

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM  
SYNTHESIS OF HIGHWAY PRACTICE

136

PROTECTIVE COATINGS  
FOR BRIDGE STEEL

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM **136**  
SYNTHESIS OF HIGHWAY PRACTICE

## PROTECTIVE COATINGS FOR BRIDGE STEEL

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TRANSPORTATION RESEARCH BOARD  
NATIONAL RESEARCH COUNCIL  
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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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## PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

## FOREWORD

*By Staff  
Transportation  
Research Board*

This synthesis will be of interest to bridge designers, materials engineers, maintenance engineers, and others concerned with coating systems used to protect bridge steel from corrosion. Information is presented on the causes of steel corrosion and the types of surface preparation and coatings used to protect the steel.

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Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Steel bridges need some type of protective coating to keep them from corroding. This report of the Transportation Research Board explains the mechanisms of steel corrosion and how coatings protect the steel, discusses the need for and types of surface preparation, and describes 20 types of available coating systems under three general categories: inhibitive systems, zinc-rich (sacrificial) systems, and barrier systems.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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# PROTECTIVE COATINGS FOR BRIDGE STEEL

## SUMMARY

This synthesis is primarily concerned with review of the technologies involved in the design and use of protective coating systems for steel bridges. Since the mid 1960s coating systems for bridges have undergone profound changes, and the once exclusively used inhibitive lead and oil systems have now been largely replaced by a plethora of complex zinc-rich and barrier systems. The changes have not been wrought without failures and, although generally cost-effective in the more aggressive environments, the newer "high performance" systems can have difficulty competing cost-effectively with the traditional lead and oil systems in the rural interiors. Of all the newer coating systems, those based on inorganic zinc-rich primers with vinyl topcoats have established themselves most securely, although new systems wherein the vinyl is replaced with epoxy and, lately, urethane topcoats may eventually achieve dominance.

Abrasive blasting has largely replaced hand- and power-tool cleaning as "normal" surface preparation, not only for high-performance systems, but for traditional lead-based systems also. Toxicological concerns over the atomization of lead compounds during the reblasting process, and the classification of large quantities of spent abrasive as hazardous or special wastes (with the consequent high cost of disposal), may, however, slow or even reverse the trend toward abrasive blasting. These considerations are spawning much interest in coating systems for non-blast cleaned and rusted surfaces, in new methodologies for blast containment, and in alternative methods of paint removal.

In reviewing what is a multi-faceted discipline, it is impossible to divorce a study of the coatings themselves from the effects of associated practices such as specification design, job execution, inspection, and in-service monitoring, which have considerable impact on the efficiency of the applied coating systems.

In comparison to the coatings materials, which seem entirely adequate to provide the performance profiles now required, the application process and its inspection are often flawed. There is much disparity of expertise among applicators, and for the most part the technological revolution that has occurred in the material sciences is still not reflected in necessary corresponding changes in job execution. Improvement of inspection forces, more than any other single change, would do much to increase the cost-effectiveness of the applied coating systems.

Good coating system specifications for bridges seem to be the exception rather than the rule. Specification writers are often insufficiently knowledgeable about the makeup and the use of the materials and processes they specify and must rely on outside sources, usually paint manufacturers and raw material suppliers, to prepare both compositional and performance specifications. Many bridge paint specifications are simply copies from one state to another. Few state DOT laboratories maintain a paint technologist on staff, but those that do produce compositional specifications of much better standards. Major trends in specification design, however, have been to

abolish the compositional specification in favor of the performance document, but the current lack of a good, reliable testing methodology that provides correlation between accelerated laboratory testing and field performance hampers the efficiency of control from product to product and batch to batch. Little scientific monitoring of bridge paint system service or cost-effectiveness is practiced at this time, and specification refinement through systemized review of system service in the field is generally hampered by lack of communication between the design departments and field inspections, or by the absence of long-term in-service monitoring. Although tools such as the bridge corrosion cost model might bring much formalization to the long-term management of bridge maintenance, they have little reliable cost and service data for input. Badly needed are the necessary rust curves and cost data from practical paintings in the field.

