
Coating Types and Selection

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Gilbert Gedeon, P.E.



Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

Chapter 4 Coating Types and Characteristics

4-1. Introduction

a. All coatings—whether used for corrosion protection, to provide good aesthetics or a pleasing appearance, or for any other purpose—will contain a film-forming material. This material may be organic or inorganic and, after application, may form a hard, impervious film, a soft porous film, or combinations in between. Furthermore, the film-forming material may be clear (unpigmented) or filled with a variety of different pigments, depending on its function. When the film-forming material (resin) contains pigments, it is called a binder. The binder will hold the pigment particles together and to the substrate over which it has been applied. When the binder (resin plus pigment) is dissolved in a solvent to make it liquid, the combination (solvent, binder, and pigment) is considered to be a vehicle. The term vehicle comes from the ability to transport and apply the liquid to the surface being coated. Once on the surface, the solvent evaporates and the vehicle becomes a pigment-binder system. Application properties of the paint usually are characterized by the vehicle in a liquid condition. The viscosity, rate of solvent evaporation, and consistency of the wet coating are most important during application. After application, the pigments determine the corrosion-inhibitive properties and, generally, the color and some flow control properties of the applied coating. The binder determines the weatherability of the coating, its environmental resistance, and the coating's ability to function in a given environment. The required surface preparation, and often the application equipment and techniques, are determined by the binder.

b. The principal mechanisms by which binders form films are reaction with oxygen from the air (oxidation), evaporation of the solvent from the vehicle (solvent evaporation), or chemical crosslinking (polymerization). The coating film attained by these mechanisms can be either thermoplastic or thermosetting. Thermoplastic materials deform and soften on exposure to heat. Thermoset materials do not deform and remain hard upon heat exposure. Each type of coating resin or binder categorized by its film-forming mechanism, different types of pigments, and the various solvent families will be discussed. Drying oils are an integral part of some coating formulations, and they as well as driers that aid in the drying reaction will be covered. Miscellaneous additives that are formulated into many coatings for specific purposes are itemized and discussed. Sections are presented on powder coatings, thermal spray organic and inorganic coatings, and galvanizing tapes and wraps. Problems with VOCs also will be discussed.

4-2. Film-Forming Mechanisms

Coating binders can be subcategorized according to the mechanism described above. However, with both oxidation and most polymerization film-forming mechanisms, solvent evaporation occurs initially, followed by a subsequent chemical reaction consisting of either a reaction with oxygen or chemical crosslinking. Solvent evaporative coatings also are called thermoplastics because, when heated, they become plastic and can soften and deform. Oxidation and chemically crosslinked coatings “set” and harden when cured; they do not soften or deform on heating and, therefore, are called thermosets. After application, most coatings “dry” by solvent evaporation to form a film that feels dry to the touch. However, the dried coating may not be cured, and additional chemical reactions may be required. Oxidation coatings require crosslinking with oxygen from the air, and polymerization coatings require a crosslinking chemical reaction between two or more coreactants to attain their final physical and chemical properties.

a. Oxidation (thermoset). Thermoset coating types dry and ultimately crosslink by reaction with oxygen from the atmosphere. All such coatings in this class contain drying oils that consist mainly of polyunsaturated fatty acids. The drying oil frequently is combined with a resin, usually by cooking or heating to enhance water and chemical resistance. The curing reaction is accelerated by the presence of metallic salts as driers. After application, the coating dries by solvent evaporation. However, to attain maximum chemical and moisture-resistance properties, the oil must react with oxygen from the air to crosslink, cure, and further harden. The auto-oxidation reaction occurs at a relatively fast rate shortly after application of the wet paint; and it continues throughout the life of the coating, although at a much slower rate. For most oil-based coatings, suitable moisture and chemical resistance occur within a few days after application, although maximum resistances may not be obtained until months or years after application. In time (often 20 or 30 years later), the oxidation reaction and continued drying of the oleoresinous binder system leads to cracking, embrittlement, and deterioration of the coating film.

b. Solvent evaporation (thermoplastic). A second film-forming mechanism is solvent evaporation. The solvent within which the resin is dissolved or emulsified may be water or an organic solvent. The liquid resin returns to a solid material when the solvent evaporates. The coating is formed as a result of solvent evaporation and drying, with no attendant crosslinking or polymerization. Solvent-based coating systems that dry solely by solvent evaporation (vinyls and chlorinated rubbers) have their usage severely

restricted because of VOC regulations. These resins must be dissolved in relatively high amounts of noncompliant solvents to be formulated into a corrosion-resistance protective coating. Latex emulsion coatings consist of pigmented synthetic resin particles emulsified in water. Because latex emulsion coatings dry by water evaporation (and perhaps one percent or less of a coalescing organic solvent), coatings formulated in this fashion comply with VOC legislation; and they have rapidly advanced in recent years to become environmentally safe, long-lasting, protective coating systems. Thermoplastic coatings in the context used here are coatings that dry principally, or solely, by water or solvent evaporation; they do not undergo chemical crosslinking. Principal coatings in this class are acrylic lattices, solvent cutbacks, and hot melt bituminous coatings and vinyl coatings (zinc chromate vinyl butyral wash primers, vinyl chloride-vinyl acetate copolymers, and waterborne vinyls).

c. Chemically crosslinked (thermoset). Thermoset coatings, by definition, are coatings that are “set,” and are nondeformable when exposed to elevated temperatures. Thermoset coatings achieve their characteristic “set” and the ability to resist heat deformation by virtue of a three-dimensional crosslinking. This crosslinking is achieved by coreacting two or more monomers, with at least one monomer having a functionality of three or greater, and the other a functionality of at least two. (The functionality is the number of reaction sites where crosslinking can occur.) This film-forming mechanism involves a chemical reaction combining smaller molecules (mers) to create a larger molecule (polymers). The reactions can consist of the same kind of mer units reacting to form larger molecules (homopolymers) or different mer units reacting to form copolymers, tripolymers, or, generically, polymers. After crosslinking, and depending on the type and extent of crosslinking, the resin system is solvent resistant, ranges from tough and flexible to hard and brittle, and does not significantly deform on the application of heat. In coating formulations, most coreactive coating systems are supplied in multipack systems consisting of two or more containers that must be mixed prior to application. However, some thermoset materials react with moisture from the air (moisture and ketimine curing isocyanates) and can be supplied as a one-package system. After application in all instances, the coating system, when properly applied and cured, forms a single, extremely large molecule by virtue of its polyfunctional crosslinking. When suitably dissolved in a solvent and pigmented, many coreactive materials can be formulated into a protective coating. Some of the more commonly used protective coating systems are based on catalyzed epoxy resins, polyurethane reactions, acrylic/vinyl ester resins, and modifications thereof. Each of these coating systems will be discussed later. Polymerization

reactions are becoming increasingly important in the formulation of modern VOC-compliant coating systems. Small molecule units, that by virtue of their low molecular weight are liquid, can be reacted with other low molecular weight liquid molecules to form a higher molecular weight molecule that will harden to form a solid (nonliquid) protective film. The most successful adaptations to manufacturing low VOC coatings have been two-pack, chemically cured coating systems such as the epoxy, polyurethane, polyester, and vinyl ester systems.

4-3. Binders (Resins)

The binder, sometimes called a resin, and a suitable solvent (to make it liquid) are combined to form the vehicle. Pigment particles then are dispersed and mixed into the liquid resin, and the paint is packaged, usually in a can or pail, for sale. Upon use, the liquid paint is applied—perhaps by brush, roller, or spray—after which the solvent volatilizes, the liquid resin dries or cures, and the pigment particles “bind” together and to the surface being painted. Binders may be natural or synthetic resins and may be organic or inorganic. The binder used in a particular coating system is primarily responsible for the coating's chemical, water, and UV light-resistant properties. However, to optimize protective capabilities, most coatings must be pigmented to provide color and opacity, to reduce shrinkage, and to obtain enhanced moisture and chemical resistance. When properly applied and dried and/or cured, the pigmented binder provides the decorative, protective layer referred to as a paint or coating. The characteristic of the binder and its method of drying and/or curing determines the mechanism of film formation. Many of the natural resins used as binders are derived from exudations from trees or insect secretions. Synthetic binders are generally by-products of chemical refining or manufacturing processes. These resins are man-made and, when refined and modified for coatings use, can be used as film formers for protective and decorative coatings. Because of their improved moisture, chemical, and UV resistant properties compared with the natural resins, synthetic resins have obtained widespread use in a variety of different service environments as corrosion-protective coatings.

a. Natural resins (oxidative). Natural resins are derived from tree exudations, fossilized vegetable remains, or insect secretions. Natural resins derived from tree exudation may be named after the region from which they originated; this accounts for some exotic names such as Kauri, Batu, Sandric, and others. Natural resins generally are cooked with drying oils to make varnishes with faster drying rates, higher gloss, and harder films than can be attained from the oil alone. Some were used as a sole binder in so-called spirit varnishes, i.e., the resin was simply dissolved in

volatile solvents. When applied to a surface, the solvent evaporated from the spirit varnish leaving a film of the resin on the substrate. This type of drying mechanism involves no substantial chemical change and is typical of what today is called lacquer. In general, clear films of natural resin, oil varnishes, and spar varnishes have poor exterior durability. Accordingly, these resins are no longer used extensively except for interior use such as for wood furniture finishing.

(1) Rosins. The natural resin, rosin, is obtained from oleoresin, a sap exudation of pine trees. Lighter fractions (i.e., the fastest evaporating, when heated, also usually the lowest molecular weight) of the sap include turpentine, dipentene, and pine oil. Rosins generally have a high acid value and poor resistance to water and alkalies. They also are sensitive to oxygen in the air and are tacky to the touch. Rosins are most commonly used to produce rosin maleic esters, and they are adducted (partially reacted) with maleic anhydride and then esterified with glycerol. These esters sometimes are combined with castor and/or soya oils to reduce yellowing and to increase the hardness and gloss of paints. Coatings manufactured from rosin maleic ester binders are clear and unpigmented and are intended for interior wood surfaces and furniture finishes.

(2) Shellac. Lac is a resinous secretion of a coccid insect from India and Thailand used to make shellac. The dry secretion is collected, crushed, and washed. Afterward, it is melted and dried in sheets that are broken up and exported for use as an alcohol-soluble coating resin. The shellac film is both hard and fairly elastic, and it has a variety of uses including knot sealers and sealers for wood and plaster.

(3) Copals. Natural resins called copals are derived from fossilized or semifossilized vegetable remains. These resins have high carboxyl-functional hydrocarbons of high acid number and, therefore, are reactive. The fossil resins frequently are cooked with vegetable oils to result in a resin with an improved drying time, hardness, gloss, and water or alkali resistance. Because of their flexibility, these resins most commonly are used for coating paper (paper labels).

b. Oil-based alkyds (oxidative).

(1) Alkyd resins are derived as a reaction product of polyhydric alcohols and polybasic acids. Alkyds use a polybasic acid derived from a semidrying or drying oil so the resin formed can undergo auto-oxidation at any temperature. This definition also includes polyester resins, of which alkyds are a specific type. The properties of alkyd coatings predominantly are the result of the properties of the drying oil used in the manufacture of the alkyd resin. Drying time, hardness, color, and moisture sensitivity all

depend on the drying oil, its type, and the degree of unsaturation (available crosslinking sites). Soybean oil has been shown to give good drying rates and good color retention. However, linseed oils generally dry faster but darken on exposure to light. Castor and coconut oils have good color-retentive properties and are used as plasticizing resins because of their nonoxidizing characteristics.

(2) The amount of oil combined with the resin influences the protective capability of the applied alkyd coating. Long oil modifications (greater than 94.6 liters [25 gallons] of oil per 45.36 kilograms [100 pounds] of resin) result in less moisture and chemical resistance and longer drying times. However, long oil alkyds have a greater ability to penetrate and seal a poorly cleaned surface. Short oil alkyds (less than 37.85 liters [10 gallons] of oil per 45.36 kilograms [100 pounds] of resin) are fast-drying coatings that usually require baking to attain full cure (approximately 95 °C (200 °F)) for a few minutes. Short oil coatings have good moisture and chemical resistance but are relatively hard and brittle. Medium oil alkyds (37.85 to 94.6 liters [10 to 25 gallons] of oil per 45.36 kilograms [100 pounds] of resin) are a practical compromise between the long and short oil modifications. They usually dry hard within 24 hours and are the oil length of choice for most new and maintenance alkyd coating systems.

(3) All alkyd coating systems initially dry by solvent evaporation and cure by auto-oxidative crosslinking of the oil constituent. Because of the presence of the drying oil, alkyd coating systems have limited chemical and moisture resistance, cannot be used in highly chemical environments (acid or alkali), and are not resistant to immersion or near immersion condensing conditions. However, their relatively low cost, ease of mixing and application, and excellent ability to penetrate and adhere to relatively poorly prepared, rough, dirty, or chalked surfaces make them the coating system of choice on steel exposed to nonchemical atmospheric service. Alkyd coatings are widely used for structural steel such as the exterior of buildings, handrails, cranes, gantries, etc. Alkyd coating systems should not be used in immersion or in environments in which the coating will be subjected to prolonged wetting, dampness, or condensing humidity. Because drying oils are saponified by alkalies, they should not be applied to alkaline surfaces, including applications over galvanizing (as a result of the alkaline nature of zinc hydroxide, a corrosion product of zinc), concrete, mortar, and most cementitious surfaces (as a result of inherent alkalinity because of the use of lime as a component of cement).

c. Alkyd modification (oxidative). Alkyds are perhaps the most widely used industrial protective coating by virtue of their ease of application, relatively low cost, color

stability, and good weather ability in most atmospheric environments; therefore, it is reasonable to assume that coating formulators would seek to improve properties of the drying oil alkyd by modification with other resin types. Although these modifications will somewhat increase the cost of the coating system, improved properties usually result and make the modification cost effective.

(1) Phenolic modification. Modification with a phenolic resin improves gloss retention, water, and alkali resistance. Phenolic alkyd resins have performed satisfactorily in water immersion, a service in which nonphenolic modified alkyd resins are not suitable.

(2) Vinyl modifications. Alkyd resins with vinyl modification are commonly formulated as universal primers. These primers generally can be topcoated with most generic-type intermediate and topcoats. The alkyd constituent improves adhesion, film build, and solvent and thermal resistance; the vinyl modification enhances recoatability and chemical and moisture resistance. These coatings frequently are used as shop primers or as tie coats between different generic coatings (e.g., over inorganic, zinc-rich primers or between alkyd primers and epoxy topcoats).

(3) Silicone modifications. Silicone modification of alkyd resins is perhaps the most widely promoted modification for corrosion-protective coatings. A silicone intermediate is added to the alkyd resin in quantities up to 30 percent to provide polymers with greatly improved durability, gloss retention, and heat resistance. Moisture resistance is greatly improved by the silicone modification, and this type of paint is used extensively as marine and maintenance paint.

(4) Epoxy modifications. Alkyd resins can be combined with epoxy resins to produce coatings with improved chemical and moisture-resistant properties. Epoxy ester coatings are similar to alkyds, and they are used when improved performance is required. Epoxy esters result from the direct esterification of an epoxy resin and a fatty acid such as a vegetable oil or rosin. The resulting epoxy ester resin is prepared by reacting it with drying oil by heating in the presence of an esterification catalyst. The same drying oils used to prepare alkyds also are used to prepare epoxy esters. Oil length is categorized as long, medium, and short with properties similar to those for alkyds. Epoxy resin oil-based coatings have better adhesion, moisture, and chemical resistance than alkyds, although they are slightly more expensive. These coatings are used as baking and air dry original equipment manufacturers' coatings applied to appliances, machinery, pumps, valves, etc.

(5) Urethane modifications. Alkyd resins are commonly reacted with isocyanates to form a so-called uralkyd or

urethane oil coating. The isocyanate reaction decreases the drying time of the coating and provides enhanced resistance to chemicals, moisture, weathering, and abrasion. Uralkyd coatings are used as marine coatings of wood boat hulls, machinery enamels, and an upgrade to an alkyd coating.

d. Waterborne acrylic emulsion coating. An emulsion is essentially a dispersion of droplets of one liquid in another liquid, in which the first is not normally soluble. Examples of emulsions are milk and mayonnaise; in both of these, fat globules are dispersed in water. For paints, emulsion technology is promising for VOC compliance because water is not a restricted solvent, and only small amounts of solvents—called coalescing solvents—are required in the formulation. The resin is polymerized to a relatively high molecular weight (10,000 or higher) in emulsion paints. The pigment is incorporated in the resin, and the semisolid resin-pigment polymer is emulsified in water. Acrylic polymers are especially popular as an emulsion resin because they provide coatings with unexcelled color retention and have excellent exterior weathering and durability properties. The hardness and flexibility of emulsion polymers vary considerably because of the types and amounts of monomers used in their molecular weights. Methyl methacrylate monomer gives the hardest thermoplastic polymer, and acrylate monomers yield the softest product. Copolymers of acrylic and methacrylic esters are used extensively for exterior acrylic emulsion paints. Vinyl acetate-acrylic copolymers also are popular, particularly for interior use. The acrylic constituent upgrades water and alkali resistance, film flexibility, and durability; and it acts as a permanent plasticizer for the vinyl acetate.

(1) Styrene-acrylic. Styrene-acrylic waterborne systems in which the styrene is copolymerized with lower alkylacrylates have gained in importance. They are characterized by high gloss and good gloss retention. When properly formulated, they dry quickly and develop good film hardness. Styrene-acrylic systems are used primarily as interior house paints or as coatings for relatively mild interior industrial service conditions. These coatings may yellow on exterior exposure and do not have good moisture resistance. They also are used as concrete block fillers.

(2) Latex emulsions. Latex emulsion coating systems have gained in popularity because of their ease of application and cleanup and their good color retention and durability on exterior surfaces. One hundred percent acrylic copolymer formulations have been developed that provide good protection as complete water-based systems (primer, intermediate, and topcoat) on blast-cleaned structural steel. Acrylic latex coating systems also are used extensively for protecting aluminum and other nonferrous metals and for

painting wood in exterior weathering environments. Because they are also VOC compliant, acrylic latex coating systems have gained popularity as shop-applied systems. Even more popular are latex emulsion intermediate and/or finish coats used in conjunction with a water-based, inorganic, zinc-rich primer. Water-based, zinc-rich primers, coated with acrylic emulsion intermediate and top coats, are rapidly becoming popular because of their VOC compliance, good corrosion protection, and aesthetic properties. Although many of the acrylic emulsion coating formulations have dramatically improved moisture resistance, these coatings are not recommended for use in areas of high condensing humidity, ponding water, splash zones, or for immersion service. The ionic surfactants used in the emulsion to provide in-can stability will result in water sensitivity after application. Water vapor transmission may be a problem for wood or masonry surfaces, and latex paints may be suitable for these surfaces because they are said to breathe. Breathing occurs as a result of irregularities during the coalescence part of film formation. A series of pores or defects in the coalesced film allow passage of water vapor but retain the larger liquid water molecule. Water-based paints develop poor film properties when applied in cold, damp weather. Both cold weather and high humidity or dampness retard water evaporation and the drying and coalescence of the paint film. The result can be a soft, poorly adherent film that, when drying finally occurs, may be cracked or brittle with poor adhesion. Too fast a water evaporation rate on a hot surface can lead to a powdery, poorly adherent paint or a film with many voids, pinholes, or cross-sectional porosities. Storing emulsion paints at excessively high temperatures for prolonged periods or freezing the emulsion may destabilize it and cause settling, de-emulsification, and/or severe viscosity changes.

e. Bituminous (solvent evaporation). Bitumens used in the coatings industry are coal tar and asphalt. These materials are distinctly different physically and chemically; but in appearance they are essentially identical black, thermoplastic, tar materials. Coal tar enamels, or pitches, are derived from the coking of coal. When coal is heated in the absence of air to a temperature of approximately 1093 °C (2000 °F), it decomposes partially into a gas and a coke. Coal tar is formed when the gas is subsequently condensed. Lighter oil fractions are removed from the tar by subsequent heating and gas extraction until the desired coal tar composition for use in coatings is obtained. Asphalt may be mined or obtained as a residue from the distillation of crude petroleum. Lighter fractions are removed during distillation until the desired asphalt tar suitable for coating use is obtained. Asphaltic coatings have much greater UV resistance than the coal tars, and they are suitable for use in above-grade atmospheric weathering applications. However, coal tar coatings are vastly superior to asphaltic coatings in

moisture and chemical resistance. Because of UV light-induced cracking, unmodified coal tar coatings most commonly are used below grade or in water-immersion service. Thermoplastic bituminous coatings are applied as hot melts, solvent cutbacks, or water emulsions.

(1) Hot melt. Hot melt application involves heating the bitumen to a temperature of approximately 178 °C (350 °F) to 246 °C (475 °F); its viscosity at that temperature is low, almost waterlike. The hot melt then is applied by mop or swab to the surface being coated, although other techniques such as brush, rolling, or spraying may be used. Flow coating of the interiors of pipes and small vessels also is possible. In this method, the hot melt is flowed onto the pipe or vessel while the item is rotated or turned. In general, hot melt applications provide the best moisture and chemical resistance, followed in order by solvent cutback and water emulsions. Pipelines coated with hot melt coal tar have 100-year successful exposure experience underground and in water immersions. In the pipe coating shop, the pipe is blast-cleaned to SSPC-SP 10 metal by a rotary blast machine. The bitumen is flow-coated onto the pipe with alternate reinforcement of asphalt- or coal tar-impregnated felt paper. The finish wrap is of kraft paper for UV protection. Field application of a hot bitumen is best done by swabbing with a mop. However, swabbing is rarely done at present because of safety considerations and the development of suitable, safer, alternate coatings that are more easily field applied.

(2) Solvent cutback. Asphaltic or coal tar bitumens are dissolved in a suitable solvent (aliphatic and aromatic hydrocarbon solvents). Dissolving the bitumen in a solvent lowers its viscosity enough that the cutback can be applied by brush, roller, or spray as appropriate. After application, the solvent volatilizes and the bitumen resolidifies into a film. The coating thickness and moisture resistance of a solvent cutback is considerably less than that achieved by hot melt application, but the convenience of not having to heat the bitumen at the jobsite immediately prior to application is a major advantage. Cutbacks are used on pipelines, pump stations, below grade, and immersion applications when hot melt bitumens cannot be applied.

(3) Water emulsion. Water emulsions are prepared by suspending minute particles of the bitumen in water using emulsifying agents. Pigmentation with inert fillers such as coal dust, powdered silica, mica, and limestone dust may be incorporated with the bitumen. After application, the water evaporates and coalescence occurs to form a protective film. Latex emulsions (both asphaltic and coal tars) are widely used as driveway or parking lot sealers and as waterproofing agents. Bitumen latex emulsions are VOC compliant. Some solvent cutback applications may not be VOC compliant

because of the use of solvents; and hot applied, hot melt bitumens may release VOCs into the atmosphere during heating and application. Furthermore, volatile phenol-containing compounds produced during the heating of the bitumen are considered carcinogenic and skin irritants. Accordingly, suitable worker protection must be provided in the form of protective clothing and appropriate respirators.

f. Vinyl (solvent evaporating copolymer). Most vinyl coatings consist of a resin comprised of a copolymer of PVC and polyvinyl acetate (PVA) in the ratio of approximately 86 percent PVC to 13 or 14 percent PVA. Approximately 1 percent or less maleic acid is used as a modifier to provide adhesion to metallic surfaces, and the same amount of hydroxyl modification (using a vinyl alcohol) provides adhesion to vinyl butyral wash primers or other organic coatings. Increasing hydroxyl modification of vinyl chloride or vinyl acetate resins enables the incorporation of the vinyl into alkyds, epoxies, and other resin systems. This incorporation improves air dry, moisture resistance, and compatibility. Maleic acid modification to the vinyl chloride-vinyl acetate copolymer improves adhesion to blast-cleaned steel, zinc-rich coatings, or other metal surfaces. Additionally, the carboxyl groups introduced into the vinyl copolymer resins provide points of reactivity for crosslinking reactions.

(1) Vinyl chloride. Vinyl acetate copolymer coatings have been used extensively by USACE for protection of submerged steel or as a coating systems specified for the protection of steel used in locks and dams. Because of the high amounts of solvents that must be used to dissolve vinyl resins, most vinyl coatings, except water-based vinyl formulations, are not VOC compliant.

