seriously affects the mechanical properties of the alloys, these elements are often used in limited quantity in the alloy manufacturing process, and consequently limited oxidation resistance is provided to the alloys as shown in Figure 16.1D. However, if mechanical properties of the alloy are the prime concern, the best mechanical properties can be produced without the addition of these elements. This leads to uncontrolled degradation of the alloy, as illustrated in Figure 16.1E.

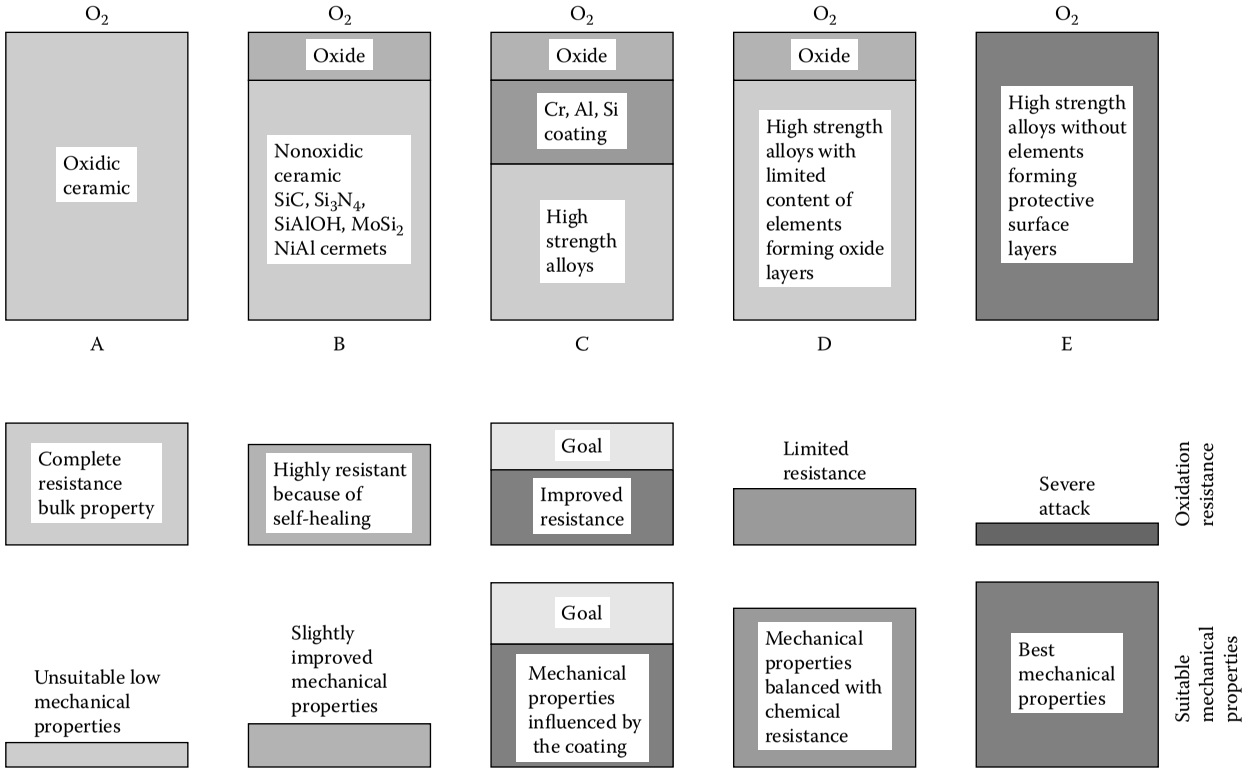


FIGURE 16.1 Schematic illustration of the possible situations for protective oxide layer formation providing oxidation resistance and mechanical properties of metallic material at high temperature.

REQUIREMENTS OF COATING–SUBSTRATE SYSTEM

A coating in oxidizing atmospheres at high temperature owes its oxidation resistance to the formation of a protective oxide layer. Consequently, it is important that the coating–substrate system meet the following requirements[2–4]:

1. The coating should form an integral coating-metal/alloy system, being chemically and thermally stable during the service life of the component.
2. The coating should have properties compatible with those of the metallic substrate.
3. The rate of interdiffusion between the coating and substrate alloy must be slow during the desired service life.
4. The thermal expansion coefficients of the protective layer and the metallic substrate should match, so as to avoid cracking and exfoliation of the coating during thermal cycling.
5. To accommodate creep and plastic deformation, a protective coating should exhibit some mechanical "elasticity" under operating conditions.
6. Depending on the specific application of the metallic components, a coating material should resist damages from impact, erosion, and abrasion.
7. The coating should exhibit a spontaneous "self-healing" property for self-repair in the event of failure due to cracking or spallation of the layer. That is, the coating should act as a reservoir for the highly oxidizable metallic constituent(s) for early development of a protective layer.
8. The coating should be easy to apply on substrates, and any defects that might occur during handling should be repairable without having any effect on the adjacent portions.

It is very difficult to develop a coating that will meet all of the above requirements. Consequently, compromises are often made that depend on the specific application of the coated material in a particular environment. In addition, as a result of the coating–environment and coating–substrate reactions, the structures of the actual protective coating systems are complex. The most successful coating systems are those that are multi-layered. Even single-layer coatings often become multi-layered during service as a result of coating–substrate and coating–environment reactions (e.g., silicide coatings on refractory metals such as Mo, W, etc.).

Therefore, there are three main factors to consider in the selection of protective systems for high-temperature applications:

1. Service or application conditions of the component
2. The structural alloy
3. The system of protection itself

The service stresses, temperature, cyclings, and other mechanical/thermal features are determined in the design of the component. The alloy properties are determined by composition, microstructure, and processing steps, all of which control the high-temperature stability. The selection of a suitable protective system is based on its resistance to environmental effects.

PROTECTIVE OXIDES

The protective layer should consist of an oxide or mixture of oxides with maximum stability. The oxides of primary interest include BeO, MgO, CaO, Al_2O_3, Y_2O_3, La_2O_3, SiO_2, TiO_2, ZrO_2, HfO_2, ThO_2, and Cr_2O_3 (as single oxide), their complex oxides, spinels, etc. CaO and La_2O_3 hydrate rapidly in air, BeO is toxic, and pure ZrO_2undergoes polymorphic transformation. However, ZrO_2 can be stabilized in the cubic form by the addition of other oxides, such as CaO_2, MgO, and Y_2O_3, thus eliminating the polymorphic transformation. It should be noted that most refractory oxides undergo chemical reactions among themselves at temperatures below their individual melting points, resulting in the formation of low-melting eutectic liquids.