The need to improve cost-effectiveness and respond to sociopolitical (environmental) pressure is engendering considerable changes within the industry at this time. The synthesis also discusses the effects of these considerations on surface preparation and coating system design, and it reviews the industry's response in dealing with them. Based on these changes and the prognosis for their further development, probable future trends are discussed.

What emerges from this study is not only a comprehensive condensation of the coatings technology and corrosion science that apply to anticorrosive systems for bridge steel but a review of the entire state of practice from the formulation of the product to the completion and service evaluation of the job.

## CHAPTER ONE

## INTRODUCTION

## SCOPE

This synthesis reviews the disciplines that influence the design, selection, and use of coating systems for the protection of steel bridges. It is a review of individual disciplines that range from corrosion science and the chemistry of coatings to the practicalities of job execution. It considers only coatings systems for structural steel.

The synthesis is compiled from data from numerous sources including the literature on corrosion science and paint technology, a review of paint specifications, case histories, and studies, and reports that are specifically concerned with protecting bridge structures with paints and coatings. Much additional data have been accessed from numerous discussions with authorities on the subject and responses to questionnaires directed at all elements of the industry.

## BACKGROUND

In many respects the technology involved in the preparation and use of anticorrosive coating systems for bridge structures was born in the middle of the 19th century. The first iron structure, the Wynch Bridge, built over the River Tees in England in 1741, was not painted and it collapsed after some 60 years from corroded chains, thereby exemplifying the need for protection (1). The cast-iron bridge at Coalbrookdale (Iron Bridge) in Shropshire, England was not painted when built in 1779, but some nine years later it was coated with a bituminous varnish. Painted many times since then, it still exists today.

In the 1880s steel came into its own with the construction of bridges in St. Louis, Brooklyn, and across the Firth of Forth in Scotland. The paint system on the last is well documented, and, in light of its similarity to systems used widely over the next 70 years, is worth note.

Before the erection of the Forth Bridge, the steel was scraped, wire brushed, and given a hot or boiled linseed oil treatment. A red lead/linseed oil primer was then applied in the shop (where possible) and after erection a second coat of the same paint was applied in the field. This was then recoated with a red oxide intermediate and one coat of red oxide finish. In other areas (tube interiors) the red lead primer was recoated with two coats of white lead and oil (1). The Forth Bridge is also interesting because a program of continuous maintenance has been in place since its erection, and the effectiveness of this is highlighted in the inspection of 1965 when the bridge was found to

be sound and suitable for continued service. In 1899 tests conducted by Smith found that one or two coats of red lead with at least two topcoats of iron oxide gave the best protection for iron structures (2).

Aside from the use of the questionable hot oil treatment, the paint system applied to the Forth Bridge is astonishingly similar to that used on the steel bridges across the United States over the first half of this century. Red lead/linseed oil primers, red lead/iron oxide intermediate coats, and white lead and oil finish coats were often the standard paint systems used by many authorities. Variations include the use of blue lead (lead sulfate) in finish coats and, later, the introduction of chromium green oxide as a pigment in finish coats and the introduction of bodied linseed oil and alkyd modification of the finish coat vehicles. The advantages of the red lead/linseed oil primer lie principally in its good corrosion resistance and low surface energy, making it almost foolproof for use over surfaces with little or no surface preparation.

Other systems less readily accepted in the United States but used with great success in Europe (e.g., the bridge at Muengsten, Germany, painted only six times since its erection in 1897) were based on the lamellar barrier pigment micaceous iron oxide (lamella hematite) (3). An early example of the more modern mixed (inhibitive primer/barrier finish) system concept is the bridge over the Victoria Falls in Zimbabwe (Rhodesia), which was originally painted with a red lead/linseed oil inhibitive primer, a micaceous iron-oxide-based intermediate barrier coat, and an aluminum-pigmented barrier topcoat (4).