(2) Vinyl butyral wash primer. Basic zinc chromate vinyl butyral wash primers have been used extensively as primers to provide excellent adhesion to a variety of surfaces, including carbon steel, stainless steel, zinc, cadmium, tin, aluminum, galvanized steel, magnesium, and even glass. These wash primers are preferred when exposure to salt water or salt spray occurs because they inhibit underfilm corrosion. Basic zinc chromate and vinyl butyral wash primers formulated in accordance with DOD-P-15328 D incorporating a vinyl butyral resin, basic zinc chromate pigments, and a phosphoric acid alcohol solvent system have been used extensively in the past. For best performance, wash primers should be topcoated with a coating based on a hydroxyl modified vinyl solution resin. This is an especially effective system in seawater and freshwater immersion and in corrosive environments. Wash primers have many application particularities. If an all-vinyl system is desired, the wash primer must be coated with a hydroxyl modified vinyl solution coating. The maleic acid

modified vinyl resin coatings in common use in USACE will not adhere to the wash primer. Many other coatings adhere well to the wash primer, including oil-based alkyds, epoxies, and urethanes. When mixing, the acid diluent must be added slowly to the base with agitation to prevent local gelation. These wash primers should be used within 8 hours after mixing; any primer remaining after 8 hours should be discarded because there will be a gradual decline in adhesion of the mixed wash primer. There may be no physical change in appearance after 8 hours but adhesion will be diminished substantially. The mixed wash primers must be applied thin (as a "wash") to a thickness not exceeding approximately 1.9 cm (3/4 mil). Coating failures may result if mixing and application instructions are not followed. Vinyl wash primers range in VOC content from 680 to 765 grams/liter (g/L) (5.7 to 6.4 lb/gal). (To convert grams per liter to pounds per gallon, divide by 119.8, for example, $250 \text{ g/L} \div 119.8 = 2.1 \text{ lb/gal}$).

(3) Vinyl chloride-vinyl acetate copolymers. These vinyl solution coatings are noted for outstanding toughness and water resistance. USACE has used a five-coat vinyl system for years on steel exposed in both freshwater immersion and atmospheric service on locks and dam gates. Although the five-coat system is somewhat expensive to apply, it is extremely durable when properly applied. Repainting intervals of more than 20 years are commonplace, although maintenance repainting and touchup of deteriorated or damaged paint may be necessary at more frequent intervals. The common USACE vinyl system uses a vinyl resin containing 86 percent polyvinyl chloride, approximately 13 percent polyvinyl acetate, and maleic acid modification. The coating system has excellent toughness, moisture resistance, and light resistance; and it can be topcoated easily after extended periods of time. Generally, PVC-PVA copolymer coatings range in VOC content from 540 to 650 g/L (4.5 to 5.4 lb /gal).

(4) Waterborne vinyl. Vinyl resins and modified vinyls frequently are emulsified vinyls modified with acrylic resins to provide enhanced flexibility, toughness, and recoatability. Vinyl acrylics are most commonly used for exterior surfaces. Waterborne vinyl coatings consisting of pigmented polyvinyl acetate are formulated for interior use. The polyvinyl acetate can be used alone as a homopolymer, or it can be coreacted with other monomers such as the lower molecular weight esters of acrylic, fumaric, or maleic acid. Latices based on polyvinyl acetate generally have relatively poor moisture resistance, light fastness, and exterior durability. They are not the preferred choice for exterior surfaces, although they are eminently suitable for interior use. Polyvinyl acetate based homopolymer and copolymers are relatively inexpensive, and they are easy to apply and clean up. These emulsion coatings are suitable for

interior use and exterior nonaggressive environments. However, an acrylic modification is required when greater moisture and exterior weathering resistance is needed.

g. Catalyzed epoxies (crosslinking copolymers). The epoxy resin most commonly used for industrial protective coatings is of the glycidal-ether type, specifically, that derived from bisphenol-A and epichlorhydrin. This combination of raw materials yields a series of related compounds that, prior to crosslinking, have an epoxide group at each end of the molecule, and a alcoholic hydroxyl group as a midchain pendant. Crosslinking takes place preferentially through the terminal epoxy groups then through the midchain hydroxyl groups. Other epoxy resins have been developed, including cycloaliphatic epoxies, that offer improvements in light stability and UV light degradation; but these epoxy resins do not exhibit the adhesion, chemical resistance, and flexibility of resins derived from epichlorhydrin and bisphenol-A. Epoxy cresol novolacs also have been developed and provide high temperature resistance and great chemical resistance at the expense of brittleness and a lack of toughness and flexibility. The epoxy molecules, particularly those of the bisphenol-A type, are relatively small and must be coreacted with copolymer curing agents to attain crosslinking properties sufficient to provide a protective coating. The copolymer crosslinker frequently is called a catalyst or curing agent, and it usually is a polyamine- or polyamide-containing material.

(1) Polyamine curing agents for epoxies. The polyamines (i.e., diethylenetriamine, hydroxyethyldiethylenetriamine, bishydroxydiethylenetriamine) are relatively small molecules with a low molecular weight compared to the epoxy resin. When reacted, they lead to tight crosslinking and high chemical and moisture resistance. However, during the crosslinking reaction, any unreacted amine may be squeezed out of the crosslinked film to the surface and develop the so-called amine blush, a hazy white coloration on the coating surface. The blush, a reaction between the amine and carbon dioxide from the air, is not detrimental and can be allowed to remain on the surface unless topcoating is necessary. However, the blush must be removed by wiping or washing it from the surface (it is water soluble) before a subsequent epoxy coat is applied. To minimize formation of the amine blush, many formulators require a 15- to 30-minute induction time after mixing prior to application. This allows the reaction to begin and initial crosslinking to occur before the paint is applied. Some of the small amine molecules will partially crosslink with the epoxy resin molecules and increase their size and reduce the tendency for migration.

(a) Polyamine crosslinked epoxy coatings generally have excellent alkali resistance and the greatest chemical resistance of the epoxies. They also have good moisture and water resistance. These epoxies are the most brittle and the least flexible; and they have a strong tendency to degrade on UV light exposure, resulting in chalking. Amine-cured epoxies, with suitable nonreactive pigments, are used widely as tank lining systems for the protection of steel and concrete in water and aqueous chemical immersion service. Because of their high crosslink density (achieved as a result of the small molecular size of most of the amines used as coreactants), amine-cured epoxies are the epoxies of choice in atmospheric or immersion environments of high and low (pH 3-12+) hydrolyzing chemicals.

(b) Phenolic modification to the epoxy resin further enhances water resistance; and phenolic modified epoxies, with amine coreactants, are perhaps the most popular coating system for freshwater and saltwater immersion and many aqueous chemical solutions, even at elevated temperatures. Phenolic modification enhances moisture and heat resistance properties of the epoxy, but it imparts slightly more brittleness and diminishes alkali resistance.

(c) Polyamine crosslinked epoxy coatings are readily formulated as VOC-compliant coating systems as a result of the low molecular weights of both the amine and epoxy coreactants. If a relatively low molecular weight bisphenol-A epoxy is used, both the epoxy and amine coreactants are in liquid form. Little if any solvent is needed to dissolve or dilute the resins, and 100 percent solids coatings are feasible.

(d) Amine adduct epoxies were developed to reduce the tendency toward amine blushing; to eliminate an induction time; and to make the low molecular weight amine less volatile, safer, and easier to mix. An amine adduct is prepared by reacting an excess of a polyfunctional (three or more reactive sites) amine with some of the epoxy resin to increase its molecular size. The prereacted amine adduct then is packaged in a separate container, sometimes with additional pigment and solvent. As with all other coreactant curing agents, the components in the separate containers are mixed prior to application. Because of the greater molecular size of the amine adduct relative to the unreacted amine, amine blush is eliminated and most of the other problems associated with small molecular weight amines are minimized. Chemical crosslinking in the applied film is not considered to be as extensive as that provided by the nonprereacted amine, and the chemical resistance is somewhat less. However, application is much easier and not nearly as dependent on thorough mixing and adequate induction time.

(2) Polyamide curing agents for epoxies. Polyamide curing agents are the condensation products of a dimerized fatty acid with the polyamine. Terminal amine functionality allows crosslinking to occur as with a straight amine, although the polyamide molecule is much larger. The crosslinked film has improved flexibility, improved gloss and flow, excellent water resistance, and good chemical resistance. However, polyamide-cured coatings have somewhat less solvent and alkali resistance than amine- and amine-adduct-cured epoxies. Because fatty acids have a water repellent tendency, polyamide-cured epoxies are said to be tough, flexible, water-repellent coatings. Compared to the amine and amine-adduct types, polyamide-cured epoxies have significantly better UV light resistance, resulting in substantially less chalking on exterior exposure. Polyamide-cured epoxies are perhaps the most widely used of the three types of curative systems, and they have wide application in the protection of steel and concrete in freshwater and saltwater immersion. Polyamide-cured epoxies have the best exterior weathering resistance and the best ability of the epoxies to recoat after extended periods. Polyamide epoxies are used to protect substrates exposed to condensation and high humidity. Specially formulated polyamide-cured epoxies have the ability to displace water from a surface. These coating materials can be applied and cured under water to form corrosion-resistant coatings.

(3) 100 percent solids epoxies.

(a) The 100 percent solids epoxies can be formulated from low molecular weight polyfunctional liquid epoxy resins. The viscosity of these resins can be lowered even further by the use of compatible reactive diluents with an epoxy functionality of one; they do not contribute to crosslinking but are chemically bound into the final crosslinked film. The liquid epoxy resin system is crosslinked by a liquid polyamine or polyamide without the addition of any solvent. A tertiary amino phenolic catalyst, such as tri-(dimethylaminomethyl) phenol may be added to produce polymerization of the epoxy resin with itself. This and other phenols act as accelerators in the curing reaction. Silicone resins may be added as flow agents, and dibutyl phthalate can be added as a plasticizer. Thus, the entire liquid paint can be converted to a crosslinked coating that becomes a 100 percent solids epoxy. These materials have little, if any, volatile organic material so they are VOC compliant. Coatings formulated in this fashion show typical epoxy finish properties; but they are less flexible than other epoxies because the films are thicker and the close spacing of the reacting groups leads to a high crosslinked density. The film is tough and relatively nonbrittle. Solventless epoxy systems have low internal stress and are less brittle because there is negligible volume contraction on curing to a solid.

(b) The 100 percent solids epoxies generally have short pot lives because the coreactants are not diluted. Some formulations require the use of special twin-feed airless spray equipment for external mixing (refer to paragraph 8-2g). When aromatic polyamines are used for curing, hardening times of 4 to 12 hours can be attained even at temperatures as low as freezing. Although these coating systems are relatively expensive, they are used primarily as corrosion-resistant linings for storage tanks (e.g., oil tankers), both on land and in marine vessels. Because of their low molecular weight liquid formulation, these materials also can be used as self-leveling epoxy flooring systems. These coating systems generally are clear or high gloss and, when applied, have a waterlike consistency that hardens to a smooth, glossy flooring.

(4) Coal tar epoxies.

(a) Coal tar epoxy is a combination of a coal tar and an epoxy resin. The epoxy resin usually is packaged separately from the curing agent, which frequently is combined with the coal tar resin. The curing agent may be an amine, amine adduct, or polyamide. The crosslinking reaction is the same as those previously described, with active hydrogens from the amine nitrogen providing a crosslinking site to the epoxide groups and, in some situations, the hydroxyl groups of the epoxy resin. The coal tar acts as a filler within the crosslinked epoxy matrix, and the resulting film has the toughness, adhesion, UV resistance, and thermal stability of the epoxies combined with the extremely high moisture resistance afforded by the coal tar. The amine-cured coal tar epoxies generally have great chemical and moisture resistance but are more brittle and harder to apply and topcoat than the amine adduct and polyamide-cured coal tar epoxies. The polyamide-cured coal tar epoxies are more water resistant, flexible, easier to topcoat, and more tolerant of application variables than the other epoxies.

(b) One problem with coal tar epoxies is recoating. The recoat window for application of a coal tar epoxy topcoat to a coal tar epoxy undercoat can be as little as 18 hours with some formulations, and with most formulations it usually is within 48 hours. Extensive intracoat disbonding may occur after this time. The disbonding is believed to result from low molecular weight hydrocarbon oils from the coal tar exuding to the surface after application and from UV light-induced oxidation. Amine-cured coal tar epoxies are more susceptible to this phenomenon than the amine adduct and polyamide types. However, even with the latter types, the first coat may cure so hard and glossy after only a few hours that adhesion of subsequent coats may be a problem. To attain adhesion between an undercoat and subsequent coats of a coal tar epoxy, it may be necessary to roughen the surface by sweep blast cleaning or other scarifying

techniques and to remove the oxidation and exudate products. Alternately, slow evaporating strong solvents such as methylene chloride and diacetone alcohol can be applied to the coal tar surface being overcoated. These solvents will penetrate, attack, and partially dissolve or swell the coal tar epoxy surface so molecular entanglement and adhesion may occur. However, because these solvents are slow evaporating, they may be retained within the coal tar epoxy film. If the coal tar epoxy is immersed in water, these relatively polar solvents may attract water and blistering may occur. Therefore, care should be taken when using solvents to increase intracoat adhesion for coal tar epoxies in immersion service. The problem is of much lesser consequence if the coal tar epoxy is used on an atmospheric or nonwater immersion surface.

h. Urethanes (crosslinking copolymer). Crosslinking reactions in urethane coatings consist of a reaction between an isocyanate containing ($-N=C=O$) material and a material with a polyhydroxylated ($-OH$) containing coreactant. Crosslinking occurs because of the high reactivity and affinity of the isocyanate group for the active hydrogen of the polyolhydroxyl or any other active hydrogen atom attached to a nitrogen or oxygen atom. The rate of this crosslinking reaction depends on a number factors, such as the type and configuration of both the isocyanate and polyol materials and temperature. However, the reaction is such that, with most formulations, crosslinking can occur at temperatures as low as 18 °C (0 °F) or less.

(1) Isocyanates. The isocyanate reactant can be either aromatic (containing the benzene ring) or aliphatic (straight chain or cyclical) hydrocarbons. Aromatic polyurethanes are prone to darkening and yellowing on exposure to sunlight because of the chromophoric nature of the benzene ring. Because aliphatic polyurethanes, by definition, do not contain the benzene ring, they do not yellow or darken and are preferred for exterior use.

(a) The most important monomeric diisocyanates used for coatings are toluene diisocyanate (TDI), 4,4, diphenylmethane diisocyanate (MDI), and 1,6, hexamethylene diisocyanate (HDI). Because of their irritant characteristics, these materials rarely are used in unreacted form for the compounding of urethane coatings. They normally are converted into isocyanate terminated polymers or adducts of polyols such as hydroxyl terminated polyesters and polyethers. The molecular weight of these isocyanates can be increased by self-reaction in the presence of catalysts to form dimers and/or trimers.

(b) Aliphatic isocyanates react more slowly and are considerably more expensive than the aromatic isocyanates, but they allow the formulation of nonyellowing, light stable,

high gloss finish coats. The appearance of polyurethane coatings formulated with aliphatic isocyanates are unsurpassed in this regard by any of the epoxies, acrylics, or other coating materials. One of the most important aliphatic isocyanates is HDI. In its monomeric form, HDI is an irritant as is true with TDI and MDI. However, HDI can be reacted (commonly with water) to obtain a higher molecular-weight modification that is less volatile and safer. When HDI or its higher molecular-weight modifications are reacted with a suitable polyol in the presence of certain metal catalysts (tin, bismuth, zinc, iron, cobalt), a urethane coating with excellent resistance to discoloration, hydrolysis, and heat degradation is produced.

(c) Because of the potential presence of unreacted monomeric forms of TDI, MDI, and HDI—all of which are respiratory irritants—an air-fed respirator should be used when mixing and applying these materials. Workers and painters may never develop an isocyanate sensitivity, or the sensitivity may occur only after prolonged exposure. However, some individuals may become sensitized quickly, on initial contact or on only a short exposure. When isocyanate respiratory sensitization occurs, it occurs suddenly and drastically, and the affected individual should be removed from the work site. The sensitization is permanent, and increased exposure leads to increased irritation to affected tissues and membranes (refer to Chapter 10).

(2) Polyols. Polyols coreact with isocyanates to form a polyurethane film. A polyol consists of large molecules (commonly acrylics, polyesters, polyethers, epoxies, vinyls, and alkyds) that have been reacted with di- or polyfunctional alcohols such as propylene glycol, trimethylolpropane, pentaerythritol, and others. The hydroxyl-terminated polyol materials are packaged separately from the isocyanate, and the packaging usually includes appropriate solvents and pigments. On application, the isocyanate and polyol constituents are mixed and crosslinking proceeds via the isocyanate-hydroxyl functions and liberates a carbon dioxide gas. To prevent bubbles and voids in the coating cross-section as a result of the carbon dioxide gas inclusion, all polyurethane coatings must be applied relatively thin (0.038 to 0.05 mm [1.5 to 2.0 mils] per coat). This allows the gas to pass easily from the coating before the coating cures and hardens. In general, the characteristics and properties of the urethane coating depend predominantly on the properties of the polyhydroxylated coreactant. The VOC content of most polyurethane coatings ranges from 250 to 550 g/L (2.1 to 4.6 lb/gal).

(3) Acrylic urethanes. Acrylic urethanes are perhaps the most widely used urethanes for corrosion protection and

atmospheric service. When properly formulated, these materials have excellent weatherability, gloss, and color retention and good chemical and moisture resistance. They can be tinted easily and pigmented to provide a variety of deep and pastel colors at a lower cost per gallon than the next most popular class, the polyester urethanes. Acrylic urethanes are not used for water immersion service and, for the most part, they do not have the chemical resistance of the polyester urethanes. However, they have excellent weathering and color retentive properties when an aliphatic isocyanate coreactant is used. These are the most popular aliphatic polyurethanes; they are widely used as topcoats over epoxy primers and intermediate coats in most nonchemical atmospheric environments. Many water tanks, bridges, railroad cars, aircraft, and other highly visible structures are coated with these light-fast, glossy, aesthetically appealing coatings.

(4) Polyester urethanes. As a result of their high isocyanate demand when coreacted, polyester urethanes form relatively hard, chemical-resistant poly films. Because they are tightly crosslinked, they have great chemical and moisture resistance; but they are not as flexible and tough as the acrylic urethanes. This high isocyanate demand also substantially increases the cost of polyester urethane over acrylic urethanes. Polyester polyurethanes are used in exterior chemical environments in which acid fumes or highly corrosive conditions are encountered. They have high gloss, are light fast, and have a good appearance.

(5) Polyether urethanes. The polyether prepolymer is considerably less expensive than either acrylic or polyester polyols. However, polyethers are sensitive to UV-induced oxidative degradation. Ether linkages within the polyether are somewhat water sensitive; and, in polyethers, they are repeated throughout the polymer chain without separation by long water-insensitive hydrocarbon chains or aromatic groups. Polyester polyurethanes are used as elastomeric urethane coatings, for coal tar urethanes, and for other urethane coatings that are sheltered or protected from light. They frequently are used as pipeline coatings or for below grade corrosion protection, and coatings for minimum service.

(6) Epoxy polyurethane. Epoxy urethanes are considerably more expensive than conventionally cured amine or polyamide crosslinked epoxies. The epoxy addition induces a tendency for an epoxy urethane to chalk, and the lower moisture resistance resulting from the urethane crosslink produces a less chemical- and moisture-resistant polymer than a conventionally cured epoxy coating. Most epoxy urethanes are formulated with a less expensive aromatic isocyanate. They are promoted primarily as low-temperature-curing epoxies; as fast curing, chemically

resistant urethanes for interior use; or as primers in exterior exposures.

(7) Vinyl polyurethanes. Urethane coatings using vinyl polyols combine abrasion resistance of the urethane with the toughness, flexibility, and chemical resistance of the vinyl. These urethane coatings are promoted for use when flexibility and abrasion resistance are important. However, vinyl urethane coatings are subject to some chalking or fading on exterior exposure and do not have the color, gloss, weatherability, or solvent resistance of the acrylic and polyester urethanes. Because the vinyl is thermoplastic and is attacked and softened by solvents, recoating after extended periods is not a major problem and is a primary advantage of vinyl urethane systems. Coatings based on these resins are used on structural steel, ships, tanks, and other steel structures for which corrosion resistance flexibility and abrasion resistance are important.

(8) Moisture-cured polyurethanes. Isocyanates can react with the hydroxyl group in water (H-OH) to form a unique class of coatings known as moisture-cured urethanes. Single package moisture-cured urethanes use an isocyanate prepolymer that, when applied, reacts with the humidity in the air to form a tough, hard resinous film. Because of their rapid rate of reaction, aromatic isocyanates are used almost exclusively in moisture-cured urethanes. The pigments must be essentially nonreactive with the isocyanate. Although it is possible to use a number of pigments, aluminum leaf is common. Properly formulated and applied, urethanes have excellent adhesion to blast-cleaned structural steel surfaces. When spray applied, urethanes form a tough, glossy, highly protective chemical and solvent-resistance film. Because of their high crosslink density, the recoat window of some formulations is less than 24 hours, or it may be more than a month in exterior environments. Sufficient solvent hardness and permeability does not occur in 24 hours, and topcoating is considered safe. Topcoating is also safe after a month or more of exterior chalking and weathering to remove the slick, glossy surface that often occurs shortly after curing. However, within the range of 24 hours to a month or more, subsequently applied polyurethane topcoats may exhibit disbonding or poor adhesion. Moisture-cured urethanes are used as primers under some epoxies, used as full system coating on steel and nonferrous metals, and as primers on marginally cleaned steel. Frequently, the moisture-cured polyurethane primer and/or intermediate coats are topcoated with a nonmoisture-cured aliphatic polyurethane to minimize yellowing and darkening.

i. Vinyl ester (crosslinking copolymer).

(1) Strictly speaking, vinyl esters can be called vinyls because of the vinyl unsaturation ($-C=CH_2$) on the epoxy

backbone chain; actually, they are manufactured from and are closely related to acrylics. Methacrylic esters of bisphenol-A or other epoxies, such as novalacs, are prepared by reacting methacrylic acid with terminal oxirane groups of the epoxy. The resins have high viscosity at room temperature and are mixed with monomeric styrene, which acts as a reactive diluent to reduce viscosity. Crosslink curing is by free radical initiation generated from peroxide degeneration using benzyl peroxide, methyl ethyl ketone peroxide, or peroxide blends.

(2) Compared to normal unsaturated polyester resins, vinyl ester resins have better chemical resistance because of the stability of the epoxy backbone and the presence of stable methyl groups on the methacrylate terminations. Compared to a polyester resin, there are fewer points of unsaturation on the backbone, and even these are effectively shielded by methacrylate terminations. Vinyl esters have excellent resistance to acids and alkalis, bleaches, and other oxidizing agents. Vinyl esters are used as thick film (1.02 to 1.52 mm [40 to 60 mils]) tank and chimney linings when great strength and high chemical resistance are required. They most commonly are applied by spray, have a short potlife, and build readily to thicknesses approaching 0.50 mm (20 mils) per coat. Because of their short potlife and high chemical and solvent resistance, topcoating after even a short period of time (as little as 3 or 4 days) may be a problem with some formulations. Because the coatings are applied so thick and because of high inherent shrinkage stresses on curing, a deep anchor pattern (0.10 to 0.13 mm [4 to 5 mils]) is required for most applications. Care must be taken to ensure that the coating is not applied excessively thick, or cracking may occur.

(3) Vinyl ester coatings can be applied as highly pigmented, sprayable coatings or with a fiberglass veil reinforcement as fiberglass reinforced plastic laminants. Vinyl ester coatings have excellent abrasion and wear resistance, and these attributes combined with their chemical resistance lead to application as high build monolithic concrete floor systems and tank linings. Because of their high volume solids content and because styrene is used as a reactive diluent (combined thinner and coreactant), little thinner is required in a formulation. Thus, vinyl ester coatings are VOC compliant.

4-4. Drying Oils

a. If a drying oil is reduced or dissolved in a solvent and pigmented, a drying oil coating results. Not all oils are drying oils. An oil is classified as drying if, when spread out in the air as a thin layer, it changes from a liquid to a solid film with a great strength, toughness, and hardness. This drying ability depends on the molecular structure of the

various chemical compounds that make up the oil. Specifically, the oil must have polyunsaturated fatty acids, commonly ethylenic carbon double bonds ($-C=C-$). When combined with oxygen and accelerated by metallic driers, auto-oxidative polymerization occurs and transforms the oil from a liquid to a solid. Some vegetable oils (e.g., cottonseed, rapeseed, peanut, and coconut oils) are not drying oils. Fatty vegetable oils that exhibit proper drying oil characteristics and can be formulated into paints or protective coatings include linseed, tung, soybean, dehydrated castor, oiticica, and fish oils. Linseed oil, one of the most widely used drying oils, is obtained from pressing the flax seed. Raw linseed oils dry too slowly for most purposes; therefore, they require processing and the addition of driers to hasten the hardening rate.

b. Processing usually consists of heating the raw oil and dissolving mixtures of manganese and cobalt driers—which are soluble in the oil at ordinary room temperatures—in the raw oil. The oil can be further treated by bodying, which consists of blowing gasses (oxygen and/or hydrogen) through the oils to increase viscosity and reduce drying time. All of these treatments (heating, blowing, and adding driers) result in an increased oil viscosity that occurs as a result of auto-oxidative crosslinking polymerization and oxygen absorption into the oil film. In general, bodied oils (those that have been thickened by heat treating and blowing air through them) dry more quickly, are tougher, and have better water, chemical, and after-yellowing resistance than untreated, unbodied oil. However, bodied oils do not wet and penetrate as well. Even if blown or bodied, drying oils may have their properties enhanced considerably by the addition of a synthetic resin. When added to the processed and treated drying oil, synthetic resins (e.g., alkyds, phenolics, epoxy esters, or urethanes) enhance the chemical and moisture-resistant properties of the drying oil.

c. Animal oils, principally menhaden fish oil, have properties similar to drying vegetable oils, except they are somewhat slow drying, become tacky in humid weather, and give off an unpleasant odor in confined spaces. Animal oils are not recommended for interior use, and they frequently are combined with other drying oils.

d. In a strict sense, oil paints consist of a pigment, a drying oil, and an aliphatic solvent used to thin the pigmented oil. The oil is not modified with any synthetic resins. The coating initially dries by solvent evaporation; this is followed by auto-oxidative crosslinking of the drying oil. The addition of driers to the oil aid in the formation of the solid film. The characteristics of these oleoresinous paints are determined primarily by the characteristics of the drying oil, and to a lesser degree by the pigments incorporated into that oil. Because these paints have a high

oil content, drying times are slow with 2- to 3-day recoat periods over the soft film. However, long oil paints were formulated for use over poorly prepared, rusted, and/or mill scale surfaces; so for these situations, long oil paints may be the best paints.