Consequently, the useful temperature range of their applications is limited. Cr_2O_3 is stable only below a temperature of 1832°F (1000°C) in an atmospheric oxygen pressure.

The rate of solid-state diffusion through the protective film determines the effectiveness of a protective film in preventing further degradation of the underlying metal/alloy. Oxides having the slowest rates of diffusion of the reactants provide the most effective diffusion carriers. Therefore, it is necessary to have knowledge of the diffusion rates of both cations and oxygen. A comparative plot of self-diffusion coefficients of cations and oxygen in some simple oxides is presented in Figure 16.2.[2] This figure indicates that oxides such as CaO, MgO, and Al_2O_3 have the smallest diffusion coefficients, while oxides such as NiO and CaO exhibit high rates of diffusion. By the same token, stabilized zirconia with a large concentration of oxygen point defects provides a poor diffusion barrier. Above 2750°F (1500°C), the transport of molecular oxygen through SiO_2 is much lower than Al ions through Al_2O_3. In general, simple oxides with large ionic character and small deviations from stoichiometry act as better protective layers. Conversely, oxides such as FeO and CaO cannot act as effective diffusion barriers unless their point defect concentrations are decreased by doped element oxides.

When alloys are exposed to high temperatures in an oxidizing atmosphere, it is not uncommon for various types of spinels to also form, along with simple oxides. It is believed that these spinels serve as effective diffusion barriers because they exhibit low diffusion rates[2] in comparison with simple oxides, as illustrated in Figure 16.3.

Based on these facts, it is seen that the following characteristic properties of the three most commonly preferred alloying elements — Cr, Al, and Si — that can form stable, self-healing, oxide layers on alloy surfaces in providing protection under oxidizing environments are:

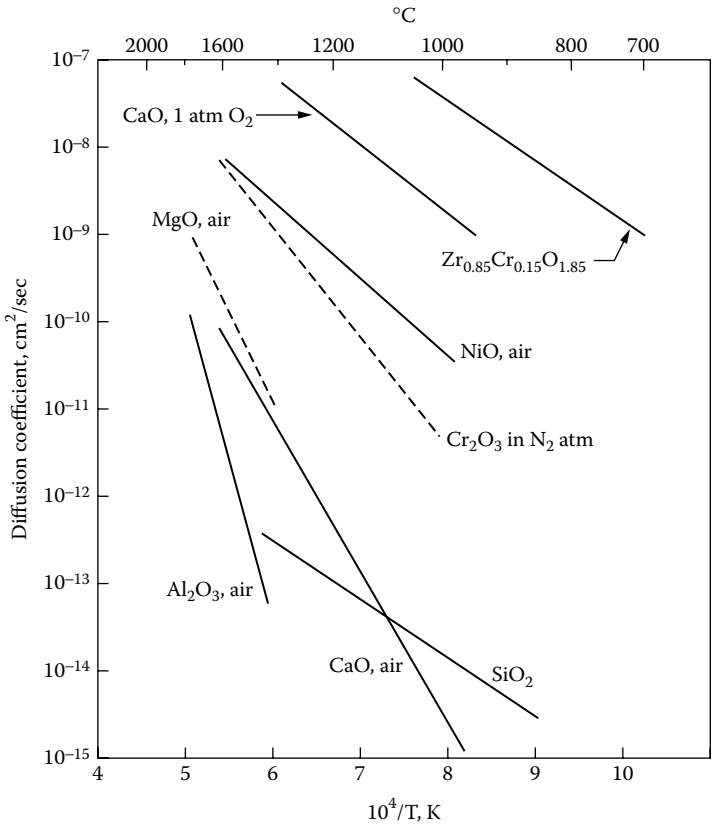


FIGURE 16.2 Comparative plot of cation diffusion coefficients in Al_2O_3, MgO, CaO, Cr_2O_3, NiO, CaO, and oxygen diffusion in stabilized zirconia and SiO_2.

1. Transport rates of aluminum cations are the slowest among the three simple oxides in the temperature range below 2552°F (1400°C).
2. In the cases of Cr_2O_3 and Al_2O_3 layers, the diffusing species are the respective cations; whereas in the case of pure SiO_2, it is primarily nonionized oxygen.
3. At temperatures above 2372°F (1300°C), the mobility of the diffusing species (oxygen in SiO_2) is the lowest among the three simple pure oxides.

These properties indicate that the addition of aluminum within the permissible limit that does not cause embrittlement to high-temperature alloys should provide sufficient protection by self-forming oxide layers at temperatures below 2552°F (1400°C). Chromium is the mildest of the three elements in so far as influence on alloy embrittlement is concerned. However, to guarantee self-forming oxide layers,

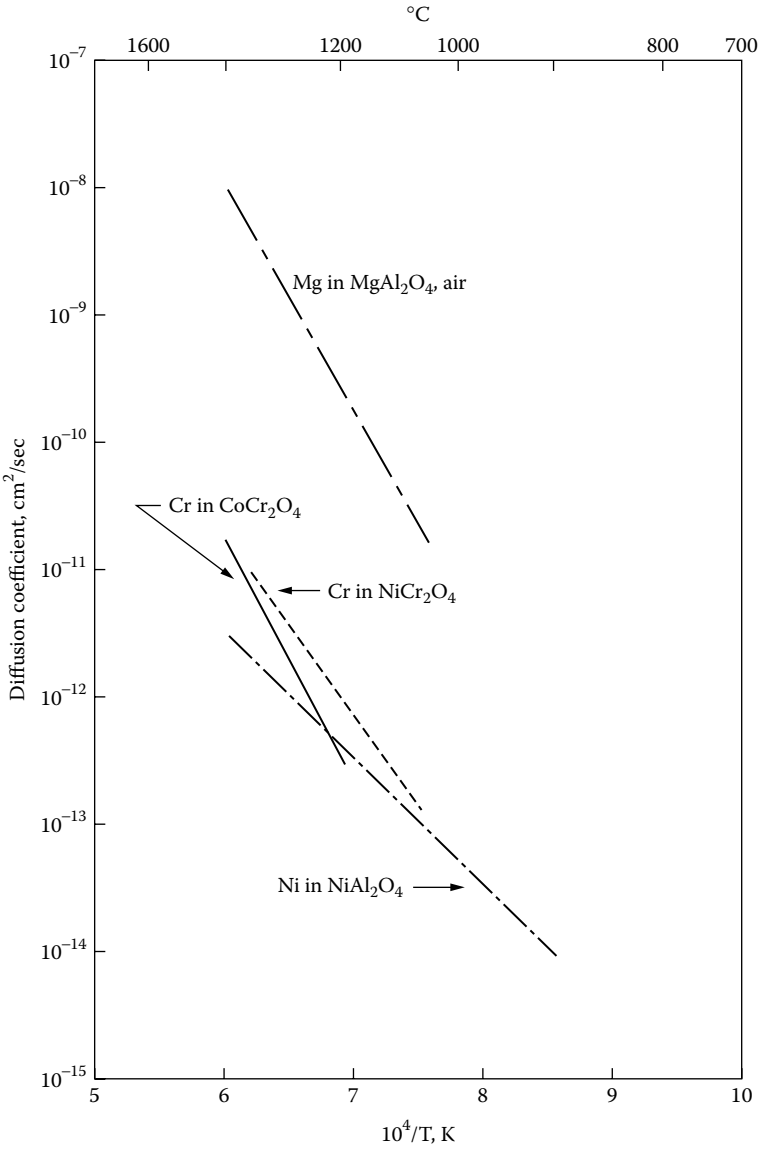


FIGURE 16.3 Comparative plot of diffusion coefficients in some spinels.