The use of aluminum pigmentation in finish coats increased with the introduction of the phenolic varnishes in the 1930s.

In the 1930s zinc yellow (zinc potassium chromate) as a corrosion-inhibiting pigment was also introduced and used with synthetic varnishes and alkyds to provide an alternative inhibitive primer for steel. Although this type of primer appears to have been used extensively on steel in other industries (e.g., shipbuilding) (5), its use on steel bridges has not been as widespread.

Next was the replacement of red lead/white lead systems with the basic lead silico chromate (BLSC) "defense in depth" system (6). The major force that fostered this change appears to be the somewhat improved stability of color and reduced chalking of the finish coats. Although the orange color of the BLSC had to be over-tinted, other colors were possible, and in many cases bridges other than the usual green were tried (blues, beiges, etc. using titanium dioxide and such tinting pigments as phthalocyanine blue, chrome yellow, hydrated yellow oxide). Because

of the reduced reactivity of BLSC and its effect on drying, alkyds were used in all three coats to modify the linseed oil. Specifications were originally prepared by the pigment manufacturer National Lead (now NL Industries) and appear to have been adopted by many state highway departments and without extensive independent testing. These primers and midcoats have now evolved in AASHTO M 229 (TT-P-615). The extensive technical service and formulating assistance provided by National Lead may have played a part in the success of the initiation of BLSC, as few state labs then, as now, had formulatory capabilities.

In the 1950s and 1960s many bridges were coated with BLSC systems. These systems appear to have given good service: in rural areas of the snowbelt many have lasted as long as 12 years between repainting. In heavy industrial areas, shorter service life ranges (5–10 years) were more normal. Comparisons with the red-lead systems are difficult because of the gradually changing patterns of application and surface preparation that has spanned this period of transition.

On several large structures in the Northeast, hybridized systems employing red-lead primers and intermediate coats and basic lead-silico-chromate-based finish coats have been employed with success.

In the 1950s, the advances that had occurred in polymer chemistry over the previous two decades began to spawn a plethora of new coating vehicles. Paint companies began to produce a variety of individual coatings, many with claims and counter claims with regard to properties and performances. Although many of these fell by the wayside, many have remained and have provided a level of performance heretofore unknown. Even in aggressive environments, instead of thinking in terms of 5 to 10 years between maintenance paintings, service is now discussed in terms of 15 to 30 years, and in some cases even these estimates may eventually turn out to be conservative.

The great number of new coating types now available for protection of steel bridge structures is geometrically increased when the individual coating types are utilized as part of full coating systems. Moreover, unlike the old lead-based systems, where oil and oil-modified vehicles were of similar types, the new coating systems are not only widely divergent in nature from the oil-based systems, but are frequently different from each other. Curing mechanisms are no longer all simply oxidizing in nature; lacquers, two-pack chemical curing systems, and moisture-curing systems are now as often the rule as the exception. An even more important factor, and one still not completely realized, is that one epoxy may be polymerically quite different from another, and the differences between individual representations of a vehicle class (epoxies, urethanes, vinyls, etc.) can provide a performance profile as different from the next as the next is from a totally different vehicle family. Even a relatively small family of vehicles, such as the vinyl

chloride/vinyl acetate lacquers, will exhibit major property changes as may be exemplified in a study of the changes in adhesion characteristics of one resin compared to another (7). Property differences wrought by molecular engineering in larger families of polymers, such as epoxies and urethanes, may be even greater.

Furthermore, paint formulating effects (such as changes in the pigment volume concentration, the critical pigment volume concentration, and the ratio of one to the other; or the selection of pigments, solvents, and additives) can bring radical differences to coatings based on even the same vehicle makeup. The extent of the difficulty in dealing with this bewildering array of products is perhaps anticipated when the effects of the following are added to the above:

- a. high surface energetics and the demand for substrate preparation;
- b. the particular sensitivities of individual vehicles and vehicle classes to phenomena such as dehydrochlorination, UV deterioration, alkali-induced saponification, etc.; and
- c. sensitivities of certain coating types to untoward phenomena developed from formulation and/or application effects (lateral adhesion failure in zinc-rich films, etc.).