4-5. Driers

Driers are materials that promote or accelerate the curing or hardening of drying oil paints. Drying of oil-based paints by auto-oxidation is affected considerably by temperature and the presence of certain catalysts. Driers act as a catalyst to aid in both surface and through drying of drying oil paints. Driers are considered metallo-organic materials that can be classified as surface driers and through driers. The metal constituent is lead, cobalt, zinc, or manganese; the organic radical of the metallo-organic dryer is usually a naphthenate derived from naphthenic acid. Surface driers are compounds of cobalt and manganese. The use of these materials will cause a surface of the drying oil paint to rapidly set to a near solid, but the underlying paint does not reach this advanced state of oxidation. In thick films an uneven hardening will cause wrinkling; therefore, through driers should be used in conjunction with surface driers. Through driers are metallo-organic compounds of lead, cadmium, zinc, or zirconium. When used in conjunction with surface driers, through driers help cause auto-oxidative crosslinking through the cross-section of the film. Driers may lose their effectiveness with prolonged storage. This storage problem affects the primary surface driers (cobalt and manganese) and, to a lesser degree, secondary driers (calcium and zinc). The loss of dryer effectiveness is believed to result from the absorption and deactivation by certain pigments, notably carbon black. If an oil-based paint is aged, it may be best to test its ability to dry by applying some of it to a nonabsorptive surface to see if it dries properly.

4-6. Pigments

Virtually, all protective coatings used for corrosion protection contain pigments. Although the obvious purpose of pigmentation in a coating is to provide color and opacity, proper formulation of pigments into a protective coating does far more than that. For corrosion-protective coatings, pigments function by providing inhibition or passivation of a metal surface, preventing corrosion; reinforce the paint film; act as a barrier to provide water impermeability to the dried paint film; and with zinc-rich coatings, sacrifice galvanically to protect the underlying steel substrate (refer to Chapter 2). Certain pigment types enhance heat, abrasion, acid, or alkali resistance to coatings. Pigment particle size and shape, ease of wettability by the binder, and bulking or properties relating to specific density

contribute significantly to the viscosity and application characteristics of the wet coating and, ultimately, properties of the dried, protective coating.

a. Inhibitive pigments. A select few pigments provide active corrosion inhibition to metal substrates when formulated into a coating composition. These pigments are slightly water soluble; and, when the paint film is exposed to and permeated by moisture, the water in the film cross-section partially dissolves constituents of the pigment and carries it to the underlying metal surface. The dissolved ion species react with the metal (commonly steel or aluminum) to form a reaction product that passivates the substrate and reduces the rate of underfilm corrosion.

(1) Chromate. Chromate-containing pigments (e.g., zinc and lead chromates) partially solubilize, liberating the chromate anion that, when carried by moisture to the underlying steel or aluminum substrate, reacts to form a chromate film on the metal surface. This chromate film strongly passivates the metal surface and prevents establishment of electrochemical corrosion cells by reducing electron transfer. Additionally, this passivating film is slightly alkaline, which further inhibits underfilm corrosion. To a lesser degree, molybdate and borate pigments also provide active underfilm passivation, but not nearly as well as the chromate-containing pigments.

(2) Lead and zinc. Lead and zinc also may disassociate partially on moisture permeation into a paint; these elements also provide inhibitive protection, but in a different fashion. When pigmented into oil-based coatings, lead and zinc react with acidic degradation products that occur as a result of oxidation and UV light exposure. If these complex organic acids reach the underlying steel, under-film corrosion may be hastened. However, the lead and zinc cations react with the acids complexing, insolubilizing, and/or neutralizing them. Lead and chromate pigments are considered hazardous paint ingredients, and many coating formulators are restricting or eliminating these materials from their formulations. Although substitute pigments may be safer, they may not offer the inhibitive properties of the pigments they replace.

b. Barrier pigments. Barrier protection is offered to a greater or lesser degree by all inorganic pigments formulated into a coating. Any permeating moisture must migrate around the pigment particle and, by so doing, increase its permeation path length to the substrate. However, some pigment types are specifically formulated as barrier pigments, or alternately impart barrier properties to the paint film. Most notable of the barrier pigments is flaked aluminum.

(1) Aluminum flake. Aluminum flake, in the form of a leafing aluminum (coated with a stearic or other fatty acid to cause it to be displaced to the surface by the coating binder) or nonleafing flake (noncoated), is specifically added to many types of coatings, particularly oil-based coatings and epoxy mastic coatings to enhance UV light resistance and reduce moisture permeation. No other pigments can provide the leafing properties that aluminum flake does. Leafing aluminum pigments are widely used in alkyd finish coats to provide a bright, shiny appearance and for resistance to atmospheric weathering (UV) and moisture.

(2) Micaceous iron oxide. Micaceous iron oxide, commonly used in Europe and to a lesser degree in the United States, has lamellar (platelike) particles. Any relatively large sized pigment particle, even if it is not plate shaped, will increase the permeating path of moisture and result in a barrier-type protection. Some recently manufactured pigments consist of hollow glass spheres that have been developed to aid in VOC compliance and to fill a coating and make it more moisture impermeable.

c. Sacrificial pigments. High purity zinc dust, with little zinc oxide or carbonate contamination, is the only sacrificial pigment used in paint manufacture. These zinc dust pigments consist of particles that are of a relatively large (1 to 3 μ) diameter and are essentially pure zinc. If the zinc pigment particles are in contact with both each other and the underlying steel surface when incorporated with a binder into a dry paint film, galvanic protection results. On the galvanic series zinc is anodic to steel and becomes the anode in a zinc-steel galvanic couple. The zinc anode corrodes and dissipates, and the underlying steel cathode remains galvanically protected. This phenomenon occurs for all zinc coatings, including those deposited by hot dip galvanizing and thermal spraying. Thermally sprayed aluminum coatings (both aluminum powder and wire) also are believed to have sacrificial capability when applied to blast-cleaned steel. However, this sacrificial capability may last for only a short time—within a few days after application until the aluminum oxidizes sufficiently to insulate the aluminum from the steel. Galvanic protection ceases after a sufficient thickness of intact aluminum oxide forms on the sprayed aluminum coating.

d. Color pigments. A number of inorganic pigments provide color to paint. Titanium dioxide in both the rutile and anatase forms is the most popular white pigment because of its high refractive index and excellent hiding power (the ability to render a paint opaque). Rutile titanium has the highest refractive index and the best tinting strength of all other pigment types. (Tinting strength is the ease by which color pigments can be mixed with another pigment to color the paint.) Other pigments, both organic and

inorganic, frequently are used in combination with titanium dioxide to add color. Natural iron oxides range in color from a yellow to a bright brown red, to a greenish brown, and a deep rich brown. Synthetic iron oxides range in color from yellow and red to brown and black. Red chromate pigments with sulfate, and sometimes molybdate additions, range in color from a light yellow to a bright orange or scarlet red. Because of their bright, clean color, lead chromate pigments frequently are used in highway striping paints and in safety color paints. Even though lead chromate is considered hazardous, the pigments in these paints will be difficult to replace because no other pigments have a similar light fastness and brightness. The purpose of organic pigments is primarily to provide paint color. Originally, organic coloring pigments were extracted as colorants from insects and vegetables. Synthetic organic pigments now have been developed, but few of these have technical or commercial importance in corrosion-preventative coatings. Compared with inorganic pigments, organic pigments generally are brighter colored, have less hiding, are more prone to bleed, have much poorer heat and light fast resistance, and are substantially higher in price. The most important class of organic color pigments are called azo pigments and are manufactured from aromatic hydrocarbons, which are available from coal tar or petroleum distillates. These pigments are characterized by the presence of a chromophore consisting of one or two azo groups ($-N=N-$).

e. Hiding pigments. Pigments with a high light refractive index provide the best hiding. Rutile titanium dioxide, followed by anatase titanium oxide, zinc sulfide, and zinc oxide have relatively high refractive indices. Conversely, silica, whiting, and barytes all have relatively low refractive indices and do not provide good hiding when formulated into paints.

f. Extender pigments. Certain types of pigments do not provide inhibition or have good barrier or sacrificial characteristics. They do not have a high refractive index and do not impart good color or hiding to a paint film. However, as reinforcing pigments and flow control pigments, they are important in coating formulation. As a class, these pigments can be called extender pigments because they are relatively inexpensive compared to most other pigments; they are used in conjunction with more expensive pigments to reduce costs. The use of extender pigments reduces shrinkage stresses within the paint film, giving it strength, and “extending” the pigment volume content at relatively low cost. Extender pigments include those based on carbonates, silicates, sulfates, barytes, and mica. Each of these types of pigments is somewhat different, but they all are relatively low cost materials that can be added in finely divided form to a paint to aid in its

rheological properties (viscosity and flow control) and to reinforce the dry film strength.

4-7. Solvents

a. In a true sense, a solvent is defined as a substance, usually a liquid, that will dissolve and change a solid to a liquid state. In the coating industry, solvents are considered any volatile liquid formulated into a paint, even though it may not have solvency power. Some liquids are diluents and, even though the diluent may not have solvency power, it may enhance the solvency of other solvents in the paint. Water is the universal solvent, except for its use as a dispersant in emulsion coatings, but it is not used as a paint solvent in durable coatings. Water-soluble resins are susceptible to softening and swelling by water; therefore, coatings made from them will not be addressed in this manual. However, water-soluble resins should not be confused with water-emulsified resins, which were discussed earlier in this chapter. Organic solvents impart low water sensitivity and are the solvents of choice when dissolving solid resins.

b. The purpose of any solvent is to dissolve solid paint constituents, reduce viscosity, and render the paint fluid enough that it can be satisfactorily applied. The solvent is undesirable after application and must evaporate from the drying coating film. In addition to enabling application of the coating material, solvents must be able to wet the substrate being coated and penetrate into and help the coating seal any crevices, voids, or depressed irregularities. Also, the solvent must volatilize fast enough to prevent runs and sags in the drying coating film. However, a solvent that is too volatile can cause solvent pops, loss of gloss, dry spray, poor surface wetting and penetration, and poor film flow and inhibit cure. Virtually all coating formulations use a blend of solvents to achieve optimum properties. Some solvents within the blend will evaporate fast, enabling the drying paint to set quickly. Other solvents may dry slower and provide wettability and penetrability. Ultimately, all solvents should evaporate to allow the coating to achieve hardness, cure, and final properties. Solvents can be categorized according to their chemical composition. The most commonly used categorization subdivides solvents into classes called turpentine, hydrocarbons, ketones, esters, alcohols, and glycol ethers.

c. Turpentine. Turpentine solvents are actually hydrocarbon solvents; they are categorized separately because they are derived from southern pine trees as opposed to solvents fractionated from petroleum and coal tar refining. Turpentine is used infrequently today in manufacturing corrosion-protective coatings, although it is widely sold in retail paint stores for field thinning of oil-

based house paints and varnishes. Gum-spirits turpentine is distilled from crude gum rosin obtained by tapping southern pine trees. Wood turpentine has a somewhat different composition from gum turpentine and is obtained by distillation of the crude rosin extracted from the ground wood from southern pine stumps. Sulfate turpentine is obtained as a by-product of the Kraft paper industry. Turpentine has good solvent power for most oil and oleoresinous binders, but its use is limited in modern paint technology because of its relatively high price and slow evaporation rate. Other turpentine-like solvents, such as dipentene and pine oil, also are obtained from southern pine trees and have specialized uses.

d. Hydrocarbon solvents. Hydrocarbon solvents are obtained from both petroleum and coal tar sources. Petroleum hydrocarbon solvents are the lighter (more volatile) fractions from the distillation of crude oil. Coal tar hydrocarbons are distillation products from coke oven by-products. Hydrocarbon solvents may be classified as aliphatic or aromatic.

(1) Aliphatic hydrocarbons. Aliphatic hydrocarbons are straight or cyclical carbon-hydrogen containing liquids that are nonpolar in character and exemplified by mineral spirits, "varnish makers and painters" (VMP) naphtha, and other materials such as hexane and heptane. For the most part, these solvents have poor to moderate solvency for all but oil-modified coatings. Their solvency can be increased by blending them with various amounts of other, more powerful solvents such as aromatic hydrocarbons or ketones. Aliphatic hydrocarbons are generally the least expensive of all solvents and can be obtained in a wide range of evaporating rates. Aliphatic solvents are considered the least toxic of any of the solvent classes, although—as with any other solvent—gloves, respirators, and protective clothing should be used by individuals applying paints containing these solvents. Naphthenic hydrocarbons are aliphatic hydrocarbon solvents, but with a cyclical ring molecular structure. The naphthenic solvents are midway between the aliphatic and aromatic solvents in solvency power. Naphthenic solvents are used in alkyd and epoxy ester coatings and asphaltic and coal tar-containing coatings.

(2) Aromatic hydrocarbons. Aromatic hydrocarbon solvents contain a benzene ring structure. The most common solvents of this type are toluene (toluol), xylene (xylol), and high-flash naphtha. Aromatic hydrocarbon solvents have a greater solvent power than aliphatic hydrocarbon solvents. They generally are good solvents for oils, oleoresinous binders, alkyds, bitumens (asphalts and coal tars), and some synthetic resins. Aromatic solvents can be blended with more powerful solvents to enhance their power of solvency.

e. Ketone solvents. Ketones such as acetone, methyl ethyl ketone, methyl isobutyl ketone, and diacetone alcohol have varying evaporation rates and relatively strong solubility parameters. These solvents exhibit strong hydrogen bonding and high polarity. When retained in a paint film, they may attract and draw moisture into the coating. As with all other solvent classes, each of the ketone solvents has a different evaporation rate; care should be taken when using ketone solvents with slow evaporative rates to minimize solvent entrapment within the coating. As a class, ketones are polar materials characterized by exceptionally strong solvency for many resins used in protective coatings. They are used extensively as solvents for vinyls, urethanes, epoxies, and acrylics. Ketones usually are more expensive than ester-type solvents, but they are cost effective because the use of ketones allows for greater use of inexpensive aromatic diluents. As with all solvent families, solvency decreases as molecular weight and branching increase.

f. Ester solvents. Ester solvents contain the acetate functionality (-C-O-R). Ethyl acetate, isobutyl acetate, ethylene glycol, and monoethyl ether acetate are examples of ester solvents. They have solvency power between the aromatic hydrocarbons and ketones, but they have a high hydrogen bonding index and a relatively high polarity. Care should be taken to avoid solvent entrapment when using ester solvents. Ester solvents are strongly polar and are used as solvents for similarly polar resin film formers. The esters are characterized by a sweet, pleasant, strongly fruity odor. Ester solvents are used in cellulosic lacquers, urethanes, vinyl, epoxy, and acrylic coatings. Slow-volatilizing ester solvents are used as tail solvents in waterborne acrylic emulsions to aid coalescence and as tails in solvent-borne coatings to maintain solvency and reduce resin precipitation. Tail solvents are designed to be the last solvents to evaporate from a coating.

g. Alcohols. Alcohols are water miscible, and care should be taken when using them so water is not introduced into the coating. Alcohols are highly polar with a strong affinity for the water molecule. They are used to dissolve polar materials; and, when formulated into a coating, care should be taken to ensure that all alcohol will volatilize. Water miscibility and hygroscopicity are reduced as the alkyl group increases, and few alcohols above butanol (C₄H₉OH) have high miscibility with water. An exception is tertiary butanol, which—because of the compactness of the alkyl structure—retains complete water miscibility. The three most important alcohols are ethanol (denatured), isopropanol, and n-butanol. Methanol is toxic and is used only as a polar additive in paint removers because its low molecular weight serves it well as a penetrant. Alcohols are used as solvents for resins such as polyvinyl acetate, some

phenolics, vinyl butyral wash primers, most epoxies, and inorganic zinc-rich coatings based on ethyl silicate vehicles. Because of reactivity of the alcohol hydroxyl group, alcohol solvents cannot be used as solvents in polyurethane coatings. Alcohol is a solvent common to many epoxies. Chlorinated solvents such as 1,1,1, trichloroethane, chloroforms, dichloroethane and dichloroethylene, and methylene chloride, although used infrequently in paints, are good paint strippers, especially for epoxies and polyurethanes. Chlorinated solvents are nonflammable and VOC compliant because they generally are nonphotochemically reactive. However, they are toxic to humans and are environmental contaminants. These solvents should not be stored in, or used with, aluminum containers or equipment.

h. Glycol ether solvents. Glycol ether solvents, such as ethylene glycol monoethyl ether and ethylene glycol monobutyl ether, are a specific subcategory of the ester solvents. The most important solvent of this type has been ethylene glycol monoethyl ether (Cellosolve®¹) acetate. However, because of toxicologic considerations, this solvent largely has been replaced by propylene glycol monomethyl ether acetate, which appears to be less toxic. Glycol ethers are tail solvents for epoxies, vinyls, and urethanes. Glycol ether solvents are water-miscible and will attract moisture in buried or immersion conditions; therefore, care must be taken to ensure they completely volatilize from coatings to be used in immersion or below grade service. Anhydrous solvent grades are necessary if glycol ethers are used in urethane formulations. Glycol ethers are particularly good solvents for epoxy resins.

i. Solvent safety. Safety should be a consideration at all times when using solvents because all solvents are combustible and some are highly flammable. Solvents with lower molecular weight or faster evaporating rates usually are more flammable. Fast volatilizing, flammable solvents can lead to explosions, especially within confined spaces. All solvents are heavier than air and tend to flow downward; so, unless adequate ventilation and air movement are used, solvent vapors will collect and concentrate in low-lying spaces. Safety considerations are discussed in detail in Chapter 10.

4-8. Miscellaneous Additives

A number of miscellaneous compounds are added by the paint formulator to paints for specialized purposes. These include antiskinning agents, fungicides, thixotropes, UV light absorbers, plasticizers, flow agents, and emulsion aids.

¹ Union Carbide, Indianapolis, Indiana.

a. Antiskinning agents. Skinning sometimes occurs on storage of coatings containing drying oils. The surface of a paint dries and forms a skin on the paint surface in the can. When used excessively, driers have a tendency to aggravate skinning. To avoid skinning, antioxidants such as certain phenols and oximes can be added. The oximes, characterized by the reactive group (-C=N-OH) are by far the most commonly used antiskinning agents. Skinning is the result of the drier functioning properly, and it usually is not a problem in unopened or full cans. Antiskinning agents are volatile and accordingly, when using some of the paint in a can, close it tightly after use.

b. Fungicides. Fungicides or mildew inhibitors are added to paints to prevent mold growth. Mildew feeds on some components of a paint film, particularly oleoresinous vehicles, most latex paints, and some polyamide epoxies that offer a source of food. Mildew spores are omnipresent in air, will deposit on the paint, and, under the right conditions, will begin to grow. In the past, compounds based on phenyl mercuric and tributyl tin compounds were used as fungicides; but, because of their high toxicity, they have been replaced by complex organics such as carbamates, benzothiazoles, alkylisothiazolinone, chlorinated isophthalonitriles, and chlorinated adamantane complexes. However, the new materials have not attained the effectiveness of the older materials. Fungicides function in the can to kill organisms that might upset paint stability, which is particularly important in latex emulsion paints that can become rancid if microbiological growth is not stopped.

c. Thixotropes. Rheological coating properties such as film build, sag control, flow and leveling, and pigment settling properties can be adjusted through the use of thixotropic additives. Thixotropes can enable a rapid increase in the viscosity of a liquid coating material and allow it to build thicknesses over edges and plane surfaces and to resist sag. However, when mixing and applying the coating, shear stresses can break down the coating thixotropy rapidly, enabling it to be applied as if it were low in viscosity. Thixotropy recovers after application, and film build and antisag resistance again occur. There are a number of thixotropes that can be added to solvent-borne coating systems, including castor oil derivatives, high molecular weight polyolefins, montmorillonite and other clays, fumed silicas, fibrated minerals, calcium sulphionate derivatives, and others. Each of these classes has specific advantages and disadvantages with each of the binder systems in which they are incorporated. Similarly, thixotropes are important for waterborne systems to provide the same properties. The more common waterborne system thixotropes are nonionic cellulosic thickeners, polyacrylic acids and salts, anionic polycarboxylic acid-based thixotropes, and, more recently, a nonionic associative

thickener based on ethoxylated polyether-based urethane block copolymers. The nonionic thickeners give the most improved flow and leveling characteristics to water emulsion coatings, providing better gloss and semigloss paints. In roller applications, the nonionic thickeners result in a significantly reduced roller spatter. Thixotropes prevent hard settling of many heavy pigments, such as zinc. Most thixotropes deteriorate on aging, which causes variations in viscosity of the paint in the can. Some paints have increased viscosity; others may suffer a viscosity decrease.

d. Flow agents. The addition of flow agents enhances the freshly applied paint film's ability to flow out after application, eliminating brush marks, roller patterns, orange peel from spraying, and other film irregularities and defects. The flow rate of paint is affected by the rate of solvent release and solvent system evaporation. Surface tension and the coating's viscosity, which vary as a function of temperature, also affect the rate of flow or leveling of the applied paint film. Depending on the type of flow problem encountered, the generic type of coating, and the coating formulation, different flow and leveling agents are added in small amounts (usually less than one percent) to eliminate or minimize problems. Most flow agents function by increasing the viscous force in the coating, overcoming the paint's tendency to flow. Surfactants also help to overcome leveling problems by reducing surface tension.

e. Emulsion aids. Emulsion aids are used in waterborne paints and often are called surfactants. Proper use of surfactants enable a waterborne emulsion to remain in suspension and keep it from settling and packing at the bottom of a can during prolonged storage. All surfactants have a hydrophilic (water-loving) group and a hydrophobic (water-hating) group, which is water repelling. The hydrophobic group is usually in the form of a long hydrocarbon tail terminating in a simple long polar alkyl group. The hydrophilic group is usually a charged species such as an ammonia ion, a polar organic group (carboxylic acid), hydroxyl, sulfate, etc. The surfactant molecules containing both the hydrophobic and hydrophilic ends orient themselves around the emulsion particles to effectively separate them and keep them apart. However, prolonged storage at elevated temperatures, or freezing the emulsion, may destabilize it and cause separation and possible de-emulsification. A number of different types of surfactants can be used, depending on cost, solution, pH, and specific emulsion requirements. Emulsion chemistry is complex and, unlike formulating solvent-based paints, often requires considerable trial and error.

f. UV absorbers. UV light, particularly in the actinic region of 280 to 315 nm, can degrade exterior paint films. Incident UV light is absorbed by the paint, raising the paint

to a higher energy state. This causes bond cleavage and release of free radicals, which leads to depolymerization, chain scission, or, in some instances, crosslinking and embrittlement. This surface effect ultimately results in degradation of the coating at either the surface (as is generally true with epoxies that readily chalk) or the coating interior, if the coating is partially transparent to UV light energy. To prevent this, UV absorbers are added to the formulation at the rate of approximately 1 to 3 percent, by weight, depending on the type of coating, the degree of pigmentation, and the type of surface. Zinc oxide is an effective UV absorber, but it sometimes leads to embrittlement of oil-based coatings and may not be appropriate for other generic types of coatings. Most UV light absorbers are complex substituted aromatic compounds that absorb UV radiation strongly without being degraded. Hydroxy substituted benzophenones and benzotriazoles are used most commonly.

g. Plasticizers. Plasticization is a process of increasing the flexibility and adhesion of an organic coating film and decreasing its brittleness, cohesiveness, and glass transition temperature (the temperature at which a polymer changes from a flexible, rubber-like material to one that is hard and brittle). Plasticization can be achieved by chemically modifying the resin polymer or by adding compounds to the coating formulation. Chemical modification of the compound can be done by reducing crosslinking or by formulating resin molecules with bulky side chains to prevent parallel orientation and crystallinity. Alternately, external plasticizers (such as monomeric phthalates, phosphates, adipates, and sebacates), chlorinated paraffin, or biphenyls can be added to a resin system to soften it and lower the glass transition temperature. The plasticizing materials generally are relatively low molecular weight, slow-evaporating materials that, when mixed with a resin, soften it by preventing crystalline orientation and terminating crosslinking sites. The type of plasticizing agent used depends principally on the generic type and molecular weight of the resin system used in the coatings formulation. In time in some applications or service conditions (such as high temperature/humidity), low molecular weight plasticizers may migrate to the surface of the coating; and the surface may become sticky and attract and hold dirt. More importantly, the coating often embrittles, becomes less flexible, or shows surface or through-cracking.