it is necessary to add more than the minimum highest permissible limit of 20 wt%. In addition, chromium as the single alloying element provides limited protection above 1832°F (1000°C) due to the formation of the volatile oxide Cr_2O_3. Therefore, it is advantageous to use low concentrations of aluminum in combination with higher amounts of chromium to guarantee protection above 1832°F (1000°C).

Note also that at temperatures above 2750°F (1500°C), the transport rates of molecular oxygen through SiO_2 layer are low in comparison with aluminum ion diffusion through Al_2O_3. As a result, silicides and silicon ceramics were developed as coating materials in oxidizing environments above 2750 to 3272°F (1500 to 1800°C). However, note that the element silicon, in addition to causing embrittlement to high-temperature alloys, similar to aluminum, has an additional negative effect on the coating-alloy performance. SiO_2 can form low-melting eutectics because of which the use of silicon in iron-based alloys as a stable oxide-forming additive is avoided at service temperatures above 1832°F (1000°C).

METHODS OF COATING

Protection of metallic materials from degradation at high temperatures in oxidizing conditions is obtained in two different ways:

1. Constituents of the coating material can react with the corrosive constituents of the environment, forming protective layers.
2. Layers of coating material can be applied over the metallic substrate that mechanically isolate the substrate from the corrosive environment. Materials used for protective coatings can be broadly classified into four groups:
   a. Metal or alloys that, on reaction with the environment, form a protective scale
   b. Intermetallic compounds such as silicides, aluminides, borides, etc.
   c. Ceramic coatings
   d. Noble coatings that do not form compounds with the aggressive constituents under operating conditions

Many methods are available for developing coatings on alloy substrates. Among these methods are electroplating, hot dipping in molten metals or fused salts, spraying (oxyfuel and plasma techniques), slurry spraying, cladding, enameling, vapor deposition, or chemical transport reactions (pack cementation, fluidized bed technique, pyrolitic deposition), vacuum evaporation, etc. These techniques are broadly divided into two groups: diffusion coatings and overlay coatings.

Diffusion coatings are formed through diffusional interactions between the coating material and the substrate alloy. Overlay coatings do not involve a direct alloying reaction with the substrate, although a diffusion step may be included to improve the bonding between the coating and the substrate.

DIFFUSION COATINGS

Pack Chromizing

The pack chromizing process by pack cementation was developed during World War II.[5] This process is still used to increase the service life of stationary gas turbine blades. It is representative of the diffusion technique. Coatings produced by this method are considered among the most effective protection from degradation.

The metal/alloy substrate to be coated is packed in a powdered mixture (cement) of the coating element (chromium), a small amount of easily decomposable activator such as NH_4Cl to produce the gas phase, and an inert ballast material (usually Al_2O_3) to prevent sintering. Reaction is carried out under inert or hydrogen atmosphere at elevated temperature (1472 to 2012°F; 800 to 1100°C) for a definite period of time, depending on the nature and thickness of the coating desired. The protective mechanism of such coatings is analogous to that of the chromium-rich superalloys and relies on their ability to develop a compact, dense, coherent oxide coating (Cr_2O_3) as a diffusion barrier against further oxidation or sulfidation. Resulting from the interaction of the hot gas and fuel ash deposit, these coatings undergo a continuous consumption that is accelerated by thermal and mechanical stressing. At times during service, the creep stress may develop above the critical limit, which may cause cracking of the protective scale at a faster rate than the regrowth rate of the oxide layer. The continued reduction of the chromium content resulting from successive Cr_2O_3 layer formation and its diffusion into the substrate alloy ultimately lead to insufficient chromium content in the coating to produce a subsequent protective barrier layer. Consequently, the chromium transport mechanism determines the life expectancy and ultimate failure of the protective system. To establish a diffusion coating layer, it is necessary to have sufficient solubility of the coating element in the substrate alloy, and the resultant solid solution should have good physical compatibility with the substrate without affecting its mechanical properties to a large extent. Such conditions are ideal for chromizing iron-based alloys, and adherent non-brittle coatings can easily be achieved with chromium contents of more than 30 wt% at the surface.

Pack Aluminizing

This process is similar to pack chromizing in that the component is imbedded in a powder mixture (cement) containing aluminum or aluminum-rich metallic powders, (e.g., Ti-Al, Ni-Al, Cr+Al alloy powders), inert filler, Al_2O_3 to prevent the sintering of the pack, and 1 to 2 wt% ammonium halide activators. The entire assembly is then heated to a temperature of 1472 to 2012°F (800 to 1100°C) in a hydrogen or argon atmosphere. At this temperature, aluminum halides form that diffuse through the porous pack and react at the surface of the substrate component, depositing aluminum either by disproportionation of aluminum halides or by a hydrogen reduction reaction. NiAl coatings are formed as a result of the aluminum diffusing into the substrate.

The formation of aluminide coatings can be broadly categorized as low- or high- activity processes, depending on the preferential diffusion of nickel or aluminum that takes place in the different layers formed during the heat cycles.

In the low-activity pack process, direct formation of an NiAl compound occurs in a single thermal cycle during the coating operation, involving preferential diffusion of nickel in the temperature range of 1832 to 2012°F (1000 to 1100°C).

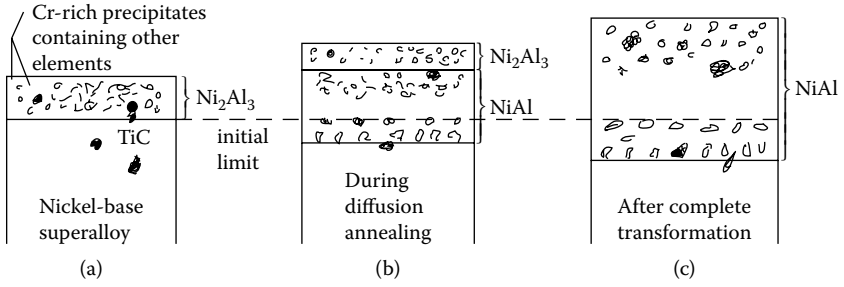


FIGURE 16.4 Schematic illustration of the formation of NiAL coating by diffusion annealing in high-activity process.