Adding to these difficulties is the fact that in many cases a complete understanding of the pitfalls of the various high-performance systems in field use is not attained by those who formulate and advocate these systems.

Because paint technology has become less an art and more a science, the individuals responsible for the compilation of modern bridge-paint systems (if they are to do their job properly) must not only be corrosion engineers, but paint chemists and polymer chemists combined.

Moreover, increased use of deicing salts and increased air pollution with oxides of sulfur have added significantly to the severity of environments in which many of the structures must perform. When this is combined with deferred maintenance because of a lack of adequate funds, the result is often an increased cost of bridge painting, particularly when structures have been allowed to deteriorate to the extent that spot repair is impractical and the entire structure must be stripped of old paint. The cost of such radical blast cleaning operations is very high. In certain urban environments, where the old paint systems bear lead-based paints, renewal of the paint system involves the initial removal of these old paints from the bridge with costly disposal (8) and containment (9) of blast debris. In these cases the process may become astonishingly expensive.

In view of the complexities and many facets of the design procedure involved, those responsible for the design of bridge paint specifications and their execution should be well trained in all facets of the technology.



## CHAPTER TWO

## CORROSION CONTROL BY COATINGS

## THEORY OF CORROSION

The metallic state of engineering metals is unstable. Once reduced from their ores, metals continually attempt to return to a more stable state by combining with their environment to form oxides or other compounds similar to the ores from which they were derived (10). This oxidative degeneration is the corrosion process. The stability of any particular metal in the metallic state will depend on the energy originally absorbed to achieve this state; the more energy required, the more unstable the metal will be; the less energy required, the less readily will the metal corrode (11).

Corrosion is an electrochemical process, which may readily be demonstrated as follows. If zinc is electrically connected to iron (see Fig. 1) and both metals are immersed in an electrolyte such as salt water, an electrical current will be seen to flow between the two metals, demonstrating that the corrosion process is an electrochemical reaction (12). In fact, a galvanic cell, not very different from a battery, has been set up.

If the ammeter in Figure 1 is replaced with a voltmeter, a voltage or potential difference will be seen to exist between the two metals. If the zinc is replaced with magnesium this potential difference will increase and the magnesium will corrode at a greater rate than did the zinc. Alternatively, if the zinc is replaced with copper, the corrosion current is seen to flow in the opposite direction, and now the steel becomes the anode and corrodes. This is because copper is electrochemically more stable than iron; that is, it has a more electropositive potential, and is therefore cathodic to iron.

Fortunately corrosion rarely proceeds at the same rate at which it was initiated. The rate usually decreases with time rather than being linear, and it is modified by the formation of films on either anode or cathode, which may increase the resistance of local cells or modify the electrochemical potentials of the particular surface on which they form.

Of critical importance in practical situations is the permanence of such films. As a metal corrodes (dissolves into the electrolyte) there is eventually an equilibrium set up between its tendency to go into solution, increasing the concentration of its ions in the electrolyte, and an opposing tendency for those ions to coat and polarize the metal as films of corrosion product, thereby reducing the concentration of its ions in solution.

Polarizing oxide films of corrosion product on some metals, such as aluminum, are so adherent that they effectively stifle all corrosion (13). On steel the corrosion product is usually porous and loosely adherent and provides little permanent protection.

Certain high-strength, low-alloy steels containing nickel, chro-

mium, and copper (e.g., ASTM A 588 weathering steel) as they corrode form more adherent oxide films, which are thought to slow further corrosion in much the same way as the oxide coating on aluminum prevents attack (14, 15). Additional evidence would suggest that this is only accomplished in certain environments, and that environments with high chloride ion concentration are not conducive to protection by such alloying techniques.