4-9. Zinc-Rich Coatings

Zinc-rich coatings, or zinc-rich primers, are unique in that they provide galvanic protection to a steel substrate. As "rich" in the name implies, the binder contains a large amount of metallic zinc dust pigment. The binder can be an inorganic zinc silicate or an organic resin such as an epoxy,

butyl, or urethane. After the coating is applied to a thoroughly cleaned steel substrate, the binder holds the metallic zinc particles together and in contact with the steel. Thus, metal-to-metal contact of the two dissimilar metals is made and results in a galvanic cell. Zinc becomes the anode in this cell and sacrifices itself to protect the underlying steel cathode. Properly applied zinc-rich coatings, zinc galvanized coatings, and thermally sprayed zinc eliminate pitting and under-film corrosion even at voids, pinholes, scratches, and abrasions in the coating system. This cannot be said of any other type of coating, and this protective capability makes zinc-rich coatings unique and widely used (refer to Chapter 2).

a. Inorganic zinc-rich binders. All inorganic zinc-rich coatings require an extremely clean surface (SSPC-SP 10 or SP 5), or application over a clean, pickled surface. Because of their inorganic nature, inorganic zinc-rich coatings are highly resistant to scuffing, scraping, and mechanical damage. They have good dry heat resistance to temperatures as high as 399 °C (750 °F) and good resistance to immersion in oil, petroleum distillate products, solvents, fresh water, and many other neutral pH aqueous solutions. Some formulations are suitable for immersion in salt water; others are not. The high conductivity of salt water enhances corrosion of both the zinc and zinc pigment particles within the coating and the underlying steel. Therefore, the protective life of zinc-rich coating in saltwater immersion may not be as long as that in freshwater immersion. In atmospheric environments, inorganic zinc-rich coatings provide long-term corrosion protection in damp, humid environments and where chemical attack does not occur. Inorganic zinc-rich coatings can be applied to steel at thicknesses of from 0.05 to 0.09 mm (2 to 3.5 mils) to provide atmospheric and immersion corrosion protection and left without a topcoat for long periods of time. Salt contamination may be a problem in marine environments; and research and panel testing done by NASA have established that zinc-rich primers, particularly inorganic zinc-rich primers, protect longer without topcoats than the same primers with an organic topcoat. However, other studies for chemical and weathering environments have established that topcoating with an organic topcoat may increase coating system longevity. Both inorganic and organic zinc-rich coatings can be specially formulated as preconstruction primers. This type of primer is applied to ships, subassemblies, and other prefabricated steel. When the steel is fabricated, welding can be done without removal of the preconstruction zinc-rich primer. Topcoating inorganic zinc-rich coatings may be more difficult than with any other coating because of the inherent porosity of the zinc primer. The binder partially wets and adheres the zinc-dust particles together and to the underlying substrate, but it does not fully encapsulate or seal the surface. Therefore,

topcoats applied over the porous surface may displace entrapped air causing pinholes, bubbles, or voids within the topcoat cross-section. This problem is not nearly as prevalent when using organic zinc-rich coatings because the organic binder more thoroughly wets, encapsulates, and seals the porosity of the highly zinc-dust-loaded dry film. Inorganic zinc-rich coatings may be one of three major groups: post-cured water-based alkali metal silicates, self-cured water-based alkali metal silicates, and self-cured solvent-based alkyl silicates.

(1) Post-cured, water-based alkali metal silicates. Post-cured, water-based inorganic silicates come as a three-package system: zinc dust, silicate binder, and curing solution all packaged separately. The binder is an inorganic alkali metal silicate, usually of the sodium, potassium, or lithium family. Zinc powder is slowly mixed into the alkali metal silicate binder, and the resulting solution is spray applied with an agitated spray pot to keep the zinc-dust pigment in proper suspension. After water evaporation and hardening of the zinc silicate coating, a phosphoric-acid-based curing solution is sprayed or brushed over the surface to neutralize the alkali metal binder. The neutralization reaction and subsequent interactions with zinc and iron ions further neutralize the silicate alkalinity and insolubilize the film. The coating becomes insoluble to water and resistant to weathering exposure. Post-cured, inorganic zinc-rich-coatings are believed to be the best performing of the inorganic zinc-rich coating materials because of their relatively complete, insolubilized, hard cure attained after application of the curing solution.

(2) Self-cured, water-based alkali silicates. The most common of these silicate binders is based on potassium and lithium silicates, or combinations. Lithium hydroxide-colloidal silica and quaternary ammonium silicate binders also can be used. The alkali silicate binder is partially dehydrolyzed so its high alkalinity is considerably reduced in comparison with post-cured, inorganic silicate vehicles. Therefore, after application, initial water evaporation, and insolubilization, sufficient neutralization and cure are attained by further reaction with atmospheric moisture and carbon dioxide. Carbon dioxide in the presence of atmospheric moisture forms a weak carbonic acid, which in time is sufficient to neutralize the alkalinity of the silicate binder. If a more rapid insolubilization or cure is desired, heat or an acidic curing solution can be applied. When final curing is attained, most water-based, zinc-rich coatings—whether post- or self-cured—experience a color change, usually from a reddish or light gray to a darker blue-gray.

(3) Self-cured, solvent-based alkyl silicates. The binders for these silicate coatings consist essentially of partially hydrolyzed alkyl silicates of the series methyl through hexyl or glycol ether silicates. Of these, the ethyl silicate type is

the most prevalent. After application and initial solvent drying, the coating system hardens; but to cure, hydrolysis with moisture from humidity in the air is required. The hydrolysis of the silicate binder liberates ethyl alcohol (or an alkyl alcohol if other alkyl silicates are used). The alcohol volatilizes, makes the hydrolysis reaction irreversible, and hardens and cures the binder. If the silicate binder is applied indoors or in an arid exterior environment, water may be sprayed onto the surface with a spray gun or a garden hose with a fine atomization. Two or three applications may be required over a 2- or 3-day period to obtain optimum curing of the binder. All inorganic zinc-rich coatings can attain VOC compliance because of their high solids content, but the water-based post- and self-curing alkali silicates have virtually no VOC release.

b. Organic zinc-rich binders. Organic zinc-rich coatings most commonly are formulated from epoxy polyamide, urethane, vinyl, and chlorinated rubber binders. Alkyds have been used for some air-dry formulations, but they most commonly are used with baking formulations, notably in the automotive industry. Drying, hardening, and ultimate curing of the organic zinc-rich coating is determined by the type of binder used. The hardening and curing mechanisms of the various organic binders have been described previously (paragraphs 4-2 and 4-3) and are the same for organic zinc-rich coatings. The major difference is that, with organic zinc-rich coatings, the pigment is zinc dust in high concentrations to attain a dry film pigment volume of 75 percent or greater. This high zinc loading enables the organic zinc-rich coatings to provide galvanic sacrificial protection. The zinc-dust particles within the coating system must be in electrical contact with the thoroughly cleaned, underlying steel surface, and the zinc-dust pigment particles must touch each other for galvanic protection. Usually when formulated into organic vehicles, the binder more thoroughly encapsulates the zinc and reduces the sacrificial capability of the applied film. However, this encapsulation does not prevent galvanic protection by organic zinc-rich primers. In fact, the encapsulation of the organic binder makes organic zinc-rich coatings more tolerant of deficient surface preparation because the binder more readily wets and seals the prepared surfaces where residues of rust or old paint may remain. Also, topcoating with the same generic type of topcoat (e.g., a polyamide epoxy zinc-rich topcoat with a polyamide epoxy topcoat) is more easily accomplished because organic zinc-rich coatings have a less porous surface and are more similar to conventional organic coatings than the inorganic, zinc-rich coatings.

(1) Organic zinc-rich coatings frequently are used to touch up and repair inorganic zinc-rich coatings because the wettability of the organic binder provides better adhesion to

the inorganic surface than another coat of inorganic zinc-rich coating. Organic zinc-rich primers generally are considered to be easier to apply by spray than inorganic zinc-rich coatings, and they are somewhat more tolerant of poor surface preparation because of the wettability and penetrability of the organic binder. Organic zinc-rich coatings have less of a tendency for mud cracking at excessive thicknesses (over 0.13 mm [5 mils]) and are easier to topcoat than inorganic zinc-rich coatings; however, they do not have the heat and abrasion resistance of the inorganic zinc-rich coatings. Organic zinc-rich coatings do not provide the same long-term corrosion protection to steel as most inorganic zinc-rich coatings.

(2) The VOC characteristics of organic zinc-rich coatings are similar to those of the nonzinc-dust-pigmented binders. Organic zinc-rich coatings are highly pigmented, but this does not substantially reduce VOC because the pigment has a high specific gravity and is dense relative to its volume. Generally there is less organic binder per gallon of organic zinc-rich paint, and VOC emissions are slightly less than for nonzinc-rich-pigmented coating systems using the same binder.

(3) Properly applied zinc-rich coatings, zinc galvanized coatings, and thermally sprayed zinc eliminate pitting and under-film corrosion even at voids, pinholes, scratches, and abrasions in the coating system. This cannot be said of any other type of coating, and this protective capability makes zinc coatings unique and widely used. The binders of zinc-rich coatings can be organic or inorganic.

4-10. Volatile Organic Compounds

VOCs are in most protective coatings. Common paint solvents such as aromatic hydrocarbons, aliphatic hydrocarbons, ketones, acetates, and alcohols are photochemically reactive. On evaporation into the atmosphere, these paint solvents react with nitrous oxides (combustion compounds from automotive emissions and burning of fuels) and sunlight to form ozone and air pollutants. In the 1960s, air pollution problems usually were handled by state and local agencies. There was no national goal to address air pollution. In the 1970s, Congress passed the Clean Air Act and established the U.S. Environmental Protection Agency (USEPA). The Clean Air Act gave USEPA the responsibility of identifying the most serious air pollutants and setting national air quality standards for each. Ozone was at the top of the list. The air quality legislation was an attempt to reduce levels of ozone and other air pollutants. Rules limiting the amount of VOCs in paint have been established since then, but they vary from state to state and even regionally within a given state. Such variability in laws regarding VOC emissions has

been of considerable concern to many coating manufacturers whose products are sold nationally. A particular coating material may comply with the laws of one state but not with those of another state. Even within a given state, the coating may be legal in most areas but illegal in certain cities or regions. For years the coatings industry has pushed for national VOC legislation that will supersede and preempt local legislation regarding VOC emissions. However, national VOC legislation has not been enacted, and permissible VOC emissions vary widely, depending on the generic type of coating and the location where it is applied. VOC compliant coatings are formulated principally by increasing the percent volume of solids, chiefly by minimizing solvent content, use of relatively high volume low density pigments, and the use of lesser amounts of stronger solvents. Additionally, the alkyd resin is combined with other synthetic resins (such as epoxies, phenols, and urethanes) and results in a more reactive higher solids coating system. Straight alkyd systems currently are formulated with VOCs of 350 g/L (2.9 lb/gal) or higher. Future formulations probably will require a VOC as low as 250 g/L (2.1 lb/gal). Chapter 11 discusses VOC regulations in detail.

4-11. Powder Coating

Powder coatings are made by mixing resins, pigments, and additives together and heating them to form a melt. The melt is extruded, cooled, and broken up by milling to produce a powder with a particle size distribution of approximately 10 to 100 μm . The article to be coated usually is preheated to 204 to 260 $^{\circ}\text{C}$ (400 to 500 $^{\circ}\text{F}$), depending on the powder to be applied. The pigmented powder is applied, either by immersing the article in a fluidized bed of the powder (which is kept mobile by the passage of air through it) or by electrostatic spray guns. After application, the article being coated is heated to the melting point of the powder so the powder flows together. The powder can be thermoplastic or thermosetting. With thermoset powders, crosslinking agents also are made into a powder, and this powder is applied at the same time as the base powder. After application, crosslinking occurs on melting. Epoxy powder coatings are by far the most popular, although polyester, polyurethane, acrylic, and other resin types can be used.

a. Powder coatings do not readily give satisfactory films at thicknesses below approximately 0.05 mm (2 mils); they require special application and heating equipment. Powder coatings form good-looking, thick, tough coatings that contain no solvent. Because they are VOC compliant, they comprise a technology that is of considerable interest in the protective coatings area. Currently, powders are used mostly in the coating of relatively small items that can be

easily heated to the melting point of the powder being applied. Fusion-bonded powder coatings are applied to preheated pipe surfaces with or without primers. The coating usually is applied 0.30 to 0.63 mm (12 to 25 mils) thick for aboveground pipe installations to eliminate chalking and to maximize surface life; topcoating frequently is done with a urethane coating system.

b. Thermally sprayed organic powders have been applied to structural steel and other large metal objects. The process is expensive and adhesion sometimes is a problem because the large item being coated does not attain a uniformly high substrate temperature when heated; and the applied powder, even though in a liquid "melt," does not have good surface wetting properties. Current furnaces or heating ovens are large enough to handle concrete reinforcing rods, small- to medium-diameter pipe, small structural steel pieces, and sheet piling.

c. Although of considerable interest to the protective coating industry, powder coating has not been used commercially to protect large steel surfaces or heavy, massive structural steel shapes.

4-12. Thermal Spray

a. Thermal spray coatings consist of a process by which an organic powder or metal wire is melted and spray-deposited onto a surface. In the past, metallizing was the term used to describe wire flame spraying. However, because of dramatic improvements in equipment used to heat and spray the molten metal and nonmetallic polymers onto a surface, the term thermal spraying is more descriptive. Thermal spraying is a process by which a finely divided molten metallic or nonmetallic material is sprayed onto a prepared substrate to form a coating. The sprayed material is originally in the form of a wire or powder. The thermal spray-gun heats the wire or powder to a molten or plastic state, and compressed air or gases propel it to the surface being coated and deposit it into a film. Refer to CWGS 05036.

b. Zinc, aluminum, and their alloys are the most widely used metals for thermal spray, corrosion-resistant coatings. These metals provide excellent protection in a variety of marine and industrial environments. After spray application, zinc is anodic to an underlying steel surface. Because of its aluminum oxide coating, aluminum exhibits galvanic protection for only a short period of time. Afterward, the oxidized aluminum coating functions principally as a barrier coat. In general, aluminum corrodes less rapidly than zinc in highly acidic conditions, but zinc performs better in alkaline environments. Zinc frequently is the preferred metal for protection of steel in fresh cold waters, although

aluminum also is suitable. Aluminum is preferable for aqueous solutions above 60 °C (140 °F).

c. Organic sealers or topcoats commonly are used over the thermally sprayed metal to extend the life of the system and provide color for decorative purposes. Common sealers include many of the synthetic resin coating systems, especially vinyls, epoxies, polyurethanes, and phenolics. Sealers are essential for most immersion or severe chemical corrosion applications. Most sealers are applied in at least two coats, the first thinned for penetration into the porosity of the thermally deposited metal coating. The second and sometimes third coat of a sealer are applied unthinned as build coats.

d. Because there are no solvents or volatile material in any metallic thermal spray system, VOC compliance is not a problem. However, VOC compliance may depend on the organic sealer coating used.

e. An advantage of the thermal spray system is that essentially no startup or cleanup procedures are involved. The wire or powder feed stock is fed to the spray gun, the heat source is ignited, and spraying of the molten feed stock begins. On conclusion of thermal spraying, the device is shut off, and the process stops, with virtually no equipment cleanup required.

f. Blast cleaning surface preparation to a clean white metal, preferably with an anchor profile exceeding 0.08 mm (3 mils) is required for any thermal spray coating. Thermal spray metal (and plastic) coatings have little wetting ability at the time of application so cannot penetrate, seal, or encapsulate any contaminants on the surface to be coated. On cooling after application, the metal particles undergo a thermal contraction that applies a shrinkage stress to the metallic film. A minimum anchor pattern of 0.08 mm (3 mils), and preferably 0.10 to 0.13 mm (4 to 5 mils), is required to withstand the shrinkage stresses and to dissipate these stresses over a greater interfacial area between the applied metallic film and the underlying steel substrate.

g. The common methods of thermospray are:

(1) Wire flame spraying. Acetylene or other common fuel gases are combined with oxygen and ignited in the spray gun. A wire—usually zinc, aluminum, or zinc-aluminum alloys but sometimes nickel, stainless steel, or another metal—is fed through the flame, is melted, and is deposited on the surface. Wire flame sprayed coatings generally exhibit lower bond strengths, higher porosity, a narrow working temperature range, and a higher heat transmittance to the substrate than plasma or electric arc spray coatings.

(2) Powder flame spraying. A common fuel gas is used with a metal or plastic powder. The powder is stored in a hopper mounted on top of a spray gun, and a small amount of oxygen is diverted from the gas supply to carry the powder by aspiration into the oxygen-fuel gas flame. The melted powder is carried by the flame to the object being coated. An air/propane mixture is used for polymer powders. The object to be coated must be preheated to at least 79 °C (175 °F) prior to the spray application of the polymer powder. Because of the lower particle velocities obtained, the coatings generally have a lower bond strength, a higher porosity, and a lower overall cohesive strength than the coatings produced by any of the other thermal spray methods. The bond strength and other film properties can be improved considerably by preheating the substrate to 49 °C (120 °F) or more prior to application of the powder.

(3) Electric arc spraying. The spray gun used in electric arc spraying uses two feed stock wires as electrodes. An electric current is applied across the wires so that an electric arc is formed at the intersection. Heat from the electric arc melts the wires, a stream of compressed air flows across the arc zone, and the melted metal is removed from the wires and propelled to the surface. Because of the high temperatures in the arc zone, the coatings have excellent adhesion and high cohesive strength. Super heating of the particles after impact may lead to a metallurgical “weld” bond with some metals, substantially increasing adhesion and cohesive strength.

(4) Plasma spraying. Plasma is a hot gas issuing from the spray gun; it resembles a bright flame and is created by passing inert gas through an electric arc within the gun. The arc heats the gas to temperatures well above the melting point of any known substance. Powder feed stock is introduced into and melted by the plasma stream that also carries the molten metal to the work piece. The plasma system produces excellent quality coatings, but the equipment is complex, expensive, and difficult to operate. Plasma spraying is used when coatings are needed to provide the utmost in corrosion protection against chemical or high temperature corrosion, and when the work can be done in a shop environment.

4-13. Galvanizing

a. Hot dip galvanizing is the process by which a zinc protective coating is applied to steel by immersing an object in a molten zinc bath. Prior to immersion in the zinc bath, contaminants on the steel must be removed. Oil, grease, and other surface deposits are removed by immersing in a hot water detergent solution prior to pickling, steam cleaning, or steam-detergent cleaning the steel. The steel surface also must be thoroughly cleaned of mill scale and

rust. This is usually done by sulfuric acid or phosphoric acid pickling. The steel to be galvanized is immersed in a hot acid bath. The hot acid aggressively attacks the steel surface, cleaning, etching, and roughening it. After continuous strip or batch pickling, the steel is water-rinsed or dipped to remove acid residues prior to immersion in the molten zinc galvanizing bath. The immersion in molten zinc may be done by one of two methods: continuous or batch processing. Sheet steel may be hot dipped by continuously passing the metal through a molten zinc bath. Continuous processing is highly automated and often is associated with steel mill operations. Batch processing generally is performed on fabricated items that range in size from large structural steel objects to small items such as nuts, bolts, and fasteners. With batch galvanizing, the objects are submerged into the molten zinc bath, held there for a suitable time, then removed.

b. A major advantage of galvanizing is that the zinc coating alloys itself with the steel. The extent of the alloy is a function of the heat of the zinc bath (the bath is generally maintained at a range of 443 to 460 °C [830 to 860 °F]) and the amount of time the steel is submerged in the bath. The greater the submersion time, the greater the extent of the iron-zinc alloying. The item being galvanized must be at the bath temperature for optimum galvanizing adhesion. This, however, has two disadvantages. The object being coated must not undergo any undesirable property changes at the temperature required for galvanizing. Also enclosed or sealed cavities in the object being galvanized (particularly with hot dip batch galvanizing) must be avoided by design or be opened by drilling to provide a vent hole to allow release of entrapped air that will expand when heated in a galvanizing bath.

c. Corrosion protection afforded steel by galvanizing is greater than that provided by thermal spraying zinc-rich or organic coatings of similar thicknesses. This is a result of the smooth, continuous nature of the zinc coating deposited during the hot dip process and the iron-zinc alloying that occurs at the interface between the zinc coating and the steel surface. For small steel objects, grating, small-diameter piping, conduit, and other configurations with a high surface area-to-weight ratio, galvanizing is preferable to painting and thermal spraying because immersion in a molten zinc bath readily coats all surface areas quickly and economically. Conversely, when coating thick, heavy steel objects with a relatively low surface area-to-weight ratio, thermal spraying and/or painting may be more economical.

d. Although almost any steel can be galvanized, steel chemistry can dramatically affect the thickness, structure, and appearance of the galvanized coating. Silicon, phosphorus, carbon, and manganese may be present in steel

and affect the galvanizing properties. The most influential steel constituent affecting galvanizing is silicon, which is added to steel as ferro-silicon to remove oxygen from the molten steel before casting. In high silicon steels, an undesirable increase in coating thickness occurs because of the accelerated growth of the zinc-iron alloyed layers. This growth is caused by the formation of loosely packed small grains or crystals in the outermost alloy layer of the coating that allows zinc from the bath to penetrate to the steel surface. In general, steels with the following maximum impurity levels are best suited to galvanizing: 0.05 percent silicon, 0.05 percent phosphorus, 0.25 percent carbon, and 1.3 percent manganese.

e. Hot dip galvanizing has a number of advantages, including the ability to coat recessed or difficult-to-coat areas (such as corners and edges) with a sufficient coating thickness. Also because the coating is metallic and metallurgically combined with the steel, it has good abrasion and corrosion resistance. When coating steel with a large surface area-to-weight ratio, galvanizing is much more economical than painting because galvanizers charge by the weight of the object being galvanized and painters charge by the square foot of surface area of the object being painted. A major disadvantage is that the hot dip process is not portable, and the object being coated must be taken to the zinc-coating facility for galvanizing.

f. Hot dip galvanizing causes no significant alteration in the bend, tensile, and impact properties of galvanized steel, so steel strength and ductility are unaffected. Welded structures have higher strength when galvanized than when uncoated because hot dip galvanizing reduces weld stresses by 50 to 60 percent. For most steels, little reduction in fatigue strength occurs as a result of galvanizing. Steel does not embrittle as a result of hot dip galvanizing. Hydrogen embrittlement does not occur when ordinary carbon or low alloy steels are galvanized. Hardened steels may become embrittled if the hydrogen picked up during the pickling cleaning operation is not expelled during immersion in the molten zinc bath. Steels of medium to high strengths that have been severely cold worked may have local areas susceptible to hydrogen embrittlement. As a rule, however, hydrogen embrittlement as a result of cold working is not a problem for steel subject to hot dip galvanizing.

g. Coatings can be successfully painted immediately after galvanizing or after extended weathering. A white rust-preventative oil or wax may be applied to the galvanized surface to prevent the formation of zinc-corrosion products such as zinc hydroxides, oxides, and carbonates that result in a white discoloration on the galvanized surface. If painting is to be done immediately after galvanizing, check to ensure that a rust preventative

has not been added. The freshly galvanized surface should be roughened slightly by light brush blast cleaning or mechanical means. Alternatively, vinyl butyral wash primers or other pretreatment primers can be applied that will etch and adhere to the underlying galvanized surface.

h. If coating after weathering, the galvanized surface will be eroded by zinc corrosion and the formation of insoluble zinc-corrosion products. The zinc corrosion roughens the galvanized surface and frequently no further mechanical roughening or brush blast cleaning is required. However, care should be taken to ensure that all loose zinc-corrosion products are removed by scrubbing or power washing the surface prior to painting. Wash primers, or primers specially formulated for application over galvanized surfaces, frequently are preferred.

i. Galvanized steel can be topcoated with any nonsaponifiable alkali-resistant paint. Zinc dust, zinc oxide-containing paints are particularly recommended, as are zinc-rich coatings. Water-based acrylic latex emulsions, epoxies, vinyl copolymer paints, and chlorinated rubber and coal tar epoxy coatings all have been applied with good success over properly prepared galvanized steel surfaces.