In the high-activity process, which is the one most frequently used, an Ni_2Al_3 phase is formed initially with preferential diffusion of aluminum during aluminizing treatment in the temperature range of 1292 to 1652°F (700 to 900°C). Subsequently during its diffusion, annealing in an argon atmosphere at temperatures of 1832 to 2012°F (1000–1100°C) in the absence of an aluminum source, Ni_2Al_3 transforms to NiAl by reacting with the substrate. The development of an NiAl coating during diffusion annealing, by interdiffusion between a layer of Ni_2Al_3 and the nickel-based superalloy substrate, is illustrated in Figure 16.4a–c. The final layer of NiAl on the alloy substrate, as illustrated in Figure 16.4c, consists of three distinct areas. The external region is almost as thick as the initial Ni_2Al_3 layer, containing various precipitates that were present in the initial layer. The middle area is devoid of precipitates. The internal region consists of precipitates similar to those found in the internal area of coatings obtained by a "low-activity" aluminizing treatment. Actually, the last two areas can be considered a "low-activity" coating, with the initially formed Ni_2Al_3 layer playing the role of cement. The high-activity NiAl coatings are distinguished from the "low-activity" coatings by virtue of the precipitates contained in the external area.

The composition and microstructure of these coatings depend on the composition of the substrate alloy; therefore, it is necessary to optimize the process parameters for a particular alloy. That is, the coatings are generally tailor-made for a given alloy composition. If a noble metal such as platinum and/or rhodium is predeposited, significant improvements will be achieved in the oxidation and hot corrosion resistance of the aluminide coatings. A thin (0.40 μm) layer of the noble metal is generally electroplated before the aluminizing process. In the low-activity process for nickel-based superalloys, a predeposit of titanium-free Ni-based alloy is recommended to trap titanium (which is often present in the alloy and can have a deleterious effect) in the form of Ti (C, N).

In the high-activity process, a predeposit of a suitable NI-Cr alloy, followed by aluminizing, produces a coating with a superficial area rich in chromium, which imparts superior oxidation resistance.

OVERLAY COATINGS

Weld Overlays

The weld overlay is the most important type of overlay coating. It is the most widely applied of all methods for bulk coating production. It is often applied to the inner surfaces of reaction vessels in the chemical processing industry. In this process,[6] the deposit is applied by melting the coating alloy on the surface by arc or gas welding processes. The coating material is supplied in the form of powder, rod, paste, wire, or strip. Standard welding processes are used to develop such coatings on components ranging in size from small components having intricate shapes to large areas of flat or cylindrical shape.

Flame and Plasma Spraying

These methods are similar to the weld overlay technique. In these processes,[7,8] a metallic or nonmetallic powder or wire is injected into a flame or plasma, where it melts to form small molten droplets. These droplets are then projected to the metal/alloy surface to be coated, freezing on impact. The integrity of the coating depends on atomization, the melting point of the particles, the degree of oxidation of the droplets, and the velocity on impact. When plasma spraying in atmospheric air, a direct-current electric arc is struck between the nozzle and the electrode, while a stream of mixed gases (commonly used are nitrogen, hydrogen, argon, and helium, or their mixtures) is passed through the arc. This results in dissociation and ionization of the gases, producing a high-temperature plasma (temperatures up to 16,273K) stream from the gun nozzle, although in practice most coatings are deposited with a flame temperature in the range of 6273 to 11,273K. The plasma torch acts as a high-enthalpy heat source and accelerates the powders to velocities up to 300 m/sec. In a short residence time of a few milliseconds, the powders transform to molten droplets, which hit and flatten on the component to be coated. The coating is built up layer by layer by repeated movement of the gun. Coatings formed by this technique tend to be porous, having a porosity in the range of 2 to 10%. In addition, their bonding to the substrate is often unsatisfactory. Improvement in bonding can be achieved by applying a first layer of a material that undergoes an exothermic reaction with the substrate, thereby developing a metallurgical bond. The intended coating material is then sprayed over the bond layer. Often, a third layer is applied to seal the top surface of the coating.

Plasma technology has changed to improve the adhesive strength and homogeneity of coatings. This resulted in the low-pressure plasma spraying (LPPS) process in which the entire unit is maintained at a low pressure (50 to 70 mbar). The LPPS process allows longer jet length and higher particle velocity, along with heating of the substrate to 1073 to 1173K. In addition, unwanted gas–metal reactions are also avoided, thereby producing coatings with a high degree of density and good adhesion. The greater procession flexibility and closer compositional control of LPPS permits deposition of coatings with desired compositions and microstructures that cannot be achieved by electron beam physical vapor deposition (EPPVD).

Another technique is laser-assisted spraying. In this technique, the coating powder is blown from the side into a high-powered laser beam, which heats it to the melting point so that the added elements are either alloyed with the substrate or embedded as solid particles in the molten surface.

Roll Bonding and Co-Extrusion

The bonding of protective layers to substrates, without resulting fusion at the interface, is widely used in industry. In such techniques, the coating is bonded to the substrate by solid-state methods that rely on a combination of surface cleanliness, temperature, and pressure to generate an intimate contact and interdiffusion, which produce a true metallurgical bond that is usually stronger than the parent metal itself. High-rate techniques comprise explosive cladding and electromagnetic impact bonding, while a slower rate uses hot isostatic pressure (HIP) to bond both powder and solid layers onto a component.

Medium-rate methods have processing times of approximately 1 minute, and comprise such processes as roll cladding and co-extrusion. The advantage of these methods is that the coating material can be carefully controlled and must have a reasonable ductility, so that it is unlikely to have a detrimental effect on the mechanical properties of the component.

Explosive cladding produces full-sized sheets of clad material, just as roll cladding does. The bond produced is metallurgical; but by use of an intermediate material, metallurgically incompatible materials can be coupled.

HIP is a diffusion process in which a metallurgical bond is formed by diffusion across the interface.

In electromagnetic impact bonding, the force is applied to the component by an intense magnetic field developed by a sudden surge of current through a coil. Products of rod and tubular form are produced by co-extrusion, particularly for creep-resisting steel bodies with internal or external cladding of stainless steels or nickel-based alloys.