The relative areas of anode and cathode have an effect on the intensity of the attack. In Figure 1 both electrodes are represented with identical surface areas. If, however, the zinc anode area is diminished to  $\frac{1}{10}$  of that depicted, then the corrosion current generated by the same large cathode and falling on the smaller anode will be 10 times as intense as before. Alternatively, if the anode is made 10 times larger in surface area than the cathode, then the same corrosion current will be dispersed over a larger area and the intensity of the attack will be correspondingly diminished. The effect is often referred to as the catchment area principle (16), and can be utilized in designing systems for reduced corrosion intensity (Fig. 2).

## Corrosion Control by Coatings

In the control of corrosion by protective coatings, one of three mechanisms is utilized: the inhibitive primer, the sacrificial primer, or the barrier coating (17). In practice, composite paint system combinations of such techniques may be employed, although care and intelligence is required in the design of such systems to ensure that combinations produce a compatible whole without the various components working against each other.

## INHIBITIVE PRIMERS

Inhibitive primers function by in-service modification of the anode and/or cathode reaction by artificial polarization of the electrode, in effect both decreasing the potential difference between the anode and the cathode, and increasing the electrical resistance across the cell (18). In consequence they can only function when applied directly to the substrate.

The primers derive their inhibitive properties from the pigment, which historically has either been a partially soluble hexavalent chromium salt (such as zinc potassium chromate, strontium chromate, or zinc tetroxy chromate) or basic lead compounds such as red lead.

The chromates are known as direct inhibitors and will function irrespective of the vehicle type with which they are com-