4-14. Tapes and Wraps

a. Protective tapes and wraps are used almost exclusively for protecting pipelines and tubular structural shapes from below-grade or (underground) corrosion. Cathodic protection is used in many situations to supplement corrosion protection. The tape or wrap must provide a barrier resistance to the below-grade environment, have good adhesion, and be able to act as an effective electrical insulator to aid in effective cathodic protection.

b. A tape is a composite material consisting of at least two layers. The first or innermost layer is usually a soft, elastomeric material formulated to adhere to an underlying substrate. The substrate can be either primed bare metal or another tape layer. The tape backing or outer layer is a monolithic polymeric material designed for tensile strength, mechanical strength, temperature, and electrical resistance. Typical tape backings include polyvinylchloride, polyethylene, polyolefin, butyl, ethylene propylene diamine monomer (EPDM), and, occasionally, nylon or glass fibers. Adhesives are usually butyl rubbers or butyl chlorinated rubbers but can be petrolatum and petrolatum wax compounds.

c. The tapes can be cold applied, hot applied, and cold applied with subsequent heat application as a heat-shrink material. Multilayered tapes frequently are used on a pipeline by applying a one-tape system then overcoating it

with a different tape system. When this is done, the inner layer is designed primarily for corrosion protection, and the outer layer is designed to resist moisture, soil stresses, UV light, or other environmental influences.

d. Most tape systems are applied over a blast-cleaned surface, usually SSPC-SP 6 or better. This standard generally is a requirement for all adhesives except those based on petrolatum wax, which can be applied over a lesser prepared surface because of its wettability and softness. Most tapes perform better when applied over a primer, which commonly is an epoxy. The primer provides a bonding surface for best adhesion of the subsequently applied tape coatings.

e. Tape systems are applied by hand or, preferably, by a hand-assisted tape wrapster that is pushed and pulled around a pipe by as many as four or five workers per machine. Powered wrapsters provide the best application and allow for a more constant tension, uniform overlaps, fewer wrinkles, and a lesser clearance underneath the pipe (as little as 304.8 mm [12 in.]). Tape wrapping machines are available that will simultaneously apply two tape layers to a pipe. These tape wrapping machines are most useful for over-the-ditch applications.

f. For tape applications in the pipe mill or fabricating shop, surface preparation by blast cleaning is the most common, usually to an SSPC-SP 10 quality. Application of a primer and two or more tape layers applied by automatic pipe-coating equipment under constant tension of 10 to 14 psi results in a tight, wrinkle-free coating. The coating is inspected by automated high voltage holiday inspection (minimum 6,000 V). After mill application of a tape system, careful handling is required to avoid damaging or stripping the applied tape system.

g. In the pipe mill, hot-applied plastic tapes also have been used. The pipe surface is cleaned to an SSPC-SP 10 and heated to approximately 121 °C (250 °F) to melt the tape adhesive to provide a good bond. Mill-applied tape coating systems require careful handling and installation, and over-the-ditch application eliminates the need to repair shipping and handling damage. However, over-the-ditch application generally is more labor intensive and is subject to weather variables and adverse application conditions. During installation of any pipeline system—whether coated by a tape wrapping system, fusion bonded system, or extruded high density polyethylene wraps—care is necessary during backfilling operations to prevent rock and stone damage and impact into the coating. Insulating mats and/or blankets are sometimes wrapped around a pipe to prevent backfilling damage or, alternatively, specially conductive backfilling earths are initially placed around the pipe layer

prior to filling the ditch. Another tape system, extruded polyethylene, is relatively new and is gaining acceptance in the United States. This coating system generally consists of blast cleaning to SSPC-SP 6 followed by the application of an epoxy primer to approximately 0.05 mm (2 mils) dry film thickness. The pipe then is heated to approximately 135 °C (275 °F) and approximately 0.20 mm (8 mils) of a polyethylene copolymer adhesive is extruded around the pipe, followed by 3 mm (118 mils) of a polyethylene outer wrap extruded spirally over the adhesive. The preheating melts the adhesive and provides wetting capability. Additionally, the polyethylene extrusion to the hot pipe shrinks to form a tightly adhered, thick, seamless coating with high resistance to mechanical damage, moisture permeation, and UV light.

h. During pipe-laying operations in the field, the joints must be protected by application of paints or protective coatings or, more commonly, a tape wrapping system.

(1) Polyvinyl chloride tapes. Tapes with a PVC backing can be used with a variety of adhesive materials, including butyl rubber and petrolatum wax. The greatest advantage of PVC-backed tapes is that they have an ability to conform to regular substrates and provide a good barrier to penetrating moisture. However, because of plasticides and migration, sometimes the backing material separates from the adhesion. PVC backings are suitable for temperatures up to 60 °C (140 °F).

(2) Polyethylene tapes. Polyethylene-backed tapes most commonly are used with butyl or chlorinated rubber adhesives. These tapes are used as outer tapes to provide increased mechanical strength and UV light resistance. They can be used over primed steel as an inner tape wrap because of their excellent adhesive quality. Polyethylene tapes are considered suitable for use in cold climates because they retain their flexibility at temperatures as low as -40 °C (-40 °F). The polyethylene backing generally ranges from 0.25 to 1.27 mm (10 to 50 mils) thick; adhesive ranges from 0.08 to 0.30 mm (3 to 12 mils) thick.

(3) Petrolatum tapes.

(a) Petrolatum wax, obtained from the refining of petroleum, is purified and used as a corrosion-protective material. The petrolatum is a soft, viscous to semisolid waxy-like material with excellent wetting properties. Petrolatum tapes are fabricated by impregnating the petrolatum into a woven or nonwoven, cellulose-free synthetic fiber fabric, usually nylon or glass fiber. Inert fillers are added to improve thixotropy. The resulting coating possesses a low water vapor transmission rate, is relatively moisture impermeable, and is nondrying,

nonhardening, nonhazardous, and nontoxic.

(b) Petrolatum tapes have some moisture-displacing capability and often are applied over hand- or power tool-cleaned surfaces (instead of blast-cleaned surfaces as required by most other tapes). Because of the high conformability of petrolatum tapes, they are suitable for use over irregular surfaces, on pipelines, and to protect valves, flanges, and other irregular shapes. Petrolatum tapes are soft and they are susceptible to mechanical damage. A polyvinyl chloride outer wrap or membrane is applied over the petrolatum tape to improve mechanical properties, particularly during handling and backfilling. This exterior wrap also keeps the petrolatum from oxidizing and drying out.

(c) Petrolatum formulations have been developed to allow use at temperatures as high as 82 °C (180 °F). These tapes are well suited for protecting metal couplings and valves and other pipeline irregularities and for coating repairs on existing pipes when the existing coating has deteriorated or failed in service.

(4) Coal-tar and asphalt tapes. Coal-tar and asphalt mastic tapes are used as hot-applied systems. The backing is usually a synthetic fiber of nylon or woven glass fiber. These tapes have good resistance to water penetration and, when properly applied, have excellent adhesion. They usually are used for over-the-ditch application and for the protection of welded joints.

(5) Butyl or EPDM vulcanized rubber tapes. Butyl or EPDM vulcanized rubber-backed tapes have excellent flexibility, mechanical resistance, and moisture resistance.

The adhesive of these tapes is usually a butyl or chlorinated rubber, and this type of tape is noted for good adhesion and resistance to mechanical damage.

(6) Heat shrink polyolefin tapes. A crosslinked polyolefin backing is combined with a high shear strength crystalline adhesive to form a heat shrinkable pipeline tape. Prior to tape wrapping, the steel is usually hand- or power tool-cleaned and preheated to approximately 60 °C (140 °F). The tape is wrapped around a pipe with a 50 percent overlap and heated with a propane torch after wrapping. Heat from the torch causes the crystalline adhesive to melt and flow, filling surface irregularities. Additionally, the backing shrinks tightly to the steel substrate to provide good adhesion and conformability. There are calorimetric heating indicators in the backing to indicate when the proper temperature has been reached.

4-15. Other Coatings

Any listing of coating systems cannot be all-inclusive. There always will be specialized coating systems that are not widely used or are of little interest to USACE. Some of these systems may include fluoropolymer coating systems, used principally for high heat, corrosion-resistant surfaces; silicone resin coating systems, used as thin film, high heat systems or in combination with metal or ceramic frits for high heat, abrasion-resistant corrosion service; chlorinated rubber, neoprene, and other coating systems that are not widely manufactured and have been replaced by other generic-type coating systems; and variations or combinations of systems that are not different enough to warrant a separate category.

Chapter 5 Coating System Selection

5-1. Introduction

a. A systematic approach to coating selection for new construction and maintenance painting is described in this chapter. The first section details the criteria for selecting a coating system based on the service environment(s), surface preparation requirements, and options for coating application. Other considerations such as VOC concerns, coating cost, supplier recommendations, ease of application, and maintainability are discussed.

b. After a coating system is selected, alternative methods of surface preparation and application are explored. Special sections are devoted to the advantages/disadvantages of shop versus field cleaning/painting, difficult to coat areas, and the use of cathodic protection alternatives in those areas. The balance of this chapter is devoted to reviewing existing systems, candidate maintenance, and new coating systems options for given USACE structures service environments. Also, special concerns or cautions associated with these coating system choices are discussed.

5-2. Criteria for Selecting a Coating System

No single coating or coating system can satisfy every service condition or environment that may be encountered in a given civil works facility. Selecting candidate coating systems for an exposure environment depends on identifying and understanding how each of the environments impact various coatings. For example, chlorinated rubber or vinyl coatings, which are thermoplastics, would not be used in locations subjected to high heat or strong solvents because they would quickly dissolve or soften. If alkyd enamels were used in an environment with, for example, caustic conditions, they would soften, swell, and quickly disbond as a result of saponification. Chemistry, experience, and the coating system performance history have illustrated these facts. The Paint Systems and Painting Schedule section of CWGS 09940 and the Supplementary Application Instructions contained therein show paint systems that will provide satisfactory, cost-effective performance based on given service environments. Characteristics of the environment that the coating system will encounter must be well identified. Once the environmental exposure has been properly determined, the process to select coatings systems that have a known history and track record of successful use in these identified environments may begin.

a. Identifying the service environment(s). Exposure environments that have the greatest impact on coatings and

coating systems performance will be described briefly here. Picking the correct coating for painting projects might be described as a process of elimination rather than one of selection. Probably the most important step in coating selection is to evaluate the conditions under which the coating must perform. This cannot be a superficial evaluation but must consider all the conditions that may exist. Even small and seemingly irrelevant factors may affect coating system performance. In most situations, a combination of two or more service environments act together to create a hostile environment. Chapter 4 provides detailed information on the environmental resistance qualities of various generic coating types and should prove valuable when used in conjunction with this chapter.

(1) Temperature extremes. Most applied coating systems are subject to temperature variances within their applied environments. For the most part, these fluctuations are moderate (normal atmosphere fluctuations). Even normal atmospheric temperature variations have an effect on coating performance (i.e., piling studies performed by USACE show a significantly higher rate of coating failure on pilings off the coast of South Florida than in the Cape Cod area. Additionally, in many instances, unique processes or system operations may generate adverse (cold or hot) temperatures outside the normal. Extreme cold or heat can cause brittleness, poor impact resistance, shrinkage, or loss of adhesion and may alter the corrosion-prevention characteristics of the coating system. High temperatures also tend to aggravate the corrosivity of the environment severely (i.e., many acids become increasingly aggressive with temperature increases). Curing mechanisms involved with conventional coatings frequently are temperature dependent. With high heat, the curing process may occur too rapidly or, conversely, in cold temperatures curing may not occur at all. Coatings to be applied in extremely cold environments must have excellent adhesion, resiliency, and plasticity. Likely candidates for heat-resistant coatings are those modified with silicone and/or metal flake (i.e., aluminum, stainless steel). Some inorganic, zinc-rich coatings can be applied at temperatures as cold as -18 °C (0 °F) and provide excellent corrosion protection in the extreme cold.

(2) High humidity. High humidity frequently is accompanied by condensation. Consequently, such a continuously wet, heavily moisture laden environment is often considered to be in a state of constant immersion. A water molecule is extremely small and can pass through the molecular network of even the most moisture-resistant protective films. Each coating and resin type has a unique moisture vapor transfer rate. Obvious coatings for such continuously moist environments should exhibit low moisture vapor permeability (MVP) and water absorption

rates. Industry practice generally has found that, the lower the moisture vapor transfer rate, the better corrosion protection the coating provides. Commonly used coatings with typically low moisture vapor transfer rates are formulations of two-part epoxies, vinyls, coal tars, and respective modifications of these coatings. Coatings pigmented with metallic or glass flake have been found to improve moisture resistance and lower the MVP rate of some coatings.

(3) Immersion. Immersion service coatings are exposed to water solutions ranging from highly pure deionized water to water containing high concentrations of various chemicals, acids, or alkali solutions. Specific immersion linings may be subject to the effects of storage of petroleum or solvents. Primarily though, water is the main exposure element in immersions. Coatings for immersion service must exhibit good adhesion, moisture resistance, vapor transfer, ionic penetration, cathodic disbondment, osmosis, and variances in temperature. Examples of coatings that traditionally have performed well in immersion are: coal tar epoxies (CTE), vinyls, untopcoated zinc-rich coatings, and modifications of epoxy coatings.

(4) Oxidizing-reduction. Oxidizing environments—such as atmospheric service or areas of ozone generation and strong oxidizing agents such as bleach or nitric acid—are more common than reduction environments. Most coatings are more susceptible to oxidation than to reduction. Oxidation may cause coating film brittleness and loss of cohesive strength; a common example of this is an old, weathered alkyd that can oxidize to an almost powdery state after many years. Generic coating types that historically have performed well in oxidizing environments are: CTEs, chlorinated rubber, and formulations of epoxies and polyurethanes.

(5) Extreme pH. Extremes of pH, such as strong acid or alkaline environments, can have a dramatic effect on coatings systems selection. The degree of impermeability of the chosen coating to the environment is of primary importance. The coating film essentially must be inert to prevent a reaction with the environment or permeation of the solution into the coating film. Alkali resistance is vitally important to a primer coating. Chemical reactions that take place in the corrosion process produce strong alkaline products that are deposited on the substrate. Subsequently, any primer that is not resistant to these by-products will have a tendency to fail because of cathodic disbondment. This failure can result in additional undercutting of the coating and the spreading of underfilm corrosion. Substrates such as concrete typically have a high alkalinity; therefore, a coating system chosen for a concrete substrate also must exhibit good alkaline resistance. Formulations of coatings that have a good history of performance in extreme

pH environments are vinyls, chlorinated rubbers, and epoxy modifications. However, alkyd or oil-containing coatings tend to have a poor resistance to alkalinity and should not be used in such an environment.

(6) Solvent exposure. The function of solvents in coating formulation in relation to the application properties of the coating is well known. However, solvents often become an exposure environment to the dry-cured coating system. The effects of the solvent on the coating system generally will vary by solvent type and the resistance of the generic type of coating that has been applied. There are numerous types of solvents. Typical solvents frequently can be classified into two categories: hydrocarbons and oxygenated solvents. A less important group of solvents are called the terpenes. Hydrocarbons are so named because their molecules contain only hydrogen and carbon atoms. The molecules of oxygenated solvents also contain oxygen atoms. But some commonly used oxygenated solvents may contain atoms of other chemical elements such as nitrogen. Hydrocarbon solvents more commonly are found than oxygenated solvents. Oxygenated solvents and hydrocarbon solvents frequently are blended for use in lacquers, catalyzed coatings, and synthetic resins solutions. As with many other exposures, a high degree of impermeability is necessary for the coatings to resist solvents. The coating system chosen must not be dissolved or softened by the solvent in the exposure environment. For example, USACE vinyl systems are resistant to solvents of the aliphatic variety and most often can tolerate spills from aromatic hydrocarbons. However, the stronger oxygenated solvents will readily attack, soften, and dissolve the vinyl film. Therefore, it is necessary to make a good system selection because the binder may be dissolved easily and softened by various levels of solvency strength. Historically, two-component highly crosslinked coatings, such as formulations of epoxy and urethane coatings, have exhibited good solvent resistance. Therefore, the blend and type of solvent in the exposure environment should be identified so the appropriate coating system can be chosen. When all pertinent factors have been identified, coating manufacturers can be consulted for system recommendations. The major manufacturers of high performance protective coatings have an excellent understanding of the temperature and chemical exposure limitations of their products. In fact, many publish tables of chemical resistance for various coatings and include some of this information in technical product data sheets. Specific facility coatings histories, manufacturers' performance history, and published coating system service life data are particularly helpful. When searching for such information, the exposure environment must be accurately assessed to select only those coating systems with a high probability of success and/or a proven track record. When a process is new and the exposure environment is uncertain, field test patches of candidate products can be applied in

that environment and evaluated. If a new environment can be identified and simulated, screening and testing of candidate materials can be performed by qualified laboratories using specially designed test apparatus. However, the key to success for any situation rests with thorough, accurate identification of the exposure environment.

(a) Hydrocarbons. There are two types of hydrocarbon solvents: aliphatic and aromatic. Special blends of these solvents have been developed to form solvents called semi-aromatics. Aliphatic and aromatic hydrocarbons differ in the way in which the carbon atoms are connected in the molecule. This characteristic structural difference leads to a sharp difference in the chemical and toxicological properties. The aromatic hydrocarbons are the stronger solvents for coating film formers. They also are more irritating to humans in both liquid and vapor forms. Typical aromatic hydrocarbons are: benzene, toluene, and xylene. Typical aliphatic hydrocarbons are: hexane, heptane, and odorless mineral spirits. Ordinary mineral spirits are mostly aliphatic hydrocarbons. Aromatic and aliphatic hydrocarbons generally are derived from heat distillation of petroleum products. They generally are found as a blend of aliphatic and aromatic components and are readily available in an extensive range of solvent strengths and evaporation rates.

(b) Oxygenated solvents. Oxygenated solvents are manufactured by a variety of processes. Those most commonly known of these solvents are: alcohols, ethers, ketones, and glycol-ethers. Typically, there may be a blend or combination of these solvents in the exposure environment. Examples of alcohol solvents are: methanol, ethanol, isopropanol, and butanol. Examples of ether solvents are: ethyl acetate, isopropyl acetate, butyl acetate, and butyl cellusolve acetate. Examples of ketones are: acetone, methyl ethyl chloride, methyl isobutyl ketone, and cyclohexanone. Examples of glycol-ethers are: cellusolve and butyl cellusolve.

(c) Terpene solvents. These solvents are derived from the sap of pine trees; examples are terpene, dipentene, and pine oil.

(7) Wet/dry cycling. Alternate wet and dry cycling, such as that associated with atmosphere and weather, may have a significant effect on the performance of a coating system. Coating subject to wet and dry cycling must exhibit strong adhesion, low moisture vapor transfer rates, and good corrosion and undercutting resistance. Although a significant number of coatings will perform satisfactorily in a cycling environment, coating system selection mainly will depend on other in-service elements that impact this environment.

(8) Thermal cycling. Thermal cycling naturally generates the forces of expansion and contraction. For a coating system to provide maximum protection to the substrate, it must have the ability to expand and contract with the substrate. For the most part, thermal cycling is associated with normal atmospheric weathering. For example, a metallic substrate may heat up rapidly when exposed to the sunlight; however, when the sun sets or if it becomes cloudy, the temperature can rapidly decrease. Such stresses must be withstood by the coating system without loss of adhesion or checking and cracking. Acrylics, vinyls, and inorganic zinc coatings have proven exceptionally resistant to fluctuations in temperature.

(9) Ultraviolet exposure. Resistance to ultraviolet (UV) radiation is extremely important. Sunlight can rapidly degrade a coating and will cause a complete loss of film integrity, resulting in chalking, loss of gloss, fading, and brittleness in a rather short period of time. Such degradation may result in an aesthetically unacceptable coating appearance. Specific generic coating types exhibit better resistance to UV light than others. For example, a two-component epoxy coating will chalk rather rapidly under exposure to UV light, but formulations of acrylic aliphatic polyurethanes remain stable on UV light exposure. Inherent in most alkyd and oil-based products is poor resistance to UV exposure, which results in chalking, loss of gloss, and loss of color. However, modifications with silicone (i.e., silicone alkyds) can greatly enhance the performance characteristics of surfaces exposed to UV light. Modifying alkyds with silicone combines the workability of the alkyds with the durability, gloss retention, general weather resistance, and heat resistance of the silicones. Silicone alkyds are widely used as a maintenance upgrade finish over conventional alkyd coatings because of these improved properties. Silicone alkyds are used rather extensively for stack coatings and similar areas where moderately high temperatures are involved. USACE structures at which alkyds are used and improved gloss retention, weather resistance, and durability are desired should be considered for upgrades with silicone alkyd products.

(10) Impact/abrasion. Impact and abrasion resistance are extremely important characteristics in coating selection. Although impact and abrasion resistance frequently are discussed in the same breath, they can designate two different exposure environments. For example, a coating must resist rupturing from the rapid expansion of a metal as it is deformed from a sudden impact. To resist this type of impact, coatings must have a high degree of flexibility such as most formulations of a vinyl coating. Formulations of epoxies and polyurethane coatings are excellent choices for abrasion resistance, but the inherent brittle qualities of the

coating would cause it to fracture easily on impact. These coatings perform best where abrasion may be in the form of heavy equipment movement, foot traffic, or even scouring by tools and equipment. Abrasion also may be a result of naturally occurring phenomena, such as windblown sand or sand carried by waves of water. Consequently, it is extremely important for the coating specifier to determine if the exposure environment necessitates a coating that will withstand constant abrasion, sudden impact, or a combination of the two.

(11) Special exposures. Special exposure environments such as food processing and potable water may be subject to regulations of the Food and Drug Administration (FDA) and the National Sanitation Foundation (NSF). In addition to mixed exposure conditions, there most certainly will be extraneous circumstances such as inaccessibility and limitations on surface preparation methods. These situations could have a significant effect on coating system selection and should be thoroughly investigated prior to choosing a coating system. Sources of help for making decisions about these situations are discussed in the ensuing paragraph.

b. Identifying areas that cannot be properly coated.

(1) Many times due to design or configuration, structures, items, or areas to be coated do not readily lend themselves to proper surface preparation and coating application. This is particularly true with items designed with back-to-back angles or cavities and crevices that can result from riveted or bolted connections, weld undercutting, overlapping plates, skip welds, lap welds, etc. Essentially, any area that provides cavities or crevices in which air, moisture, dirt, or debris can become entrapped is a candidate for premature coating failure, unless properly sealed and/or caulked. Some initial design considerations such as full seal welding or alternative construction materials (i.e., fiberglass) could be used to avoid such problem areas. However, most structures are already built, and it would not be cost effective or practical to institute design changes. Consequently, caulks and sealants are widely used in many areas. For example, caulking compounds perform well when immersed in fuel oils, water, and chemicals. However, caution should be used when selecting caulks and sealants for immersion environments. Previous successful use in a given immersion environment should be an essential selection factor. Coating suppliers and manufacturers can be a good source of information about whether a particular caulk or sealant will provide good protection in atmospheric or immersion service environments.

(2) Recently, technological developments in the use of low viscosity, penetrating epoxy sealers make them practical for use in areas that are difficult to coat. These two-

component products are tolerant of poor surface preparation, produce minimal stress in the curing process, and are 100 percent solids. These products work with wicklike action, which penetrates and effectively seals off the hard to reach areas; and they can be applied by flooding the surface (with a garden-type low pressure sprayer), much like using a penetrating oil, and allowing the epoxy product to "wick in" and seal back-to-back angles and cavities. Products such as these are proving to be viable alternatives in lieu of, or in conjunction with, caulking compounds in atmospheric exposure.

c. Identifying regulated requirements. In addition to performance restrictions on coating types in various service environments, there are regulations on the type and amount of VOCs that can be emitted into the atmosphere. These regulations vary from state to state and even from county to county. Compliant coatings are being formulated with a higher solids content, less solvent, and with water as the solvent. Prior to specifying a coating, it is important to investigate national, state, local, and corporate regulations regarding the use of non-VOC-compliant coatings. The Clean Air Act and the Clean Air Act Amendments of 1990 are affecting the coatings industry by requiring the U.S. Environmental Protection Agency (USEPA) to restrict emissions of VOCs into the atmosphere. (Chapters 4 and 11 provide additional information.)

(1) Because of the emissions from coatings (solvents in particular can contribute to the formulation of ozone at low atmospheres), the USEPA has been directing the use of VOCs. Nationwide regulations are being developed to restrict the VOC content in architectural and industrial maintenance coatings for field applications. These restrictions list the maximum VOC per gallon of paint, and they vary according to the category of coating and its usage.

(2) Before specifying coatings for marine, architectural, or industrial use, the state and local bureaus of air pollution control should be contacted to determine the specific restrictions that may apply. Regulations may specify the maximum allowable VOC per gallon or the total number of gallons permitted to be applied per day or year. After the limitations are determined, the coating manufacturers can be consulted to determine the specific brands that are suitable for use. Note that when investigating acceptable coatings, it is the VOC "as applied" that counts rather than the VOC "in the can." For example, a solvent-based coating containing 419 g/L (3.5 lb/gal) VOC in the can that must be thinned 10 percent for application will exceed the 419 g/L (3.5 lb/gal) threshold at the time of application. If the local regulations restrict the use of materials to those containing 419 g/L (3.5 lb/gal), this coating could not be used.

d. Identifying surface preparation alternatives for new construction. Coating selection is influenced by the degree of surface preparation that can be achieved as well as by the method of coating application that may be allowed. Surface preparation usually is determined by the severity of the service environment (i.e., immersion, normal weathering, dry interior), the type of substrate, and the coating system. As a general rule, the more aggressive the environment is surrounding the item to be coated, the higher the degree of cleaning required. Cleanliness has a direct influence on adhesion and long-term service life. For example, in immersion service, a minimum acceptable surface cleanliness is generally in conformance with SSPC-SP 10, although SSPC-SP 5 is preferred. Cleanliness is only one factor in surface preparation. Profile or surface roughness also is a factor. A rule of thumb for profile or anchor pattern is that the depth of profile should be from one fourth to one third of the total coating thickness, up to a thickness of 0.30 mm (12 mils). For example, a coating system of 0.30 mm (12 mils) should be applied over a profile of from 0.07 to 0.10 mm (3 to 4 mils). The purpose of the profile is to allow for mechanical bonding of the coating to the surface. Profile actually increases the total amount of surface area wetted by the coating system. In new construction, there generally are few logistical limitations of blast cleaning, if the substrate is to be shop-prepared. However, because of the proximity to sensitive areas in the field, abrasive blast cleaning may not be allowed. The relative advantages and disadvantages of each procedure are discussed below. (See Chapter 7 for additional details on surface preparation.)