Vapor Deposition and Related Techniques

Physical vapor deposition (PVD) involves the evaporation of the element required to form the coating, by directing an electron beam onto the substrate in a high-vacuum chamber and allowing the elements to condense on the substrate. The substrate can be preheated to improve the adhesion, and rotated to improve the uniformity of the coating.[9] Application of coatings to the interiors of holes or into hidden cavities is difficult. In addition, the adhesion of the coating is poor.

Ion plating is a related technique where, by increasing the gas pressure ($\approx$1 MPa) in the deposition chamber and creating a glow discharge, the energy of the ionized gas atoms (usually argon) can be used to clean the component surface by sputtering for improved adhesion of the coating.

In chemical vapor deposition (CVD), a molecular species containing the element or elements required for the coating are volatilized and subsequently

decompose onto the component surface, depositing the element/elements. The coating is therefore obtained either by thermal decomposition (pyrolysis) or chemical reaction in the gaseous phase. A typical example of thermal decomposition of the gaseous phase is:

$$TiI_{4(g)} \xrightarrow{1473K} \underbrace{Ti_{(deposit)}} + 2I_2 \uparrow$$

Decomposition of the gaseous phase by reduction reaction with hydrogen or a metallic vapor is:

$$WF_{6(g)} + 3H_{2(g)} \longrightarrow W_{(deposit)} + 6HF \uparrow$$

and

$$TiCl_{4(g)} + 2Mg_{(g)} \rightarrow Ti_{g(deposit)} + MgCl_2 \uparrow$$

The gas phase can be composed of organometallic compounds, metal carbonyls, metal halides, metal hydrides, etc. Reactions usually take place in the temperature range of 423 to 2473K and frequently between 773 and 1373K. Most CVD processes are conducted in open-loop systems (although closed-loop systems are also used) where the reactant gases are continually supplied from one end of the reactor and removed from the other end.

CVD processes have the following advantages:

1. Various types of deposits can be formed (elemental metal/alloy, TiC, TiN, Al_2O_3, etc.)
2. Production of good-quality deposits with varying structures (amorphous, crystalline, epitaxial, whiskers, etc.)
3. High rates of deposition
4. Complex-shaped bulk components can be coated

Hybrid processes such as plasma-assisted CVD (PACVD) and laser-assisted CVD (LACVD) are gaining popularity. PACVD is being used industrially in the fields of optics, solar energy devices, microelectronics, etc. In this process, plasma is used to assist in creating chemically reactive species from the gas phase.

The laser is used as a heat source in the LACVD process.

Ion Implantation

This technique is basically a research tool and has at yet to find industrial applications. The process is carried out in a fairly high-vacuum chamber and

involves the bombardment of the metal/alloy surface with a high-energy beam of ions of the chosen element to be implanted. The ions are accelerated to an energy of approximately 100 keV, but their penetration into the surface is limited to less than 0.5 μm with an approximate Gaussian distribution. Once the ions are implanted, no diffusion occurs and heating of the substrate is minimal. The fraction of implanted ions can be as high as 0.30 locally. Its principal use in high-temperature applications is limited to the implantation of reactive elements such as yttrium, cerium, lanthanum, etc. into the metal/alloy substrate.

THERMAL BARRIER COATINGS

Thermal barrier coatings (TBCs) are used to insulate and protect critical air-cooled components of gas turbine engines.[8,10] A large amount of energy derived from the fuel combustion process is dissipated through the engine structure and the cooling system. Components in a diesel engine, such as pistons, valves, liners, cylinders, covers, etc., reach high surface temperatures during combustion. To retain the mechanical, thermal, and corrosion-resistant properties, the absorbed heat must be removed. Approximately 50% of the energy produced in the combustion process is removed with cooling water/air and through exhaust gas. To save energy, it is necessary and advantageous to protect the hot parts of an engine with a thermally insulating layer. A ceramic layer would prevent heat transfer from the combustion zone to the coolant and surroundings, allowing a reduction in temperature of the metallic surfaces and providing protection against corrosion.

The thermal barrier coatings consist of an insulating ceramic coating adhering to an underlying oxidation-resistant metallic bond coating. The insulating nature of a TBC is shown in Figure 16.5. Such a system permits the use of higher gas temperatures, increasing the thermal efficiency while still using the same metallic component. In addition to providing insulation, TBC along with oxidation-resistant bond coating also provide metallic components with resistance to corrosive environments by lowering their temperatures. Therefore, the requirements for a material to be used as a TBC are:

1. Low thermal conductivity
2. Resistance to corrosive and erosive environments
3. High thermal coefficients of expansion (for compatibility with metallic materials)
4. Thermal shock resistance

ZrO_2-based coatings satisfy the above requirements and are commonly used as TBCs. A comparison of the thermal conductivity of different materials is:

Gray iron, 20 W/mK
Aluminum alloys, 117 W/mK
Ceramic silicon nitride, 20 W/mK
Plasma sprayed, stabilized ZrO_2, 1.5–2.4 W/mK

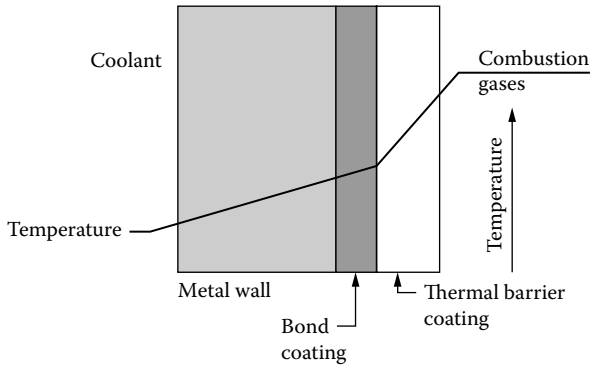


FIGURE 16.5 Schematic representation of a TBC-bond coating system, indicating the temperature profile on an air-cooled engine component.

In addition, ZrO_2 has relatively high coefficients of thermal expansion, which reduces the interfacial stresses between the TBC and bond coating.

With the addition of sufficient stabilizer (Y_2O_3 MgO, CaO, CeO_2, etc.), the ZrO_2 structure can be fully stabilized and retained in cubic form even at ambient temperatures. However, by maintaining the addition of stabilizer at a low value, it is possible to obtain partial stabilization of ZrO_2 and all three phases (cubic, tetragonal, and monoclinic) can be retained on cooling to room temperature. Partially stabilized ZrO_2 (PSZ) is a superior TBC material compared to fully stabilized ZrO_2, due to its better thermal shock resistance and lower linear thermal expansion coefficient.