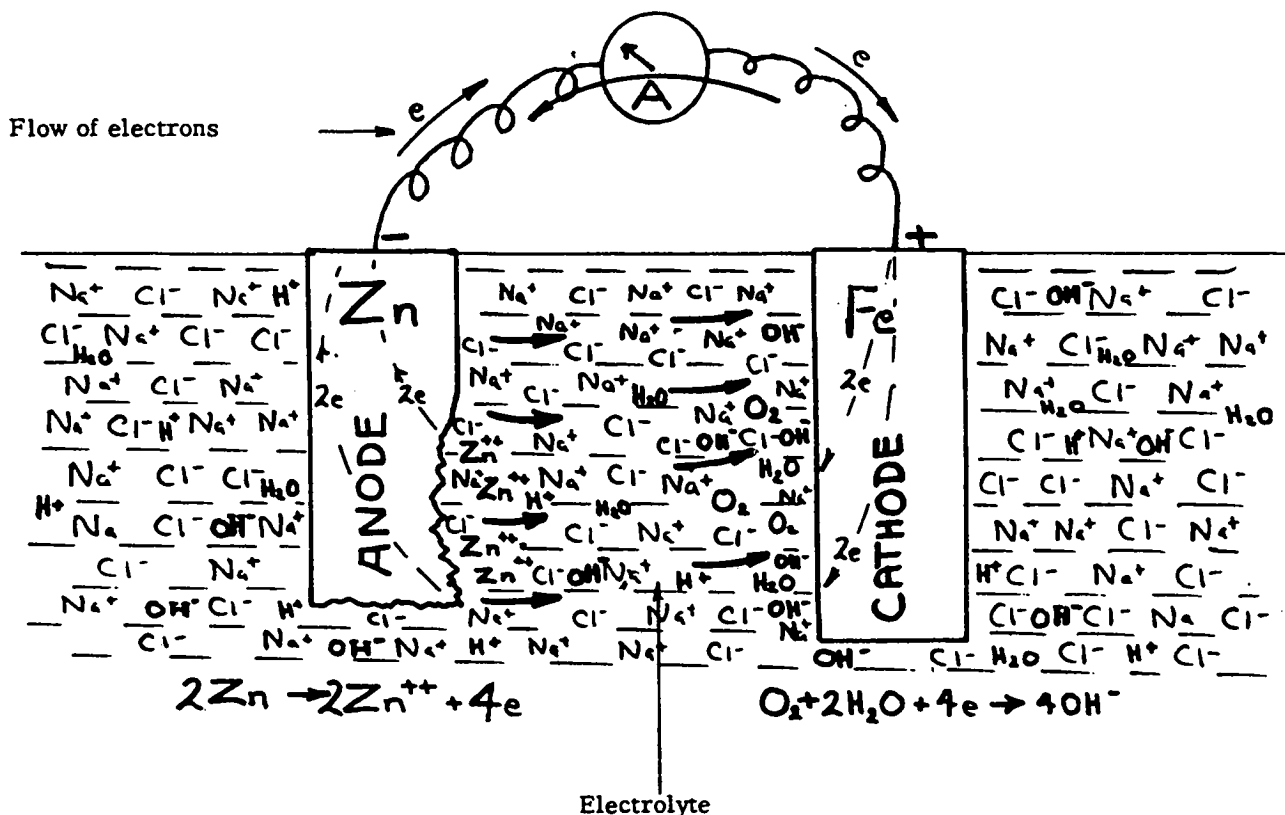


FIGURE 1 Electrochemical corrosion cell.

bined, as long as the volumetric ratio of the pigment to nonvolatile vehicle is such that small quantities of moisture may slowly penetrate the coating. Essentially, such pigments act as a reservoir of inhibitive ions, which dissolve slowly in minute amounts of water that penetrate the coating film, and are carried to the metal interface where they may effectively modify the electrical resistances by fostering the formation of passive films (Fig. 3).

Lead pigments, sometimes referred to as indirect inhibitors, are thought to function via reaction with acidic derivatives of specific vehicle types, such as certain vegetable oils and vegetable-oil-modified vehicle species (alkyds, epoxy esters, uralkyds, etc.) (19). The resultant lead salts dissolve in water in much the same manner as do the chromates and again function by modifying the nature of the metallic substrate.

Since the early 1980s, both lead and hexavalent chromium compounds have become a source of some toxicological concern, which has severely curtailed their use (20). The concerns have fostered the development of a wide range of alternative pigments having reduced toxicological profiles. A score or more of these pigments are now available. They may be loosely grouped together under their various chemical identities, e.g., borates, borosilicates, phosphates, phosphites, phosphosilicates, molybdates, and ferrites (21–25). Most are basic materials and are salts and compounds of calcium, zinc, strontium, aluminum, and barium. Some controversy exists concerning the acceptability of barium compounds as nontoxic materials (26). None of the new inhibitors are found to be as efficient as either the basic lead pigments or the chromates (27). Basic pigments such

as zinc oxide (28), magnesium oxide (29), and calcium silicate (30) have also been shown to be valuable auxiliary pigments in inhibitive primers. Early independent test data of many of the nontoxic inhibitors were quite disappointing, but this could well be related to the primitive nature of early formulations (31). As experience with such pigments has grown, better performance profiles have been achieved, if not up to the levels found with the conventional pigments. Several states and authorities are now evaluating coatings based on such materials on actual bridges.

#### SACRIFICIAL PRIMERS

Sacrificial primers function by the same general principle as do sacrificial anodes used in the cathodic protection of steel hulls, buried pipe, etc. Their function is similar to galvanized films and metallized zinc films. They set up generalized cells in the presence of which all local cell activity on the steel surface ceases as the steel becomes totally cathodic and thereby protected from corrosion (32, 33). The anode, by definition, must be electrochemically negative compared to steel, and for all practical purposes is always zinc metal (Fig. 4). Alloys of zinc and aluminum, also providing cathodic protection to steel, have been used in metallizing (thermal-sprayed coatings) (34) and as hot-dipped coatings (35). In coatings, the zinc is dispersed as a pigment throughout the paint film and is applied directly to the steel surface being protected. Pigment loadings must be sufficiently high so that the effects of highly dielectric vehicles, such