(1) Total field blast cleaning and painting of new steel. Blast cleaning and painting of new steel may be performed entirely in the field after erection, or they may be accomplished entirely in the shop. The primary advantage to total field blast cleaning and painting is that damage to the paint system prior to service is essentially eliminated. Total shop-applied systems may be damaged by handling and the installation/erection process or onsite repair procedures. Uncontrollable variables, such as weather and climate, often adversely affect field operations and eventually shop allocation if the shop is poorly equipped.

(a) Neither field blast cleaning nor painting may be performed during high humidity, rain, fog, haze, etc. Typically, paint specifications prohibit any work when the surface temperature of the steel is less than $-15\text{ }^{\circ}\text{C}$ ($5\text{ }^{\circ}\text{F}$) above the dew point. The influence of the dew point is more of a concern on coastal sites or in the cooler northwest and northeast sections of the country. If work is performed when the dew point is too high, the consequence may be flash rusting of the freshly cleaned steel, moisture entrapment between the paint and the substrate causing poor

adhesion, or moisture mixing with the freshly applied paint inhibiting proper curing. Conversely, extremely dry, arid conditions can present problems if the coating specified requires a certain amount of moisture in the air to properly cure (i.e., moisture cured urethanes and ethyl silicate type inorganic zinc-rich primers).

(b) Wind also may interfere with the field work by causing clouds of blast cleaning waste and overspray to drift onto the roadways, neighborhoods, and rivers. The liabilities incurred from drift on automobiles or into nearby residential neighborhoods may be substantial. Many specifications prohibit spray painting where wind speeds exceed a certain level or blow in a specific direction. Furthermore, on some days the wind is too strong to work from staging for safety reasons. Paint application by brush or roller can prevent drift; but it is slower, more labor intensive, and more expensive. In addition, not all paints readily lend themselves to application by brush or roller. This is especially true of some formulations of the high performance coatings such as vinyls, inorganic zinc-rich, acrylic urethanes, and other high-build high solids coatings.

(c) Temperature is another factor that may interfere with field work. The temperature of the steel after overnight cooling is less likely to be at least $-15\text{ }^{\circ}\text{C}$ ($5\text{ }^{\circ}\text{F}$) above the dew point. Many paints, especially epoxies, cannot be applied when the steel temperature is below $10\text{ }^{\circ}\text{C}$ ($50\text{ }^{\circ}\text{F}$), because the curing process is temperature dependent. Few paints can be safely applied at or near $0\text{ }^{\circ}\text{C}$ ($32\text{ }^{\circ}\text{F}$). Because low temperatures restrict coating application, it is impossible to blast clean or paint for months at a time in the northern areas where winters are severe. High temperatures, above $32\text{ }^{\circ}\text{C}$ ($90\text{ }^{\circ}\text{F}$), also can present problems by reducing coatings pot life or by causing solvents to flash off too rapidly. This results in incomplete film formation, poor wetting, dry spray, loss of gloss, and poor adhesion to the substrate because of poor wetting. Also, topcoats applied over inorganic zinc primers are more likely to bubble and pinhole at high temperatures.

(d) To blast clean and paint a structure in the field, the erection of extensive scaffolds and staging may be required. Staging may be an additional expense, and a subcontractor may be needed to erect the staging and coordinate scheduling arrangements. Staging may have to be moved a number of times before the job is completed. Blast cleaners and coating applicators have limited mobility and accessibility when work is done from staging or scaffolds. Such limitations decrease the amount of work performed and the production quality. Limited accessibility hampers the applicator as well as the inspector.

(e) There is a greater opportunity for surface

contamination when all of the blast cleaning and coating are performed in the field. Uncoated beams generally receive less care and may be dragged across the ground and/or be subjected to dirt or road salts in transit, and the beams may be exposed to coastal or industrial atmospheres at the jobsite. Contamination may occur on the steel or in between field-applied coats of paint. Steel contaminated with corrosive salts or anions is difficult, if not impossible, to thoroughly clean later.

(f) Health and environmental considerations related to blast cleaning in the field also must be evaluated. Current Occupational Safety and Health Administration (OSHA) guidelines require the contractor to take precaution to protect workers from exposure to free silica and nuisance dust during blast-cleaning operations. (See Chapters 10 and 11 for detailed information on these subjects.)

(2) Total shop cleaning and painting. Greater control over the working environment and easy accessibility to the entire surface are the principal advantages to performing work in the steel fabrication shop. Accessibility to all areas of the structural steel is greatly improved in the fabrication shop. The use of overhead cranes to manipulate pieces of steel reduces manpower requirements and virtually eliminates the need for scaffolding during the blast-cleaning and coating operations. However, the shop cleaning and priming procedure has drawbacks. A major drawback is that full-time inspection is rarely available, at least on small- and medium-sized fabricating jobs. Thus, shop inspection may be limited. Little can be determined concerning surface preparation and paint application after the work is done. Another major drawback is that shop coating results in a lengthened waiting period between priming and subsequent application of field coats. During this period the primer coat becomes hard and weathered, and it can become contaminated with dust, grease, and other surface soils that are detrimental to the adhesion of any subsequent coats. Long field storage periods tend to increase the opportunity for marring and scratching of the primer coat and, in extreme cases, may lead to its general deterioration. The paint application section of CWGS 09940 requires shop-coated steel to be stored out of contact with the ground and in a manner that will minimize the formation of water-holding pockets. This provision is considerably important. The shop coat of curved tainter gate sections field stored for months with concave surfaces up has on occasion deteriorated and rusted appreciably during storage as a result of water standing in the depressions. This is an understandable reaction because linseed oil paints are entirely unsuited for extended immersed exposure in a storage area. The guide specification additionally states that shop-coated steel shall be cleaned and repainted or touched up whenever it becomes necessary to maintain the integrity of the coating paint film; this requirement also is important.

In one known case, shop-coated steel was stored at the construction site for more than 18 months, and the provision to periodically touchup and repaint was not enforced. Consequently, at the time of erection the steel was in such poor condition that it required extensive cleaning and the application of a new primer coat, for which the contractor put in a claim for additional payment. This raises the question about what criteria should be used by field inspection personnel in determining if the shop coat needs touching up or a complete renewal. (Chapter 6 will be particularly helpful to inspection personnel in determining what type of corrective action is necessary.)

(a) Other shop problems and mishaps also have been observed. Air in heated shops warms more quickly than the steel surface; and, because the relative humidity increases as the air warms, condensation on the steel is possible. Paint is sometimes stored in a cold, unheated room and under such cool conditions can become very viscous. The resultant cold, thick coating may cause the applicator to thin the material excessively to reduce the viscosity and make it more sprayable. Excessive thinning reduces the volume solids of the coating and results in a lower dry film thickness and inadequate substrate protection.

(3) Shop primed plus field topcoated. A compromise may be found between accomplishing the work entirely in the field or entirely in the shop. This entails performing blast cleaning and applying the prime coat in the fabrication shop. The topcoat and any intermediate coats are applied in the field. This compromise includes the advantages from performing the work in the fabrication shop and the advantages with field application. Unfortunately, although there are advantages, such compromise is also not without shortcomings.

(a) The most obvious advantage to a compromise procedure is that the steel arrives at the jobsite with at least some degree of protection. Contamination of the steel substrate has not been eliminated because the prime coat may become contaminated while the steel is in transit to the site, in storage, or during construction. This is especially true if the steel is exposed to an industrial or coastal environment. Solvent wiping or high pressure washing of the prime coat prior to the application of further coats of paint may be specified to remove contaminants.

(b) Touchup of the prime coat generally is required to repair damage incurred in transit or during construction. Field welds, nuts, bolts, and areas around bolted connections also must be addressed. Surface preparation is vital. Some coatings (such as alkyds) may require only hand-tool cleaning; other coatings (i.e., zinc-rich coatings) require the type of surface preparation that can be achieved only by abrasive blast cleaning. Experience has shown that as much

as 30 percent of the surface area of water tanks often needs touchup, and some bridges may require only 10 percent touchup. Occasionally, the question arises about whether the responsibility for touchup lies with the fabricator or the contractor in the field, and how much touchup the responsible party should be required to perform. Accordingly, adequate field touchup should be clearly outlined in the project specification and understood by the parties responsible for the work.

e. Identifying surface preparation alternatives for maintenance. Based on the decision to maintenance paint an item or structure, several maintenance recoating alternatives may be considered: spot priming only, spot priming followed by full overcoating, or total removal and replacement. This paragraph will discuss the alternative methods of surface preparation that can be used in conjunction with these maintenance recoating methods. (See Chapters 6, 7, and 8 for additional information.)

(1) Spot priming only. Prior to spot priming, the mechanism of spot surface preparation and the cleanliness to be achieved must be determined. Spot preparation is required to remove localized areas of visible corrosion and/or loose, deteriorated, or poorly adherent coatings. Prior to general surface preparation, any grease and oil contaminating the surface should be removed by solvent cleaning in accordance with SSPC-SP 1. General surface preparation techniques such as abrasive blast cleaning and hand- or power-tool cleaning have a tendency to spread and/or redistribute grease and oil on the surface rather than removing it. Spot removal of loose coating, loose rust, and loose mill scale can be accomplished by hand- or power-tool cleaning or spot abrasive blast cleaning.

(2) Spot priming followed by full overcoating.

(a) The mechanisms of spot surface preparation given in the previous paragraph can be used if this recoating alternative is chosen. However, the method of preparing intact, well adherent coatings for overcoating must be addressed. The primary concern in overcoating an existing coating system would be system compatibility. The compatibility of recoating systems could be assessed by preparing a test patch. After an overcoating system is found to be compatible with the existing coatings, methods should be used to remove surface dirt, chalk, grease, oil, and other surface contaminants. These methods include solvent cleaning, pressure cleaning with detergent at less than 34,450 kiloPascals (kPa) (5,000 psi), high pressure water jetting with detergent (34,450 to 137,800 kPa [5,000 to 20,000 psi]), high pressure water cleaning (34,450 to 137,800 kPa [5,000 to 20,000 psi]) with abrasive injection, ultra-high pressure water jetting (137,800 to 275,600 kPa

[20,000 to 40,000 psi]) with abrasive injection, or brush-off blast cleaning using fine sand and low abrasive blasting pressures.

(b) Glossy, hard, smooth, or slick existing coating systems may require roughening to promote adequate adhesion. Hand- or power-tool roughening of the existing coating may be done by using hand- or power-tool methods such as sanding. The surface gloss must be removed and the visible surface roughened after preparation. Brush off blast cleaning (SSPC-SP 7) also may be used to clean and roughen the existing coating using the methods outlined here.

(3) Complete removal and replacement. If the recoating decision process has found that the most economical and practical option is complete removal and replacement of the existing coating, the following surface preparation methods may be used. These alternatives in conjunction with the desired surface cleanliness will produce a substrate that essentially can be recoated as a "new" surface. Standard abrasive blast cleaning, high pressure water jetting with abrasive injection, ultra-high pressure water jetting with abrasive injection, or wet abrasive blast cleaning to the desired cleanliness may be used to completely remove the existing coating. When blast cleaning cannot be used, power-tool cleaning to bare metal (SSPC-SP 11) can be used to remove old coatings.

f. Identifying coating application alternatives. In addition to surface preparation alternatives, coating application alternatives should be explored. Local regulations on spray application of coatings (proximity to roads/highways, parking lots, residential areas) may restrict the application method used. Brush or roller applications may be required, which may restrict the choice of coating system used because certain coating systems do not lend themselves to application methods other than spray (e.g., vinyls, inorganic zinc-rich primers). Some coatings (referred to as "dry falls") are formulated so the overspray during atomization dries prior to landing on an undesirable resting place.

g. Cathodic protection system as an alternative. The primary function of cathodic protection and coatings is to prevent corrosion. As corrosion protection has become more critical, a marriage of the two processes has occurred. Experience has shown that damage to organically coated surfaces is almost unavoidable during construction and in service. Cathodic protection frequently is used in conjunction with coating systems and immersion service where breaks and holidays in the coating expose an unprotected metal substrate. Protecting some structures in these environments may be difficult, if not impossible, with

coating systems alone, especially on complex, configured structures. Thus, the combination of coatings and cathodic protection actually provides good, reliable corrosion protection. USACE has found cathodic protection systems in conjunction with CTE systems to be excellent choices in this regard. (Detailed information on cathodic protection is given in Chapter 2.)

5-3. Coating Selection Criteria

The final selection criterion is to determine how effective the coating system will be in preventing corrosion of the underlying surface in the service environment. Clearly and accurately defining the service environment, soliciting coating manufacturers' recommendations, applying test patches of candidate coating systems in the service environment, and obtaining a successful field history of a generic coating system in an identical or similar service environment will enable the coating specifier to select the coating system that will provide long-term protection of the plant and/or facilities.

a. Supplier recommendation. Major manufacturers of coatings and coating systems typically have invaluable information on application parameters of their coating systems, both in terms of temperature restrictions and chemical resistance. Therefore, the suppliers of coating systems should be asked about information on the types of products that will perform in the service environment(s) identified. However, most manufacturers do not have exhaustive information on every service environment that may be encountered; and previous experience with a given coating system in a certain environment may not always be available. Also, some suppliers may not have information because they are not familiar with Government specification paints unless they are actual producers of them. In these instances, a test patch applied and evaluated in accordance with ASTM D5064 at the location of intended service is highly recommended prior to large-scale application.

b. Ease of application. The ease with which the coating can be applied will impact applicator productivity and coating film integrity. That is, if a coating material cannot be applied without complicated equipment and specialized techniques to produce a continuous, void-free film, it may not be cost effective to apply such a system unless, of course, the service exposure demands such a system. Therefore, ease of application should be an important consideration during coating system selection.

c. Maintainability. The maintainability of a coating system is another factor to be considered, and how it will be maintained (by outside contractor or by plant personnel). If plant personnel are responsible for coating system

maintenance, it is imperative that they be familiar with any specialized equipment or application techniques and properly trained in their use. The surface preparation that will be required during maintenance painting also must be considered. It may be as simple as a solvent wipe (SSPC-SP 1) and reapplication, or as extensive as scarification (SSPC-SP 3 or SP 11) or abrasive blast cleaning of the surface followed by application of the repair system.

d. Cost. Appropriate coatings systems selection must take into account paint performance as well as paint economics and balance performance against total cost. Top quality coatings should be compared generically, but identification by generic name in itself is no guarantee of quality. Coatings should be purchased on specifications from reliable coating manufacturers. A protective coating should not be purchased unless its volume solids content and the resin content of the solids are known. Economics plays a key part in selecting a coating system. In fact, under some circumstances, economics may determine the system choice. Therefore, coating costs, in most instances, should be less important than the coating properties that provide the basis for long-term, effective coating protection. Costs should be considered only after the coating or coatings have been selected that will satisfactorily overcome the corrosion problem for which they will be used. For example, during the selection process, two or three coatings all may have the necessary qualifications. Cost then can determine which of the coatings that entirely satisfy the conditions involved will be the most economical choice. Additionally, the cost of the coating system depends on the generic type, the spread rate, the ease of application, maintainability, and projected service life of the system. When choosing the most economical coating system, factors for determining this suitability may include the following.

(1) Environmental resistance. Coatings will be cost effective only if they are used within the limits of their environmental resistance. If an environment is too severe for a coating, that coating will require expensive maintenance, and a different coating material or construction material should be used.

(2) Duration of protection desired. Most coating materials will deteriorate because of their organic or sacrificial nature, and they will require maintenance and periodic renewal. The length of time required for refurbishment may be less in some environments than in others. The cost and difficulty of refurbishment or replacement must be assessed to arrive at the appropriate coating or construction material.

(3) Surface preparation required/allowed. Most coating

systems must be applied over a relatively clean substrate such as that obtained by blast cleaning, grinding, or acid etching. If the required surface preparation is not economical, the use of other construction materials may be more cost effective (i.e., stainless steel, plastics).

(4) Application/curing conditions. If ambient conditions cannot be made suitable for the application and/or cure of the coating system, other means of corrosion protection must be considered (i.e., cathodic protection).

(5) Availability of labor/material. The application of coatings is labor-intensive, and if sufficiently skilled equipment or labor is not available, the cost effectiveness of using protective coatings may be reduced.

(6) Health and safety considerations. Solvents, resins, and certain pigments in coatings may be hazardous to personnel applying the protective coating or the safety and health of personnel in the surrounding area. Safety, health, and environmental considerations at the time of original application and during touchup and repair may be sufficient to reduce the cost effectiveness of coatings compared to other construction materials.

(7) Mobilization/demobilization. There are costs associated with bringing equipment, material, and labor to a jobsite. The costs for transportation and setup of equipment are commonly called mobilization costs. The costs to remove equipment and material from a jobsite are called demobilization costs. These costs can be considerable on large projects, and they must be considered in assessing the costs of a coatings operation. For fixed-site coating facilities (i.e., paint shop) the item to be coated must be transported to and from the shop. These costs may be significant and should be included in cost estimates.

(8) Access costs. The cost of rigging, scaffolding, or otherwise gaining access to the work area can be expensive, particularly when coating a large bridge, water tank, or elevated structure.

(9) Preparation costs. Prior to actually starting surface preparation and/or coating work, certain preparation costs must be assessed. The cost to mask or otherwise protect items not to be painted, to grind or round sharp edges, to enclose the work area, or to protect adjacent work areas or the environment can all be considered preparation costs.

(10) Coating system installation costs.

(a) Coating material costs. Coatings are usually supplied in 1-, 5-, or sometimes 55-gallon containers, and they generally are invoiced at a dollar cost per gallon. These

costs may be considerable on a large job; and, as a rule of thumb, they range from 10 to 15 percent of the cost of the total jobs. However, the coating material cost may be a substantially higher percentage of the total cost if other costs (i.e., surface preparation) are minimal. Rather than the cost per gallon, some specifiers consider the system cost per square foot (i.e., the cost to cover a given area at the required film thickness). Thus, a coating system that builds to a greater thickness in one coat, or has a higher percent solids by volume, ultimately may be cheaper even if the cost per gallon is higher than another material. In this case, application labor would be saved because fewer coats would be required to attain a given thickness. Other specifiers consider cost per year of service life. The evaluation incorporates the expected service life of the coating system in the assessment of its cost. Therefore, a coating that costs \$10 per gallon and lasts for a year will be more expensive than a coating that costs \$20 per gallon but lasts for 5 years. The most comprehensive assessments consider the system cost square foot per year and try to optimize both application savings and service life longevity.

(b) Coating application costs. Labor time associated with the actual application of the coating must be considered. The number of coats required is a major factor in establishing this cost as each coat application is a separate operation. The cost of application labor is a major expense on most jobs, usually second only to the surface preparation.

(c) Surface preparation costs. The labor cost of surface preparation is a major consideration for all coating work. The costs for surface preparation can vary considerably, depending on the method and the extent of surface preparation requirements. As a general rule, when blast cleaning or using other thorough degrees of surface preparation, the costs of labor and equipment may approach 40 to 50 percent of the entire cost of the project. The surface preparation required usually is determined by type of coating system chosen for application. Some coating systems (i.e., vinyl, inorganic zinc rich) require thorough, labor intensive surface preparation such as that by blast cleaning to "White" or "Near White" metal cleanliness; other coating systems are more tolerant (i.e., epoxy mastics) and may not require as thorough, or as expensive, a degree of surface preparation. However, the service life of virtually all coatings is increased by a greater surface cleanliness.

(d) Equipment costs. The cost of wear and tear on surface preparation equipment and application tools and equipment (including operational and maintenance costs) must be considered. Rental rates that can be used as a guideline for equipment costs frequently can be obtained from equipment rental companies.

(e) Curing/drying considerations. Some coatings require an extended cure time prior to being placed in service. Heat curing may be required for certain coatings used as tank linings. If required, special curing conditions may increase the cost of the coating system.

(f) Trade or craft interference/downtime. The coating application process (e.g., surface preparation) is time consuming and may require traffic control, stoppage of operating equipment, or downtime in the immediate vicinity of the work area. Also, nearby workers may object to the noise, odors, and potential hazards associated with the coating operations. Those indirect costs also should be evaluated when considering coating work costs.

(g) Environmental/health and safety costs. Environmental, health, and safety factors are extremely important and may be difficult to assess, but potentially they can be expensive. The Federal Government, most states, and many local communities have strict environmental laws that must be obeyed. Similarly, in the area of worker protection, OSHA requirements must be obeyed on any painting job. The cost of compliance during field painting may be high in comparison to another construction material or another means of corrosion protection. Compliance may be easier during painting in the shop as opposed to painting in the field. Compliance considerations ultimately may be among the most important cost considerations. Environmental protection costs can be as much as, or more than, all of the other costs combined. (Chapters 10 and 11 provide additional information on this subject.)

(h) Indirect costs. Painting projects, as is true with most other construction or maintenance projects, must be properly planned and require specifications, proper management, and adequate inspection to ensure specification conformance. Although these costs also must be considered when evaluating other methods of corrosion protection, they are vital considerations for all coating projects.

(11) Cost estimation and decision making. Preparing accurate estimates of the cost of painting is not easy, and even professional estimators working for painting contractors sometimes estimate inaccurately. Most cost estimates are based on one or more of the following: an estimation of the surface area to be painted, an estimation of costs per unit surface area, an estimation of the man-hours required, and an estimate of the materials and equipment costs.

(a) Surface area to be painted. The surface areas of each item to be painted are measured or estimated, and the cost of painting per unit area (i.e., a square foot) is then applied to achieve a total painting cost. For example, if an area to be painted has a number of pipes of various diameters,

doors, windows, floors, pieces of equipment (e.g., tanks, pump housings, fans, and motors), structural steel, and overhead truss work, the total surface area of each of these items would be estimated or measured. Books and tables are available for estimators to use when making unit area (square foot) calculations. The Painting and Decorating Contractors of America (PDCA) estimating guide provides tables for calculating unit areas in square feet as well as labor rate figures for coating each of these unit areas. After the square footage has been calculated, the time required to conduct surface preparation and/or paint application also must be calculated for each unit area for each category of work (i.e., speed at which a wall or floor can be coated might be entirely different than the rate for coating a series of 76-mm [3-in.] pipes). Thus, appropriate labor rates for each work item should be applied to the unit area of that work item. The cost for unit area multiplied by the total area within each category provides the total cost of painting when all categories are summed.

(b) Man-hour estimates. Many nonpainting operations are part of the overall costs of coating work. For example, mobilization/demobilization, rigging and scaffolding, time for inspection, time for cleanup, and time for equipment maintenance all must be considered when estimating costs. These costs usually are estimated in man-hours or man-days by the estimator. By knowing the particulars of the project, including its size, shape, completion date, and areas to be coated, the estimator can approximate the size of the crew and the equipment required. With this information, a knowledgeable estimator will prepare a schedule sequencing a work order for the job. The work order will indicate when moves must be made from one area to another during the course of the work. The nonproductive costs associated with each move (i.e., transported equipment, rigging, or scaffolding) then can be estimated for each move and applied to the total job costs. Similarly, during the painting operations, other costs (for inspection, cleanup, touchup of defective or damaged areas, maintenance of equipment, etc.) also should be included. These costs usually are estimated in man-hours per unit operation. The estimator evaluates the work to be done and estimates the man-hours needed to complete it. The surface area being painted is not calculated.

(c) Wage rate. The wage rate of most workers usually is known, but the speed at which they work is difficult to estimate. Estimates of labor rates are in estimating guides; however, most painting contractors and experienced coating estimators know by experience what work productivity rates are. Most painting contractors and professional estimators use their own labor rates and do not rely on estimating guides. However, most specifiers use the labor rates presented in estimating guides.

(d) Cost of materials and equipment. The number of gallons of paint, thinner, cleanup solvents, etc., must be estimated, based on the square footage of the areas being coated and estimated loss factors during the course of application. Material loss factors, including overspray and materials remaining in the can, generally range from 20 to 50 percent of the total paint purchased, depending on weather conditions and the type of surface being coated. Based on these estimates, the total amount of paint to be ordered and used on a job can be calculated. The cost of the equipment used on a job also must be estimated and might include charges for the use of compressors, spray guns, airless or conventional spray pots or guns, air and paint hoses, etc. Fuel costs for diesel compressors and electrical generators (if required) also must be estimated. Most painting contractors have developed standard cost estimates for items such as diesel fuel and electrical consumption and can estimate these rates on a daily, weekly, or monthly basis. These equipment/material costs must be factored into the cost of painting. The cost of consumable supplies and equipment must be estimated; abrasives, cleaning rags and cloths, respirators or respirator cartridges, overalls or protective clothing, masking tape, and small tools such as scrapers or wire brushes are all considered expendable consumable items. The cost of these items must be estimated and applied to the total cost of the job. When each cost category is properly estimated and totaled, the comprehensive budget estimate for the painting job can be made. Costs for overhead, insurance, licenses, taxes, etc. must be added to the direct cost to arrive at a total cost.