TBCs are deposited on superalloys by air plasma spraying on top of a vacuum plasma-sprayed M-Cr-Al-Y bond coating. The optimum chromium and yttrium contents should be 14 to 18 wt% and 0.3 wt%, respectively, for reducing the tendency for spallation at the TBC-bond coating surface.

DEGRADATION OF COATINGS

The degradation of TBCs during service can occur by two processes:

1. Diffusional interaction between coating and substrate
2. Degradation of the coating via reaction and interaction with the environment

Degradation via Diffusional Interaction between Coating and Substrate

During operation at high temperatures, chemical reactions occur between the reactive element or elements of the coating and the reactive species of the

environment, forming a stable, impervious, protective barrier layer that protects the substrate from degradation. However, at the same time, diffusional interaction between the coating and substrate continues. These interactions can take place either through diffusion of the base metal/alloy constituents into the coating, or through diffusion of the element/elements of the coating into the alloy substrate.

Aluminized coatings on nickel- and cobalt-based alloys are formed by outward diffusion of nickel and cobalt from the respective alloy substrate. The NiAl and CoAl phases, which on oxidation form a stable barrier layer of Al_2O_3,[11] determine the protective properties of the coating. Deterioration of the coating continues during high-temperature operation as it becomes gradually diluted in the component that forms the protective oxide scale. The NiAl phase is gradually transformed to the Ni_3Al phase, which has poorer protective properties. Aluminum is consumed in the formation of a protective Al_2O_3 scale that, as a result of thermal shock and erosive gas flux action, is continuously destroyed. Meanwhile, aluminum diffusion from the coating into the alloy substrate occurs simultaneously. Under these conditions, an Ni_3Al phase forms simultaneously at the $NiAl/Al_2O_3$ interface and at the substrate-aluminum-depleted NiAl boundary layer. Precipitation of the Ni_3Al phase at the Al_2O_3/coating boundary is detrimental because increased oxidation takes place along such precipitates. Such a situation occurs when continuous growth of Ni_3Al crystallites connects the inner surface of the coating layer to the inner Ni_3Al layer adjoining the substrate. This results in the complete loss of protective properties of the diffusion coating. Rapid oxidation along Ni_3Al crystallite boundaries together with penetration of the oxidant to the inner Ni_3Al layer cause exfoliation of the protective scale. Figure 16.6 illustrates the mechanism of such a coating deterioration process.[11]

In a similar way, the deterioration of aluminide coatings on cobalt-based superalloys is attributed to the formation of the aluminum-depleted CoAl phase through simultaneous Al_2O_3 layer formation and outward diffusion of cobalt. Over a period of time, the cobalt transforms to a cobalt phase.

Refractory metals are better protected in high-temperature service by the formation of self-healing SiO_2 layers formed on silicide coatings. Al_2O_3 layers developed on aluminide coatings do not provide adequate protection. The protectiveness of silicide coatings results from the[12]:

1. Formation of glassy SiO_2 scales
2. Low diffusivity of molecular oxygen in these scales
3. High flexibility of SiO_2 in being able to form modified glasses or silicates as a result of uptake of elements from the substrate or environment
4. Self-healing properties of SiO_2
5. Adjustment of thermal expansion by the use of additive elements
6. Inertness of silicon against sulfidation

The diffusion of silicon into a refractory metal substrate having acceptable mechanical properties produces a silicide coating forming $MoSi_2$ or WSi_2, which,

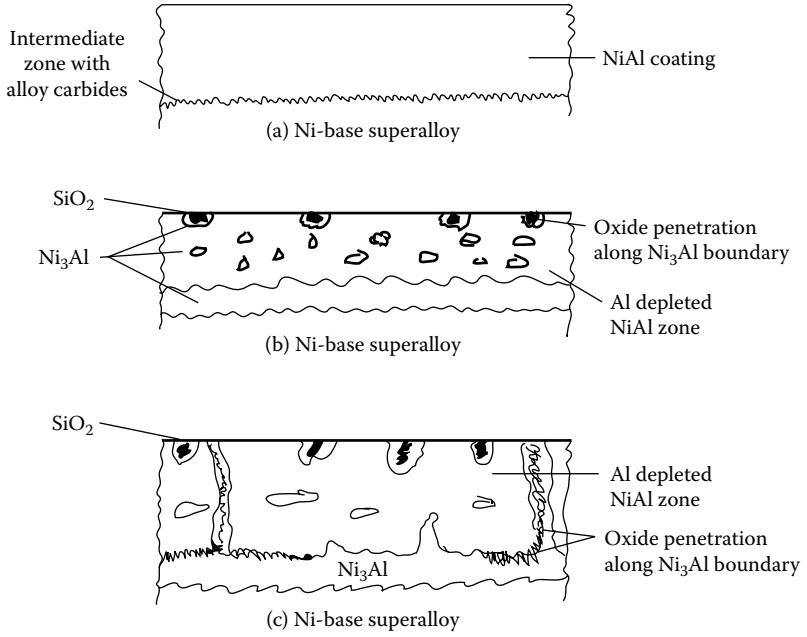


FIGURE 16.6 Schematic illustration of aluminide coating deterioration mechanism on nickel-based alloys: (a) coating prior to exfoliation, (b) changes during exfoliation, and (c) breakdown of coating and spalling.

on oxidation at high temperature, forms a thin protective, glassy layer of SiO_2. This layer provides protective properties to a temperature of 1973K, which is close to the melting point (1998K) of crystobalite-modified SiO_2. Silicide coatings are not normally used to protect nickel-based alloys, primarily because of the brittleness of the coating and the rapid rate of Si diffusion into the alloy substrate during high-temperature exposures.

The useful upper temperature limit of a silicide coating in oxidizing environments is determined by the refractoriness of the coating compounds, their rates of conversion to oxide, the necessity that the oxide be silica, the rate and site of vapor phase material loss, and the rate of diffusional reactions between the coating and the substrate.[18] The refractoriness of the coating depends on the melting point of the initial material and the product of reactions between the substrate and the environment. The silicide coatings formed on refractory metals are primarily composed of a layer of the most silica-rich intermetallic in the binary system, which gets converted to lower silicides by solid-state diffusion, and silica during high-temperature exposure to oxidizing environments. This is depicted in Figure 16.7.[13] $MoSi_2$ and WSi_2 are the desired intermetallics formed on Mo and W during the coating process; however, during their service conditions, they are converted to lower silicides by diffusion processes, forming Mo_5Si_3 and Mo_3Si.[2]

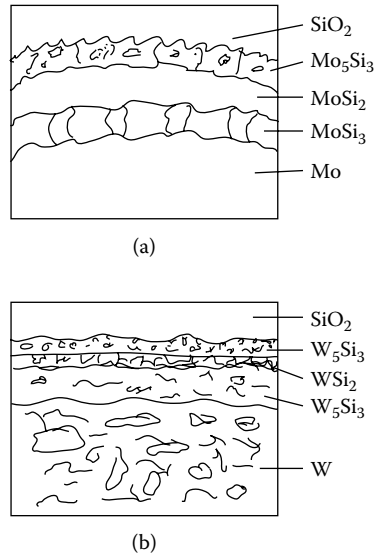


FIGURE 16.7 Schematic illustration of the degradation of disilicide coatings to lower silicides by coating–substrate interaction during oxidation: (a) $MoSi_2$ on Mo after 30 hr at 1948K and (b) WSi_2 on W after 13 hr at 1923K.