(12) Alternate ways to prepare coating budgets. Rather than taking the time and making the effort to detail the costs of a painting project as described here, many estimators budget coating work by other means. These estimates are generally less accurate and may be subject to some bias. The accurate determination of painting costs is important to management's decision to provide budget funds for painting operations. Some commonly used budgeting techniques are given here:

(a) Budget estimates for the current year based on the cost of painting conducted in the previous year. Budget estimates may be allocated on a "total funds" concept whereby a certain percentage of maintenance funds are attributed to maintenance painting.

(b) Funding allocations—whether new construction or maintenance painting—only a certain amount of funding is set aside for coating work. No real budget estimates are made, and work is done by either a contractor or in-house plant painting force until the funds are depleted.

(c) Contractor estimates—items or areas to be painted are determined, then one or more painting contractors are asked to provide a cost estimate to conduct the painting work.

(d) Single-source painting programs—some coating manufacturers and independent coating consultants have established single source painting programs whereby a contract is extended to the plant or facility owner (usually at a certain cost per year over a multiyear period). For the contracted cost, a complete painting program is established, and all painting work is conducted. Detailed budget estimates are made by the single-source contractor rather than the facility owner. The facility owner is given an annual cost amount for painting to include in his maintenance budget.

(e) No budget estimate—some owners do not prepare budgets but contract with a friendly local painter or use their own work force to paint on an "as needed" basis. Costs are invoiced, usually on a monthly or weekly basis. At the end of the painting season, the amount expended for painting work can be totaled.

(13) Life cycle costs of coating systems. Accurate budget estimates should be made for each of the corrosion protection methods to be considered. The budget estimates should include costs for the initial work as well as for all future maintenance activities to obtain a "life cycle" cost. For example, initially the cost of installing a stainless-steel-clad lining to a tank may be twice as much as painting the tank, but over a 20-year expected life there may be no maintenance costs. So although it may cost half as much to paint the tank interior as to use a stainless-steel lining, the tank will need to be repainted every 5 years. Thus, over a 20-year-life cycle of the tank, it will cost twice as much to paint the tank as it would to protect it with a stainless-steel cladding. However, when cash flow is slow, painting may be the most economical means of corrosion protection. If a decision to paint is made, a hope may be that future cash flow or profitability will improve and enable the payment of expected higher future maintenance costs. Factors involved in decision making are complex and specific, and they vary considerably because of return on investment strategies, tax considerations, cash flow availabilities, potential for technological advancement, legislative restrictions and marketing, or sales analyses. However, the costs of corrosion prevention alternatives (including painting) must be estimated properly to provide management with the proper tools to make a prudent decision. Thus, there are many alternatives available to the informed engineer to protect a structure. Ultimately, however, the economic selection of a particular system involves two criteria:

duration of effective protection and costs to obtain effective protection.

(14) Estimating the duration of protection.

(a) The length of protection of a properly selected and applied protective coating system will depend on the corrosive environment. Specific coating recommendations for a given environment can be subclassified as subjective and objective. The problem with subjective recommendations is one of credibility—whom to believe. The experience and biases of a person making the statement must be considered prior to accepting a solution to the problem. A subjective recommendation may be satisfactory for most small painting jobs or industrial application for which little money will be expended. However, for large jobs when substantial funds will be expended, or the consequences of failure will be serious, misinformation may be costly. As a result, evaluation of protective coatings using an objective approach may be desired. Objective evaluations of the protective life of a coating system are based on the observation of actual performance of coating systems in a given environment. If properly conducted, empirical evaluations generally are considered more accurate and usually provide the basis for knowledgeable recommendations. Objective empirical testing for convenience can be subcategorized into laboratory testing and field testing.

(b) Laboratory testing consists of standardized tests involving various atmospheric or immersion test chambers and devices for measuring flexibility, extensibility, adhesion, scratch or impact resistance, and other coating characteristics. Field testing involves coatings exposed in a nonlaboratory corrosive environment; examples are test sections on a bridge or water tank or coated test panels placed in various corrosive environments. Generally, laboratory testing precedes any field testing. During the course of either laboratory or field testing, the coating being tested is observed to determine its mode and rate of failure.

(c) Laboratory tests frequently are designed to accelerate failure conditions found in the field to reduce the time of coating failure to a reasonable period (usually about 30 to 60 days). Acceleration usually is accomplished by increasing the exposure extremes or increasing the frequency of exposure to corrosive elements (such as salt fog cabinets and weathering cabinets in which a cycling exposure of water and UV light repeats every hour or so). Both the exposure extreme and the frequency of exposure may be combined in one test (such as reagent or immersion tests for coatings that in service are not expected to withstand strong chemical or immersion conditions). These tests will give a “ranking of performance” and provide a screening, but not necessarily a “duration of protection.” Generally, the best

performing coating specimen in a laboratory test series will also perform well in actual use. However, this is not always a valid assumption. Actual field testing is often the preferred and most accurate method to provide an estimate of duration of protection, which is generally expressed in months or years.

(d) Most field tests are not accelerated tests but are coating exposures in the actual (or similar) service environment in which the coating is expected to be used. Therefore, failure is not accelerated. Coating systems being tested will deteriorate at the same rate as the coating will be expected to deteriorate in actual service under the same conditions. Field tests may not be fully representative of field conditions if there are environmental changes, mechanical or flexural influences, and other factors that are not adequately induced into the test protocol. Because coating systems for atmospheric exposure protect for 15 years or more, real time testing to “failure” is not practical. However, close observation of candidate coatings and their comparative rate of degradation will enable selection of the best coatings prior to complete failure. This observation is commonly done in field testing and when using test panels. Suitable selection criterion can be obtained within 6 to 24 months for many systems. The best method of determining the extent and duration of protection is to observe and record the failure history of a given system in actual use. If care is taken and proper records are kept, this determination can and should be done for every protection system in use. Unfortunately, information thus obtained often becomes obsolete as superior coatings and protective methods become available and technology advances.

5-4. Service Environments for USACE Structures

Of primary importance in coating selection is the degree of surface cleanliness. Proper surface preparation is necessary to create a satisfactory level of adhesion between the applied coating system and the substrate. Adhesion is a key characteristic affecting coating performance. Various generic coating types may achieve adhesion by different methods. For example, the coating may form a protective thin film by merely lying on the surface, or there may be a chemical reaction with the substrate. Good coating adhesion is an essential coating characteristic and becomes even more important as the aggressiveness of the exposure environment increases. When properly applied, a coating’s rate of success is directly in proportion to its adhesive bond strength. As a result, various USACE exposure environments will be discussed below with regard to the minimum surface preparations required to provide adequate adhesion for the various exposures. Four exposure environments can be used to categorize a vast majority of

USACE painting projects: interior; atmospheric, normal weathering; atmospheric, severe weathering; and immersion or frequent wetting by splash, spray, or condensation from fresh or salt water. Although immersion and frequent wetting initially may appear to be different exposures, experience shows that, generally, the same generic coating systems are successfully used in both exposures. The information on selecting a coating system discussed earlier in this chapter will be particularly helpful in identifying coatings that will perform well in these exposures.

a. Interior exposure. Interior surfaces are classified as those that are located within weather-tight structures and are not exposed to atmospheric elements. Although the majority of these exposures are mild, there may be circumstances under which conditions may alter an environment and a more corrosion-resistant coating may be required. For example, unanticipated leakage or equipment malfunctions may result in added environmental stresses, such as condensating moisture or high humidity within an otherwise “normal” environment. Additionally, areas or items that, for various reasons, may become inaccessible after installation or construction should be carefully coated to assure that a coating system for adequate long-term protection is applied. Interior exposure is the mildest exposure environment a coating will encounter. Products used on interior surfaces may be used for aesthetics or decorative purposes only. However, in some instances a coating system must be able to perform in areas of frequent cleaning and scrubbing (i.e., high traffic areas, restrooms). Generally, there are restrictions on the type of preparations that can be performed indoors. There are few, if any, extraneous influences that could stress a coating under circumstances to adversely affect adhesion. However, care must be taken to choose coating systems that are compatible with each other and the substrate to which they are applied. Particular assistance in this regard is discussed in Chapter 4.

b. Atmospheric, normal weathering. Weather resistance is the key variable in atmospheric exposures, but this environment can be extremely complex. A coating in atmospheric exposure must be capable of withstanding a variety of conditions that include cyclic heating and cooling, airborne contamination, alternate wetting and drying, UV resistance, and maximum exposure to the deteriorating effects of oxidation. Exposures also may vary from hot, dry climates and humid, tropical environments to constantly cool or cold climates. Therefore, a coating system capable of withstanding a variety of exposure conditions is essential. With strong adhesion qualities, the coating can withstand most environmental stresses that otherwise would affect its integrity.

c. Atmospheric, severe exposure. A salt-laden marine

environment or a heavily contaminated industrial exposure is extremely corrosive. Coatings with increased resistance to these environmental conditions are required. These types of exposure conditions are considered to be moderate to severely corrosive to a coating system, and coating systems must be selected accordingly.

(1) When a weathering environment becomes further complicated by the addition of severe exposure elements (e.g., corrosive chemicals, high humidity, severe abrasion, or salt conditions), more sophisticated surface preparation techniques must be used. These added exposure elements will stress the coating system at the point of weakest adhesion. The coating must exhibit good adhesion, and a high order of coating resistance will be required (e.g., a two-part epoxy or urethane coating). As the service demands on a coating system become greater, so does the need for more thorough surface preparation. Abrasive blast cleaning is required to achieve optimal cleanliness and adhesion.

(2) New generation two-part surface tolerant epoxy mastic coatings are gaining rapid acceptance in severe atmospheric exposures. Technological advances within the protective coating industry have brought about development of coatings that exhibit excellent surface wetting characteristics, rust inhibition, abrasion resistance, and chemical resistance. These mastics can be applied to marginally prepared surfaces, such as hand-tool or power-tool cleaning, and show improved service life in situations in which abrasive blast cleaning may not be feasible. Although epoxy mastics provide improved performance, they do not perform as well as equivalent paints applied to a higher degree of surface preparation. As a general rule, the more severe the environment encountered, the more resistant the coating must be; consequently, the more precise the surface preparation requirement becomes.

d. Immersion or frequent wetting exposure.

(1) Most immersion or frequent wetting of USACE structures involves exposure to fresh water or seawater. The effect of water on most coating materials is extremely severe. Resistance to water is perhaps the most important coating characteristic because all coatings come into contact with moisture in one form or another. Water, which affects all organic materials in some way, is actually close to being a universal solvent. Therefore, no one coating system can be effective under all water conditions. For example, dam gates and trash racks may require a coating system different from that of the flume bringing water into the dam. Additionally, different types of water may be encountered, such as deionized acidic or sulfide water. Highly conductive water, such as seawater, leads to rapid formation

of anode/cathode areas on the steel that result in severe pitting. The rate of corrosion is proportional to the amount of oxygen in the water; water with a high oxygen content will create similar anode cathode corrosion areas. Therefore, no single type of material will provide a universal answer to coating problems. The water molecule is extremely small and has the ability to penetrate into and through most inorganic compounds. The water molecule passes through the intermolecular spaces of the organic material and either can remain there in an absorbed state or can pass through the compound. Moisture generally will come to an equilibrium, with as many water molecules passing into the organic material as evaporating out of the surface. So a relatively constant water content is maintained in the organic material, depending on the moisture vapor at any given time.

(2) Because of this highly penetrating characteristic, water has more of an effect on organic compounds than any other material. Because most coatings are organic in nature, they must have the highest possible moisture resistance to maintain their properties and provide their structure with a long period of corrosion protection. For a high performance, corrosion-resistant coating to have a water resistance, it must withstand continuous immersion in water or seawater, and it must do so without blistering, cracking, softening, swelling, or loss of adhesion. It also must withstand repeated cycles of wet and dry conditions and abrasion from floating ice and debris. Coatings tend to absorb and retain water in their molecular spaces, and each coating has a level of water absorption. If a coating is strongly adhesive and there is no interface between the coating and the substrate, the moisture will remain in a relatively inert state. At any given moisture pressure, as many molecules leave the coating as enter it. Thus, the best corrosion-resistant coatings generally have the lowest water absorption rates (e.g., CTEs, vinyls, and inorganic, zinc-rich coatings).

(3) The moisture vapor transfer rate is the rate at which moisture vapor transfers a protective coating when there is a difference in moisture vapor pressure on one side of the coating compared to the other side. Each coating also has a characteristic moisture vapor transfer rate. Generally, the lower the moisture vapor transfer rate, the better the protection provided by a corrosion-resistant coating. The transfer of moisture through a coating depends on the difference in pressure between the two sides of the coating. There is no difference in pressure from one side to the other if the coating has excellent adhesion, and the coating soon comes to equilibrium with the moisture in the air or the water in the surface of the coating. The water molecules penetrate into the coating and are absorbed while an equivalent number are evaporated from the coating, so the amount of moisture in the coating remains constant.

(4) If the coating has poor adhesion, either inherently or because it has been applied over a contaminated surface, there is an interface between the coating and the steel (as in dam gates and trash racks) and moisture vapor can transfer into this area. Soon after the coating is applied, there is little moisture vapor pressure on the interface area, so there is a tendency for moisture to pass in the direction of the poor adhesion. Moisture can condense in this space or, if the temperature of the coating increases, the moisture vapor within the void can develop sufficient pressure to create a blister. With poor adhesion, the moisture vapor can penetrate between the steel and the coating, expanding the blister.

(5) The primary requirements for coating to be used for immersion are good adhesion and resistance to moisture vapor transfer, ionic penetration, osmosis, chemicals, cathodic disbondment, and variations in temperature. Snow water, distilled water, or deionized water are close to if not the most penetrating of all the chemicals in which a coating is immersed. But, as the content of the water is increased it becomes more aggressive; primarily because it is much more conductive and corrosion can take place at a much more rapid rate. Although it is commonly known that seawater is aggressive, polluted fresh water may be more destructive to coatings than some seawater. When choosing a coating system for an immersion environment, the conditions should be precisely determined prior to selection. Even solutions with minor contaminants that were scarce enough to be deemed unimportant have caused many coating failures in immersion conditions.

(6) Protecting metallic structures immersed in fresh water is a complex problem. However, when the additional corrosive elements in seawater become apparent, the destructive magnitude of this exposure environment becomes considerably more intricate and complex. Structures immersed in seawater, like their freshwater counterparts, naturally experience multiple exposure environments. The salinity of seawater and its associated high electrical conductivity, along with the surface growth organisms, greatly contribute to the overall corrosivity of seawater. These organisms become destructive when they attach themselves to, and physically penetrate into, a coating film. This growth process is commonly known as fouling; coatings developed to prevent or inhibit this process are called antifoulants. Unfortunately antifoulant coatings are not formulated with exceptionally long service lives, primarily because they are used to prevent marine organisms from fouling on smooth and regular surfaces of ships at rest. Since ships are frequently dry docked, and cleaning and repainting operations can take place, the need for antifoulant coatings with an extended service life is not necessary. Initially, antifoulants would appear to be a logical system choice for USACE structures with similar exposures.

However, on closer examination and through experience with questionable performance of antifoulants applied to irregularly shaped fixed structures (such as gates), this system option has not proven to be highly successful. Therefore, choosing antifoulant paints as a coating system for some USACE structures should be carefully considered. A discussion of coating systems for structures immersed in seawater would be remiss if it did not also reference splash zone or surfaces continually wet by well aerated seawater. Experience has shown that paint films normally deteriorate more rapidly in splash zones than in other zones, primarily because the abundance of oxygen fuels the corrosion process.

(7) Coating systems applied in such environments as immersion or frequent wetting exposures require a high degree of surface preparation. The minimum requirement is generally that presented in SSPC-SP 5. All forms of surface contamination, including possible chloride contamination from salt water, must be removed, and coatings formulated for the required immersion resistance need to be used. Coatings that typically perform well in immersion or frequent wetting exposures are discussed in Chapter 4.

5-5. Coating System Selection for Ferrous Components in Fresh Water

a. Ferrous metal components.

(1) Current alkyd coating systems required in CWGS 09940 (systems 1 and 2) are: alkyd primer/phenolic aluminum paint (two coats), rust-inhibitive linseed oil and alkyd primer (two coats), and rust-inhibitive linseed oil and alkyd primer/alkyd gloss enamel (two coats). Because these coating systems are for mild interior exposures and basically consist of primer only formulations, they are readily touched up. Surface preparation may be performed by hand- or power-tool cleaning.

(2) Candidate maintenance systems would be new technology versions of direct-to-metal (DTM) 100 percent acrylic waterborne industrial coatings and higher solid VOC-compliant alkyd primer systems.

b. Ferrous metal components subject to atmospheric weathering—normal.

(1) Current coating systems. Current alkyd coating systems required in CWGS 09940 (systems 1 and 2) are: linseed oil primer/phenolic aluminum (two coats) and linseed oil and alkyd primer/phenolic aluminum (two coats). In this normal atmospheric weathering exposure, many

formulations of alkyd generic coatings would perform satisfactorily.

(2) Candidate maintenance systems. Candidate maintenance systems would be high solids VOC-compliant lead- and chromate-free versions of alkyd primers and finish coats. Most existing alkyd systems can be successfully recoated with long oil alkyd resin systems. Additionally, DTM waterborne, 100 percent acrylic primers and finishes are successful in overcoating existing or aged alkyd systems. New generation acrylics provide more superior gloss retention, color retention, flexibility, and weatherability than traditional alkyd systems. Water-reducible alkyd systems also have found market acceptance; however, their performance characteristics do not rival those of DTM acrylics.

(3) Candidate systems for new steel. Candidate systems for new steel would be high solids VOC-compliant versions of exterior alkyds both waterborne and solvent reducible. Strong competitors to the traditional alkyd systems are the new generation waterborne acrylic industrial primers and finish coatings. Much like their alkyd counterparts, waterborne acrylic coatings are easy to apply and relatively inexpensive, but have the added advantages of improved gloss retention, weatherability, and low odor.

(4) Special concerns and cautions. Portions of these alkyd coatings applications will be done in the shop. Surface preparation for a normal atmospheric weathering exposure is commonly accomplished by complying with SSPC-SP 1, SSPC-SP 2, or SSPC-SP 3. Of primary concern is that these ferrous metal components are often shop-primed and placed in storage for an extended period prior to final erection and finish coating. Untopcoated, these primers do not possess good weatherability; therefore, appropriate precautions must be taken to properly protect the structure while in storage. Adequate protective coverings to protect from moisture and debris accumulation on the substrate are necessary. Additionally, proper blocking and stacking techniques should be used to avoid ground contact in storage. Prior to erection and before finish coating, a careful inspection will be necessary to identify deficiencies (such as prime coat handling or erection damage) and for preparation and touchup as appropriate.

c. Ferrous metal components subject to atmospheric weathering—severe.

(1) Current coating systems. Current alkyd coating systems required in CWGS 09940 (systems 1 and 2) are: linseed oil primer/phenolic aluminum (two coats) and linseed oil and alkyd primer/phenolic aluminum (two coats).

Other systems would be those as identified in 5-5*b* above, with the special concerns and cautions identified in item 5-5*c*(4) below.

(2) Candidate maintenance systems. Candidate maintenance systems would be those described in 5-5*b* above, with special concerns and cautions as identified in 5-5*c*(4) below.

(3) Candidate systems for new steel. Candidate systems for new steel would be those previously described in 5-5*b* above, with the special concerns and cautions as identified in 5-5*c*(4) below being applicable.

(4) Special concerns and cautions.

(a) The anticipated difference between normal weathering and severe weathering environments generally does not necessitate changing the coating systems. Traditionally, systems that perform well in “Atmospheric Weathering—Normal” environments also will perform under these “Atmospheric Weathering—Severe” exposures. However, the longevity of the system may shorten. Consequently, several options can be used within these normal and/or severe atmospheric weathering environments to improve system service life, e.g., improving the surface cleanliness or applying additional coats of paint. For example, applying a second coat of primer or another finish coat would improve the protective quality of the coating. Additionally, surface preparation may be upgraded to abrasive blast cleaning per SSPC-SP 6. However, there may be instances when a unique exposure will require a change in a generic coating type. These situations can be addressed on a case-by-case basis.

(b) There is no clear-cut parameter to describe a marine-exposure environment. Although corrosion is accelerated by the moisture- and salt-laden air, the degree of corrosivity varies from mild to severe. Generally, corrosion is intensified or decreased in proportion to the distance from the shore, with a rapid decrease in corrosivity as the distance from the shore increases. As with other severe atmospheric exposures, a mild marine environment can be adequately protected by improving surface preparation cleanliness or adding coating film build as previously described in 5-5*c*(4)(a) above. Because corrosion and film undercutting, especially at points of discontinuity in the coating film, are greatly accelerated in the presence of salt, locations close to salt water require special attention. Chlorides (salt) are often invisible contaminants, and their presence may go undetected. Salts can present complex problems in surface preparation if they are not successfully removed. Specialized test methods assure that chloride contamination has been adequately removed (see Chapter 9).

Because the salts are water soluble, common methods of removal are by steam cleaning or pressure water blasting. The methods should be accomplished prior to general surface preparation to prevent the redistribution of chloride contamination. In highly contaminated environments, the complete removal of salts and the upgrading of surface cleanliness are extremely important.

(c) Alkyd systems generally have been found to provide adequate protection in mild-marine environments, with corresponding improvements in surface preparation or added film build, as the severity of the exposure increases. In more severe exposures, as on complex structures in proximity to seawater, consideration must be given to choosing a generic coating of superior resistance. Experience has shown that vinyl systems perform well in these situations. Improved protection is noted when this vinyl system is coupled with an inhibitive zinc-rich primer.

d. Ferrous metal immersion and frequent wetting—fresh (inland waters) or prolonged wetting by splash, spray, or condensation.

(1) Current coating systems. Metallized systems requirements are specified in CWGS 05036. Current vinyl, CTE, and epoxy polyamide coating systems specified in CWGS 09940 are:

- Vinyl (four to five coats)
- Zinc-rich vinyl/vinyl (three coats)
- CTE (two coats)/CTE (two coats)
- Zinc-rich epoxy (two coats)/CTE (two coats)
- Epoxy polyamide (two to three coats)
- Zinc-rich epoxy (two coats)/epoxy polyamide (two to four coats)
- Systems which have performed well in “Immersion and Frequent Wetting—Fresh (Inland Waters) or Prolonged Wetting by Splash, Spray, or Condensation” environments which are not listed in CWGS 09940 are formulations of phenolics, coal tars, asphalts, Neoprenes^{TM1}, inorganic zinc-rich, and organic zinc-rich coatings.

(2) Maintenance painting. Maintenance painting, such as spot touchup, frequently is required to repair smaller failing or damaged areas on a structure. This process further lengthens the service life of a structure with an otherwise intact coating system. These maintenance repairs frequently are made to structures that cannot be taken out of service for long periods of time. Proper spot repair can

¹ DuPont Company, Wilmington, Delaware.

permit the structure to remain in service until it is feasible to shut down for complete maintenance repainting. Obviously, surface preparation techniques are limited and are generally on the order of those given in SSPC-SP 2 or SSPC-SP 3. Viable candidates for such nonpermanent repairs are solvent-based coal tars and surface tolerant, two-part immersion-grade epoxy mastic coatings. Keep in mind that these repairs are considered only temporary to preserve the structure until proper blast cleaning and recoating with a system shown in CWGS 09940 can be accomplished.

(3) Candidate systems. Candidate coating systems for new steel are recent technological developments in formulations of epoxies, such as epoxy novalacs and 100 percent solid epoxies. Additionally, 100 percent solid versions of polyurethane coatings are rapidly gaining recognition. Unfortunately, as with some new technologies, specialized methods of application are necessary. The 100 percent solid coatings often require complex plural component spray equipment. Therefore, skilled applicators are essential when using these systems. Industry-wide use of these systems will become prevalent as more restrictive VOC limits are enacted.

(4) Special concerns and cautions. Special concerns and cautions with existing systems are straightforward. The coating systems listed in CWGS 09940 for "Immersion and Frequent Wetting—Fresh (Inland Waters) or Prolonged Wetting by Splash, Spray, or Condensation" all require a high degree of surface preparation, generally, a minimum of abrasive blast cleaning per SSPC-SP 5. Because high performance systems are generally spray applied, highly skilled applicators are required, particularly on detailed and intricate structures. Vinyls are solvent deposited so they are easily cleaned and softened by higher solvent strength aromatic hydrocarbons and ketones, such as methyl ethyl ketone (MEK). Properties such as ease of cleaning and resoftening with solvent allow vinyls to be easier recoated and provide good bonding between cleaned coats. Also vinyls, as a result of their curing mechanism, often can be applied at much cooler temperatures. Unfortunately, the manufacture of VOC-complaint formulations of vinyls is progressing rather slowly, and the future use of these coatings may become more restricted.

(a) CTEs provide exceptional performance but are inherently difficult to apply. Because of their exceptional hardness, they are prone to intercoat delamination problems if critical recoat times are not observed. When overcoating for maintenance purposes, CTEs can present special surface preparation difficulties. When overcoating is required, the manufacturer should be contacted for special surface preparation requirements. Generally, the minimum requirement would be brush-off blast cleaning.