In Figure 16.7A, the Mo_3Si phase is not observable for the limited exposure time of the coating. Tungsten also exhibits similar silicide phases. The oxidation resistance of these silicides decreases in the order $MoSi_2 > Mo_5Si_3 > Mo_3Si$ with decreasing silicon content in the silicide. The two lower silicides can eventually exhibit protective properties but due to their low silicon content, a longer period of oxidation is required.

During the diffusion process, the thickness of the different layers is controlled by the relative rates of diffusion in each layer and the chemical potential gradient of the diffusion species. If diffusion through one layer is rapid, the corresponding layer will be thick; whereas if the diffusion rate through a layer is slow compared to neighboring layers, the thickness of the grown layer will be thin, providing the temperature dependencies of growth of the layers are identical. By predepositing a high-melting-point metal prior to application of the coating, diffusion of the coating constituent into the substrate metal/alloy can be reduced.

Oxidation of molybdenum and tungsten silicides leads to the formation of protective SiO_2 and to the formation of trioxides of the respective metals (MoO_3 and WO_3), which are highly volatile. The oxidation behavior of these silicides is determined by the degree to which the coating constituents are oxidized, the rate of evaporation of the trioxides, and the structure and composition of the reaction products.

Silicide Pest

In the temperature range 723 to 87K, oxidation of molybdenum disilicide ($MoSi_2$) exhibits an interesting phenomenon, wherein accelerated corrosion takes place at an almost linear rate, but as the temperature rises, the rate decreases rapidly.

This phenomenon is termed "silicide pest" and involves not only surface oxidation of the disilicide but primarily intercrystalline oxidation of $MoSi_2$, in which each grain eventually becomes surrounded by reaction products. Eventually, the silicide coating disintegrates to a voluminous pile of powder. It is important to note that this process takes place within a temperature range where MoO_3 is stable. All silicides, not only molybdenum silicide, are subject to this condition. The onset of pest can sometimes be delayed by modification of the coating, but it cannot be prevented.

Degradation via Reaction with the Environment

As discussed, the composition and microstructure of the coatings can change during service as a result of coating–substrate interaction by diffusional processes. Because of these changes, the corrosion resistance of the coating can also be expected to change. Coating formation techniques are also a factor. Coatings may contain porosities, as with plasma sprayed coatings, that allow penetration of the reactive constituents of the gaseous reactant into the coating. At times, the penetration may even reach the substrate, causing degradation of the metal/alloy, which was assumed to be protected.

Chemical reactions between the coating and environment can promote vaporization as well as simple evaporation. When the operating temperature is raised, or the pressure is decreased, or when the product of oxidation is volatile in nature, a previously formed protective oxide layer may dissociate. In either case, changes in operating pressure affect the vaporization rate. As the operating pressure is increased, the rate of vaporization due to dissociation alone decreases steadily. However, vaporization resulting from volatile oxide formation increases initially with increasing oxygen pressure because the rate of oxide formation and subsequent vaporization depends on the rate of oxygen availability. Eventually, the vaporization rate will decrease with increasing pressure as a result of the formation of a blanket of the volatile oxide.

When metals from the platinum groups are used as coatings in oxidizing atmospheres at high temperatures, they are eroded as a result of volatilization of the oxides such as PtO_2.[2]

Depending on the type of protective scales formed during service, protective coatings are classified into three main groups:

1. Chromia formers
2. Alumina formers
3. Silica formers

The chromia and silica forming coatings have the following limitations resulting from reactions with the environment producing volatile oxides.

1. Chromia scale forming coatings should not be used at temperatures above 1273K in oxygen at or near atmospheric pressure. Under such conditions, Cr_2O_3 is oxidatively evaporated to CrO_3. These coatings can be used at higher temperatures in lower oxygen partial pressures.
2. Silica scales on silicide coatings are not stable at reduced oxygen pressures and at high temperatures due to the formation of volatile SiO. In general, SiO_2 forming coatings should not be used at temperatures above 1873 to 1973K because the low viscosity of silica is maintained only below this temperature range. It is the viscosity of silica, rather than its melting point, that must be considered in applications, although silicide coatings are used occasionally at temperatures above its melting point. In the temperature range 2273 to 2773K, silica is relatively fluid. The glassy films of silica are not prone to break-away, possibly because of their excellent ductility and thinness. The oxide film thinness formed on silicides is probably the result of vapor-phase loss of silica. These losses can result from two processes: simple evaporation and decomposition to volatile SiO, which bubbles out through the outer protective layer of silica, thereby causing early coating failure.[13]

Thermal cycling, which leads to the cracking of the protective layer as a result of the differences in thermal expansion between the scale and substrate, reduces the service life of a silicide coating. Crack formation during cooling does not necessarily lead to failure of the protective properties of the coating because SiO_2 can grow during subsequent heating as a self-healing layer. During subsequent heating, cracks heal partly by thermal expansion and sintering, and partly by formation of new oxide. The deteriorating effects of thermal cycling can be minimized by depositing a layer of molybdenum boride between the metal and the disilicide. This results in the better filling and sealing of the cracks resulting from the flexing action of boron oxides.

The protective properties of an SiO_2 layer are affected by the structural changes of the SiO_2 layer. At temperatures above 1473K, it is glassy; while at lower temperatures, it becomes increasingly crystalline. At 1073K, the scale on $MoSi_2$ consists of crystalline SiO_2 (crystollite) associated with a complex $MoSi_2$ phase. The best protective properties are provided by the glassy layer that forms above 1473K. Because the SiO_2 layer undergoes transformation from glassy to crystalline during the intermediate cooling range of 1273 to 1473K, it is advantageous to pre-oxidize $MoSi_2$ coatings at 1673 to 1773K before using the coated component at lower temperatures.[11]

A reduced oxygen partial pressure in the environment also adversely affects the protective properties of $MoSi_2$. At reduced pressures, the degradation process becomes localized, thereby resulting in numerous pinholes. With a reduced oxygen

partial pressure, the oxidizing power of the gas phase is not sufficient to permit formation of a continuous protective film of SiO_2. In addition, at low oxygen pressures, SiO_2 evaporation also becomes an important factor.