(b) Zinc-rich epoxy and zinc-rich vinyl coatings, in addition to being somewhat difficult to apply, require constant agitation to prevent heavy metallic zinc particles from falling out of suspension in the container. If not properly agitated, the resultant spray-applied film will not be homogeneous in regard to proper zinc particle distribution throughout the dry film. Consequently, the galvanic protection properties of the zinc coating are inhibited.

e. Painting of penstocks, spiral cases, spiral case extensions, and draft tube liners.

(1) Interior water contacting surfaces.

(a) Preferred systems. Of the existing systems listed in CWGS 09940 for painting penstocks, spiral cases, spiral case extensions, and draft tube liners, CWGS 09940 system 6, based on CTE, has provided a good history of corrosion protection and would be considered the preferred coating option. CWGS 09940 vinyl systems of the 4, 5, and 6 series have also proven successful when painting penstocks, spiral cases, spiral case extension, and draft tube liners.

(b) Special concerns/cautions. The curing mechanism of CTE is temperature dependent. Therefore, cool (surface, material, ambient temperatures <10 °C (50 °F)) temperatures would slow the curing/reaction process and could negatively impact construction scheduling. Conversely, vinyls, such as the 4, 5, and 6 series, cure by the mechanism of solvent evaporation, which permits application and curing. Where there is severe abrasion or high water velocities with large amounts of suspended abrasive matter (debris, ice, etc.), vinyls provide comparable performance to CTEs, but with the added flexibility of application at lower temperatures and fast dry/cure.

(2) Exterior surfaces of penstocks and appurtenances.

(a) Preferred system. Because of variable exposures of items on the exterior surfaces of penstocks and appurtenances ranging from outside weathering surfaces of penstocks to penstocks in humid tunnels, various systems are needed to adequately protect exterior surfaces of penstocks and appurtenances. Because there may be considerable variability in exposures, it is necessary to choose a system that will perform in the most severe exposure (high humidity and condensating moisture). Therefore, CWGS 09940, system 3 (vinyl) is the preferred system of corrosion protection. Also, because vinyls dry rapidly by solvent evaporation, they are more readily adaptable to the difficult drying condition encountered on exterior surfaces of penstocks and appurtenances than other generic types, such as epoxy or CTE.

(b) Dehumidification equipment. Particularly in summer months, condensating moisture and humidity present difficult problems in the coating of penstocks. Warm, moisture-laden air passing through the cool air naturally causes condensating moisture on the surfaces. Dehumidification equipment will be necessary to create ambient conditions more favorable to coatings application.

(c) Special concerns and cautions. In repair, replacement, or new construction of penstocks, hydrostatic pressure testing usually is required prior to placing the system in service. Testing requires that certain weld seams remain uncoated until testing is complete. Field touchup of welds may leave the structure with an aesthetically unpleasing patchwork appearance, and adjacent coating may be damaged in the repair process. Therefore, USACE prefers to prepare and coat penstocks completely in the field. Unfortunately, field painting of completed penstocks presents particular health, fire, and explosion hazards, which must be carefully controlled with properly engineered ventilation systems (see Chapter 10). Special concerns with spent abrasive recovery, handling, and disposal also must be addressed.

f. Surge tanks.

(1) Interior surfaces of surge tanks. Surge tank interiors are well protected by using CWGS 09940 vinyl systems (3, 4, and 5 series) and CTE system (system 6). When painting surge tank interiors, mixed exposure conditions necessitate coating systems formidable to the exposure. Although there appears to be no clear preference for CTE or vinyl, a case-by-case consideration can aid in system selection. For economic reasons and simplicity, it is advisable to coat the surge tank surfaces with the same system as used in the penstocks.

(2) Exterior surfaces of surge tanks.

(a) Exterior surge tank surfaces can be effectively protected with CWGS 09940 system 2, linseed oil and alkyd primer/phenolic aluminum or system 3, vinyl, with the determining factor being the actual exposure.

(b) Special concerns and cautions are necessary when painting surge tank exteriors. As with many other USACE components, normal weathering predisposes the use of system 2 when climatic conditions or reservoir temperatures produce frequent wetting or prolonged periods of condensating moisture. Under such conditions, vinyl (system 3) should be used. Surface preparation would be sandblasting as outlined in CWGS 09940. If the exposure environment is not clearly defined, the vinyl system, which exhibits good resistance to both exposures (normal weathering or high moisture), should be used.

g. Crest gates.

(1) Existing exposures on crest gates may range from normal weathering exposure to areas of immersion and frequent wetting. Exposures such as immersion and frequent wetting are best protected using CWGS 09940 system 3, 4, or 5. Normal weathering exposure areas of crest gates would be well protected using CWGS 09940 systems 1 and 2 for steel in normal atmospheric exposures.

(2) Special cautions/concerns in coating crest gates may include variable exposure environments impacting on crest gates and depending on whether the painting surfaces are exposed upstream or downstream. The upstream side usually will receive the most severe exposure (immersion, abrasion, etc.). However, depending on certain conditions such as high tailwaters, downstream surfaces also may experience rather harsh exposures. Therefore, the most long-term, cost-effective method of coating would be the exclusive use of CW 09440 system 3 (vinyl with aluminum topcoats); or, if superior abrasion and mar resistance to debris and/or seasonal ice is desirable, use CWGS 09940 vinyl system 4 or 5 series.

h. Control gates and valves of reservoir outlet works.

(1) Preferred systems. Existing coatings listed in CWGS 09940 for control gates and valves of reservoir outlet works frequently are dependent on the level of exposure. CWGS 09940 systems 3, 4, 5, and 6 series, vinyls, and CTE are viable choices. Special attention should be given to the following concerns and cautions when specifying a coating system.

(2) Special concerns and cautions.

(a) Coating selection may vary considerably from project to project, depending on the following variables. Whether the water control device is operated fully opened or partially opened is important. If operated fully opened, whether the component is removed from the flowing stream of water should be noted; the component may be exposed to various degrees of abrasive ice- and/or debris-filled, fast-moving, turbulent water. If operated in the partially closed position or if exposed to flowing water, the severity of erosion and abrasion would be magnified. Additionally, the elevation and other characteristics of the service inlet may permit abrasives (ice, debris suspended matter, etc.) to adversely impact the system's service life. With this in mind, the following coating recommendations should be carefully considered. Structures in low-to-moderate water velocities (45.7 to 61.0 mm/sec [15 to 20 ft/sec]) with abrasive qualities are good candidates for coating with CWGS 09940 system 4 or 5 series or CTE. However, if extremely severe conditions can exist, neither of these systems are advisable,

and one of the specially reinforced systems (see Chapter 4) may be appropriate. Many types of gates (slide gates, tainter gates, tractor gates, fixed wheel, etc.) can be painted without difficulty; however, special attention is required when painting tractor gates. Specifically, the stainless steel roller chain and track assembly must be carefully protected during field painting. While in the erection phase, the roller chain most likely will not be installed, the stainless steel track will be bolted to the gate. Care must be taken to mask off or otherwise protect these track surfaces properly from blast damage, and to seal off bearings and other rubbing surfaces from abrasive blast particles.

(b) As previously discussed in this chapter and Chapter 2, a strong potential for galvanic corrosion can be set up by the coupling of dissimilar metals, such as stainless steel roller chains and tracks with tractor gate carbon steel surfaces. Therefore, a cathodic protection (CP) system frequently is used for enhanced corrosion prevention of the carbon steel surfaces on these gates. The specified coating must exhibit high dielectric strength, in addition to being carefully applied to avoid holidays. In this regard (high dielectric strengths), the use of CTE is superior to vinyl systems and is recommended for use on control gates and valves of reservoir outlet works in conjunction with a CP system. Discussions of total field painting procedures revealed that fewer holidays are noted when surface preparation and painting are done entirely after erection in the field. Therefore, these gates should be totally field painted with CP systems attached. Alternatively, total shop painting with CTE and attaching CP anodes prior to installation, with no field touchup, also has proven to be effective and economical. Also, CP is particularly effective in protecting bare steel exposed as a result of damage from impact or abrasion which may occur while the structure is in service.

(c) If the foregoing preferred options are not possible, careful consideration of the difficulties with recoating CTEs should be addressed. Specialized surface preparations, such as brush blasting, will be required if critical recoating times are exceeded.

(d) Hydraulic lines on control gates and valves of reservoir outlet works also present unique coating problems, particularly if they are immersed in water because hydraulic lines are vulnerable to exposure damage (from ice, debris, etc.). These hydraulic lines should be isolated with dielectric coupling and cathodically protected.

i. Trashracks for water intakes.

(1) CWGS 09940 systems 4 and 5 series (vinyl) with zinc-rich primers provide the best protection to difficult-to-

coat trashracks. From a design standpoint, trashracks present numerous coating difficulties, such as sharp edges. Because of their design and the fact that they are subject to flowing water with abrasive debris, seasonal ice, and mechanical raking damage, coating service life typically is shortened. Therefore, trashracks may best be left uncoated, with the possible exception of those in environments of severe corrosivity. If these items are coated, a periodic structural integrity inspection program is highly recommended. Oftentimes, it is more cost effective and easier to fabricate new racks than to attempt to refurbish existing ones.

(2) Special concerns/cautions when coating these items are straightforward. When the abrasive gouging action of ice is present, systems 4 and 5 series (vinyl) perform well; the zinc-rich primer systems provide the best performance. If the outage period is short or the weather is cool, the faster dry, low-application-temperature (>2 °C (35 °F)) vinyl systems would be appropriate coating choices.

j. Navigation lock gates, valves, and miscellaneous submerged metal. Lock gates and valves are well protected in this exposure using CWGS 09940 vinyl (systems 4 and 5 series) and CTE (system 6). The massive lockwall armor and protection angles are not critical to basic project functioning. Painting on construction (CWGS 09940 system 2) and possibly periodic maintenance for aesthetic purposes appears to be practical.

k. Navigation dam gates.

(1) Systems in existence are CWGS 09940, vinyl systems 4 and 5.

(2) Special concerns and cautions in painting navigation dam gates involve exposures unique to the structure. Gates are generally of the roller, tainter, or vertical-lift type. The exposure environment is that of turbulent water, physically trapped abrasive debris, drift materials, and seasonal ice. The abrasion-resistant qualities of system 4 or 5 generally are thought sufficient to provide good protection. However, in extreme conditions, metallized systems (see Chapter 4) should be considered. Roller and tainter gates have interior and exterior surfaces that require painting. Because grating protects the interior from abrasion, CWGS 09940 system 3 will provide adequate protection. Vinyls are high in solvent fumes and highly flammable; therefore, special care (see Chapter 10) is required for ventilation systems when coating with vinyls.

l. Freshwater (including potable) tanks.

(1) Preferred systems. Existing systems for freshwater

tanks are CWGS 09940 vinyl system 3, 4, or 5 series.

(2) Special concerns and cautions.

(a) Potable water tank lining demands coating systems free of harmful toxic chemicals. Special regulations, such as those of the NSF, govern such coating systems. Vinyls, because of their inert qualities, readily lend themselves to immersion in freshwater (including potable) tanks. They are neither toxic nor physically harmful to the person who drinks water that has come in contact with these coatings.

(b) Abrasion action from ice movement is often a factor in colder climates. Systems 4 and 5 series should be used in lieu of the less abrasion-resistant system 3.

(c) In conjunction with cool water stored in a tank interior, condensating moisture frequently is found on the exterior surfaces of the vessel. If this condensation becomes commonplace, the use of CWGS 09940 system 3 on the exterior surface is advisable.

m. Equipment for local protection projects. The equipment for local protection projects (slide gates, flap gates, etc.) and the portion of pumping units below the pumping station operating floor should be painted with a cold-applied coal-tar paint system, system 7 from CWGS 09940. This system is used because the manufacturers of the equipment involved are not prepared to thoroughly blast and apply the more costly and less user-friendly vinyl systems. Moreover, local flood-protection projects are given to local authorities, who are responsible for the maintenance of the completed project, and the maintenance of surfaces painted as advised here is more within their capabilities and experience. In essence, the recommended systems are more user-friendly and surface tolerant to the inexperienced applicator. Miscellaneous items of fabricated steel should be hot-dip galvanized after fabrication. Specifications for pump discharge lines are given in EM 1110-2-3105; they are to be coated on the inside with hot-applied, coal-tar enamel; however, this procedure is difficult in coating operations in small diameter piping. If the lines are buried in soil, the outside of the lines must be coated with hot enamel plus a felt wrap, which is applied in the shop in accordance with the American Waterworks Association (AWWA) Standard C203-91. The CTE, CWGS 09940 system 6 or 6AZ, also would be highly effective on discharge lines but it is not routinely available as a shop-applied coating.

n. Floating plant (steel construction) operating in fresh water. Varying surfaces and exposure environments are associated with the painting of a floating plant. Although this in itself is not unique, the additional color scheme

regulations imposed by ER 1125-2-303 often require the specifier to employ some alternative system combinations. Federal Color Standard 595 is used to dictate many of the color schemes for floating plants. Certain of the smaller crafts, such as skiffs, rowboats, launches, small boats, barges, and scows, are exempt from color scheme requirements. The following paragraph addresses coating application to the component.

o. Exterior surfaces of steel hulls.

(1) Certain modifications of CWGS 09940 vinyl systems 4 and 5 can acceptably accomplish coating of the entire hull. When special color concerns as identified in CWGS 09940 are necessary, such as hull surfaces above the waterline, substituting the last two spray coats of vinyl system 4 or 5 and/or substituting two black vinyl coats per V-103 is appropriate to achieve the special color. Also two final coats of Fed. Spec. TT-E-489 (black alkyd) may be used to achieve the special color.

(2) A garnet-reinforced system has been used for hull bottoms because frequent running aground results in severe abrasion and gouging of the coating system. Additionally, abrasion protection can be achieved by first priming the hull bottom with 2 to 3 mil of vinyl zinc-rich primer VZ-108, and following with the garnet-reinforced coating.

p. Interior surfaces of steel hulls. Hull interiors are subject to accumulating water, condensating moisture, and high humidity. Like other exposures of this type, these surfaces are well protected using CWGS 09940 systems 3, 4, 5, and 6 series. However, these systems necessitate sandblasting and may prove costly. A less expensive alternative would be to use a cold-applied, solvent-based coal tar (MIL-C-18480A(3)) in a two-to-three coat application. The saving is realized because of the lesser degree of surface preparation required by the manufacturer and the overall material costs. If the hulls remain dry, there are many less expensive systems, such as alkyd primers/alkyd topcoats, that can be applied over lesser degrees of surface preparation (i.e., SSPC-SP 3).

q. Painting of steel decks.

(1) Steel decks, if painted, are prescribed by the referenced regulation to be deck red, color 10076 of Federal Standard No. 595. The color requirement is waived when special, approved types of deck coatings are to be used. Red deck paint (Mil. Spec. DOD-E-18210B), three coats, is intended primarily for use on interior decks of naval vessels. It is based on a durable alkyd-phenolic-type of vehicle and is considered suitable for either interior or exterior use on floating plants operating in fresh water. This type of paint

should be used only on well prepared surfaces that are sandblasted to a commercial or better grade. Sand reinforcement of the second coat would be desirable when a nonskid surface is needed. Substitution of an inhibitive-type primer instead of the first coat of deck paint might be beneficial to the three-coat Mil. Spec. DOD-E-18210B system, but it is not considered essential for plants operating in fresh waters.

(2) Vinyl paint system from the 5 series having the V-106 topcoat from CWGS 09940 is the correct finish color and will perform well as a deck paint, although it would be somewhat difficult to sand-reinforce for antiskid purposes because of its fast-drying characteristics. The addition of fine garnet directly to the finish coats of this system will provide added abrasion resistance but minimal benefit in improved antiskid properties.

r. Exterior surfaces of floating plant.

(1) The color scheme for the painting of floating plant surfaces is prescribed in ER 1125-2-303. The surfaces involved are subject only to atmospheric exposure; although beneficial, blast cleaning may not be justified. If wire brushing and scraping (per SSPC-SP 2) are used, the surfaces will have corrosion products and mill scale present. One or two coats of a primer with good wetting properties, such as an alkyd rust-inhibitive primer, is advisable. Primed surfaces then could be finish coated with two coats of a semigloss enamel conforming to Fed. Spec. TT-E-529 (2) Class A. Enamel conforming to Fed. Spec. TT-E-489 Class A, or TT-V-1593 (silicone alkyd) should be used if a high gloss finished surface is desired. Both of these specifications include a range of gray, ivory, black, and red from which those suited to the floating plant color scheme may be selected. The finish coat enamels are relatively fast-drying materials and should not be applied to surfaces primed with slow-drying, alkyd primers without proper drying times.

(2) If an upgraded system is desired, the surfaces subject to atmospheric exposure could be cleaned by blasting to at least the commercial grade, and one or two coats of an alkyd rust-inhibitive primer should be applied. Finish coats of enamel conforming to Fed. Spec. TT-E-489 or TT-E-529 then could be used to comply with the required color scheme.

(3) Stacks of floating plants are required to be painted black with trim colors of red and aluminum. The use of special paints for these surfaces is determined by their maximum operating temperatures. Ordinary alkyd black paints, such as those included in Fed. Spec. TT-E-489 or

TT-E-529, will tolerate temperatures of up to about 135 °C (275 °F) for extended periods, as would an aluminum paint made with an alkyd vehicle (Fed. Spec. TT-V-109). Black paints (Fed. Spec. TT-E-496) will withstand temperatures of up to 204 °C (400 °F). For temperatures higher than 204 °C (400 °F), paints made with silicone or modified silicone binders must be specified. Fed. Spec. TT-P-28 covers a modified silicone-aluminum paint with a heat-resisting capability to temperatures up to 649 °C (1200 °F). MIL-P-14105C formulated products will resist temperatures as high as 760 °C (1400 °F) and are available in some colors. However, these products are expensive and frequently are available on a special order basis only.

5.6. Coating System Selection for Ferrous Surfaces in Seawater

a. Ferrous metal surfaces of fixed structures.

(1) Current systems. Current systems found in CWGS 09940 are:

- CTE (two to three coats).
- Epoxy zinc-rich primer/CTE (two coats).
- Epoxy polyamide (two to three coats).
- Epoxy zinc-rich primer (two coats)/epoxy polyamide (two to four coats).

Other existing systems (not listed in CWGS 09940), which have performed well, are formulations of coal tars, asphalts, Neoprenes™, and organic zinc-riches.

(2) Candidate maintenance systems. Maintenance painting, such as spot touchup, frequently is required to repair small failings or damaged areas on a structure. This process further lengthens the service life of a structure with an otherwise intact coating system. These maintenance repairs may be made to structures that cannot be taken out of service. Proper spot repair can permit the structure to remain in service until a time that is feasible to shut down for complete maintenance repainting. Surface preparation techniques are limited and generally are on the order of SSPC-SP 2 or SSPC-SP 3. Viable candidates for nonpermanent repairs are solvent-based coal tars and surface tolerant two-part immersion-grade epoxy mastic coatings. Keep in mind that these repairs are considered only temporary to preserve the structure until the time proper blast cleaning and recoating can be accomplished.

(3) Candidate systems for new steel. Candidate coating systems for new steel are recent technological developments in formulations of epoxies, such as epoxy novalacs and 100 percent solids epoxies. Additionally, 100 percent

solid versions of polyurethane coatings are rapidly gaining recognition, and inorganic zinc-rich coatings topcoated with organic paints also have performed well. Specialized methods of application may be necessary and most commonly require complex plural component spray equipment. Therefore, skilled applicators are essential when using these 100 percent solid epoxy and polyurethane systems. Industry-wide use of these systems will become prevalent as more restrictive VOC limits are enacted at the Federal, state, and local level. Contemplated systems must all be evaluated individually and specifically in this seawater immersion environment.

(4) Special concerns and cautions. Special concerns and cautions for immersion service in seawater were discussed in paragraphs 5-2a(3) and 5-4d. Additionally, the coating systems listed in CWGS 09940 for exposure to seawater all require a high degree of surface preparation—abrasive blast cleaning to white metal.

b. Steel piling.

(1) Existing CWGS 09940 CTE systems for coating steel piling are systems 6 and 6AZ (CTE). Systems 6 and 6AZ are suitable for protection of steel pilings. However, there are many questions about steel piling painting.

(2) Special concerns and cautions associated with the coating of steel pilings include the fact that no method of corrosion protection is used on certain portions of steel piling. Studies have shown that the corrosion rates of piling driven into undisturbed soil on the ocean floor corroded at slow rates mainly because of the lack of oxygen. Obviously, as the pilings emerge from the ocean mud floor, the presence of oxygen and consequent corrosivity increases. Moving soils, basic saltwater immersion, tidal movement, abrasives, contaminated waters, and aerated splash zone activity rapidly accelerate corrosive forces.

(a) The installation of pilings by driving them into the sea floor is believed to be particularly abrasive to a coating system. Initially, it was not known whether a coating system could withstand this installation without irreparable damage. However, it has been demonstrated that, when properly coated with CTE coatings, damage is limited to a few inches on the leading edge of the piling and relatively minor scratching in the interlock area. The addition of proper CP can protect these areas from corrosion.

(b) Interlock areas on sheet piling present some unique surface preparation coating difficulties, particularly the grooved areas. Even the best applied coatings to these interlock areas were believed to be damaged in the driving installation process. However, the damage is not as severe

as originally believed. In addition, this is the thickest part of the piling, and corrosion will have little effect on structural integrity. A suggested remedial action is to minimize corrosion through the use of galvanically protecting zinc-rich primer and periodically monitoring the corrosion rate and structural integrity. Experience has shown that, although corrosion will occur, it usually is of a localized nature and not critically harmful to structural integrity. However, corrosivity can vary from site to site, and periodic monitoring is considered vital.

(c) In cool environments, the temperature-dependent cure times of CTE and scheduled coatings operations (in shop and/or field) must be observed. Because exposure environments of pilings may vary (i.e., buried, immersion, splash zone), it seems proper to coat the pilings as outlined here.

(d) Underground portions of steel piling, which are a moderate distance below the groundwater table (or below the water-mud line if driven through surface water) do not seriously corrode. Therefore, the coating system may not be necessary 5 to 10 ft below these indicated levels. Sections of pilings subject to weathering and aerated splash zone activity would also be adequately protected using CWGS 09940 system 6 or 6AZ.

c. Cathodic protection (CP) and immersion in seawater.

(1) Certain inherent characteristics of seawater make it of greater corrosivity than fresh water. Because of this heightened corrosive nature, the use of CP in conjunction with immersion coating systems frequently is used for structures in seawater.

(2) High dielectric strengths, or the ability of the coating to withstand the additional stresses of the CP current is extremely important. Because the CP current forces water through the film in a process called endoelectrosmosis, a coating that can withstand this stress, such as CTE, is an important choice in conjunction with CP-induced stresses, of cathodically produced hydrogen gas and alkalis that are generated at the paint-metal interface. The desirable coating quality of high dielectric strength essentially forces the CP current along the painted film to breaks or discontinuities in the coating where it is needed for protection of the bare steel substrate. When choosing a CP system for a structure that is partially seawater immersed and partially atmospherically exposed in the splash zone, CP may not provide adequate protection to the splash zone portion. The highly oxygenated splash zone is severely corrosive and requires higher CP rates that could be detrimental to the submerged CP-protected areas. Additionally, coating choices must be resistant to these forces when used with CP.

5-7. Coating System for Iron and Steel Pipe

a. Black iron or steel pipe. Existing systems for coating black iron and steel pipe are alkyd inhibitive primers, with ready-mixed aluminum and alkyd topcoats. CWGS 09940 also specifies the use of vinyl systems in some exposures. A clear, varnish-like coating sometimes is present on black and steel pipe. In nonsevere exposures, the coating generally is compatible with alkyd coating systems. Solvent cleaning and hand-tool cleaning generally are adequate for coating with alkyd systems. However, if the exposure environment becomes more severe, a corresponding upgrade in surface preparation and coating choices, such as a vinyl (CWGS 09940 system 3), is appropriate. The required spray application of vinyl on piping in place can prove to be labor intensive. Upgraded surface preparation and protection with additional coats of alkyd or phenolic topcoats may prove to be a viable alternative.

b. Galvanized pipe.

(1) Coating systems for galvanized pipe are generally for appearance purposes or for the refurbishing of damaged galvanized components. Zinc-rich epoxy polyamides and

coatings specially formulated for galvanization are useful in this regard. The zinc-rich coatings are abrasion, chemical, and moisture resistant. Consequently, they frequently are used without a topcoat, even in severe exposures. Adhesion to this substrate may be variable because of the galvanizing process, and care must be taken in the surface preparation process to assure that all galvanizing process oils are totally removed before painting. This normally can be accomplished by solvent or detergent cleaning.

(2) Threading and welding of galvanized pipe after production leave exposed steel, which requires touchup. Epoxy zinc-rich primer coatings are extremely effective in this regard. These coatings have good adhesion qualities to existing galvanized surfaces and, in themselves, provide similar galvanic protection to the touchup areas.

(3) Thinly applied vinyl wash coats (0.0076 to 0.013 mm [0.3 to 0.5 mil] dry film thickness [DFT]) also have proven to be an effective tie coat on galvanized pipe that provides a sound base coating for high performance barrier-type topcoats. Primarily though, these systems are used only in frequent condensation and moderate corrosivity, when the galvanization itself may readily react and rapidly deteriorate by galvanic action.