If silicide-coated molybdenum will be used in atmospheres having low oxygen activity, pre-oxidation of the coating in an atmosphere having high oxygen activity should be undertaken in order to develop a thin SiO_2 layer on the coating surface.

There is a definite gradient in the physical, mechanical, and chemical properties of the coating-metal/alloy system containing silicon as the primary protective element. Thermal expansion mismatch and brittleness lead to cracking and spallation during thermal cyclings. The inherent brittleness of silicide intermetallics is one of the most important reasons for their failure, although the ductile–brittle transition temperatures of silicide coatings are higher than those of other coating systems.[12] To maintain the silicon content in the surface layer of the coating unaffected from loss due to oxidation over long periods of exposure, tough matrices and dispersed silicide reservoir phases in the Ni-Cr-Si and M-Cr-Si-Ta overlay coatings systems are used. The addition of refractory metals such as Ta, Ti, Nb, or Mo will reduce the problem of interdiffusion in silicide coating–substrate systems. Ta is the most effective refractory metal in reducing the diffusion rate.

Silica scales provide better protection than chromia scales, which are susceptible to vaporization loss via $CrO_3(g)$ at temperatures above 1273K. Alumina scales are definitely superior to silica scales at gas turbine operating temperatures. At operating temperatures above 1773K, silica scales are more effective barriers in inhibiting degradation and are used to protect refractory metals at super high temperatures (approximately 1973K).

DURABILITY OF TBCS

Partially stabilized zirconia (ZrO_2/22 wt% MgO or ZrO_2/6–8 wt% Y_2O_3) is the preferred material for thermal barrier coatings because of its inertness, insulating property with low thermal conductivity, high resistance to corrosive and erosive atmospheres, high coefficient of thermal expansion to be compatible with metallic substrates, and thermal shock resistance properties. In addition, other properties, such as adhesion strength, residual stresses, porosity, etc., add to the integrity of the coating system.

Any thermal expansion mismatch between the TBC and the alloy substrate results in interfacial residual stresses, leading potentially to coating delamination. The residual stresses depend on a variety of mismatch strains and on the extent to which these strains result in mismatch stresses. Thermal gradients and the transition from molten to solid state generate stresses in plasma-sprayed ceramic coatings. In all melt coating processes, the liquid–solid volume shrinkage, which may be as high as 10% for ZrO_2, results in large strains. Porosity and stress concentration are the result of such shrinkage.[8] The porous nature of the TBC improves its thermal shock resistance, but it permits easy penetration of corrodents through

the coating, which can result in rapid degradation of the substrate metal/alloy. To reduce such effects, an intermediate bond coat of a material having high oxidation and corrosion resistance properties is applied between the TBC and substrate. This also minimizes the thermal expansion mismatch.

Ni-Cr-Al-Y coatings are normally used for such bond coats. The FCC matrix of the Ni-based alloy is selected for high-temperature applications because of its nearly filled third electron shell, which provides phase stability even in the presence of alloying elements. Chromium and aluminum increase the strength of the nickel matrix by solid solution strengthening and also form protective Cr_2O_3- and Al_2O_3-rich through reaction with the environment. In addition, aluminum aids in the formation γ phase, which results in antiphase boundary strengthening. Chromium in the superalloy complex reduces spalling of the protective film. Scale adherence is improved by the addition of yttrium.

Most TBC bond coating system failures occur at the ceramic/bond coating interface as a result of high compressive stresses in the TBC. The extent of these stresses are determined by the degree of strain relieved (by plastic deformation or by microcracking). Some of the thermal expansion strain may or may not be counteracted by the transformation strains, which are inversely dependent on the degree of stabilization of ZrO_2. In addition, microcracking associated with phase transformation or porosity is a potential mechanism of relieving mismatch strains.

When the TBC bond coating system is operating at high temperatures, the interfacial bonding oxide, which is mainly Al_2O_3– or Cr_2O_3–rich grows in thickness. When the oxide layer reaches sufficient thickness, its own thermal shock resistance property comes into play. This is the single most time-dependent factor that limits the service life of a TBC.

The bond coating material should form an impervious, tenacious oxide bonding layer that does not permit the oxide layer to grow in thickness with time at the operating temperature. Al_2O_3 has poor thermal shock resistance; therefore, the currently preferred bond coatings are adjusted to low aluminum with higher chromium to utilize the superior shock resistance properties of Cr_2O_3.

REFERENCES

1. Fitzer, F. and Schlichting, J., in *Proceedings of the Conference on High Temperature Corrosion,* R.A. Rapp, Ed., NACE, Houston, 1983, p. 604.
2. Kofstad, P., *High Temperature Oxidation of Metals,* John Wiley & Sons, New York, 1966.
3 Petit, F.S., in *Coatings for High Temperature Applications,* E. Lang, Ed., Applied Science Publishers, London, 1983, p. 341.
4. Nicol, in *Coatings for High Temperature Applications,* E. Lang, Ed., Applied Science Publishers, London, 1983, p. 269.
5. Bauer, R., Grunling, H.W., and Schneider, K., in *Materials and Coatings to Resist High Temperature Corrosion,* D.R. Holmes and A. Rahmel, Eds., Applied Science Publishers, London, 1978, p. 369.

6. Bucklow, J.A., in *Coatings for High Temperature Applications,* E. Lang, Ed., Applied Science Publishers, London, 1983, p. 139.
7. Steffens, H.D., in *Coatings for High Temperature Applications,* E. Lang, Ed., Applied Science Publishers, London, 1983, p. 121.
8. Kvernes, I., in *Coatings for High Temperature Applications,* E. Lang, Ed., Applied Science Publishers, London, 1983 p. 361.
9. Duret, C. and Pichoir, R., in *Coatings for High Temperature Applications,* E. Lang, Ed., Applied Science Publishers, London, 1983, p. 33.
10. Fairbanks, J.W. and Hecht, R.J., *Material Sci. Eng.,* 88, 321, 1987.
11. Mrowec, S. and Werber, T., *Gas Corrosion of Metals,* translated from Polish by W. Barloszewski, published by National Bureau of Standards and The National Science Foundation, Washington, D.C., 1978.
12. Gruninling, H.W. and Bauer, R., *Thin Solid Films,* 95, 3, 1982.
13. Dickinson, C.D., Nicholas, M.G., Pranatis, A.L., and Whitman, C.I., *J. Met.,* 15, 787, 1963.

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