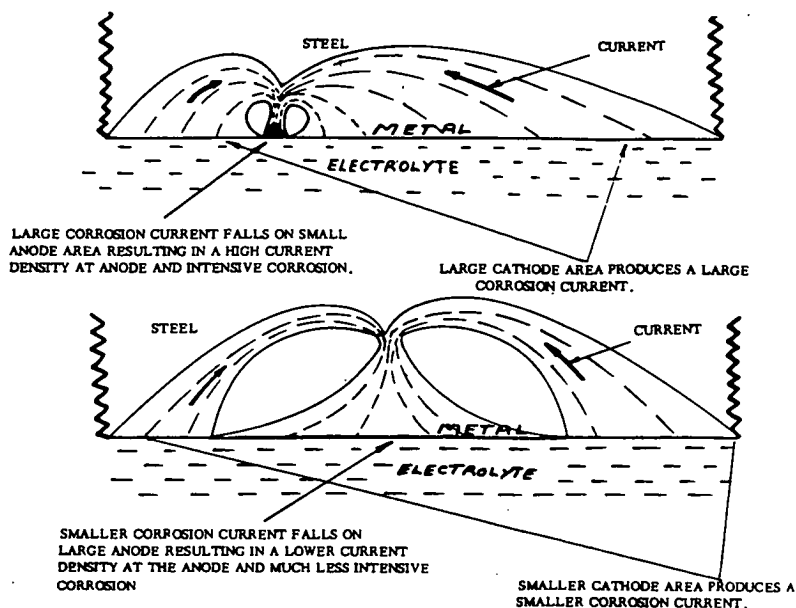


FIGURE 2 Catchment area principle.

as organic binders separating each particle of zinc from each other and from the steel substrate, are minimized, but not so high that cohesive integrity of the primer film is compromised (36).

#### Organic Zinc-Rich Primers

The organic zinc-rich primer is quite properly considered an organic coating, pigmented at a pigment volume concentration (PVC) that equals or even exceeds the critical pigment volume

concentration (CPVC) (that level at which the pigment packing is tightest and there is just enough vehicle to surround each pigment particle with a monomolecular layer of vehicle and fill in the interstices between the pigment). If the primer is much beyond the CPVC, the compositions lose interstitial vehicle and become porous and weakly cohesive; if it is much below the CPVC the particles of zinc are separated so that the electrical resistance of the film becomes too high to maintain cathodic protection. There is, in consequence, a relatively limited formulating window within which such compositions must be controlled (37).

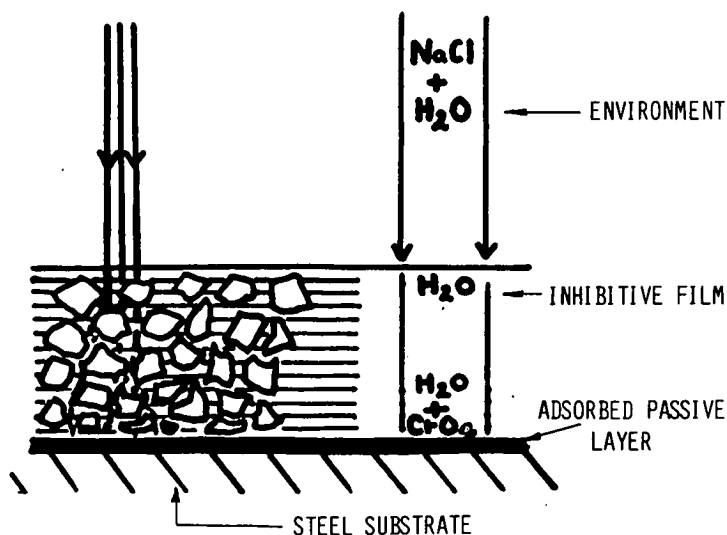


FIGURE 3 Mechanism of steel protection by inhibitive primers. Film is slightly permeable to water but not to ionic solutions. Inhibitive ions, dissolved from pigment by pure water, are adsorbed onto the steel to form a surface less prone to corrosion.

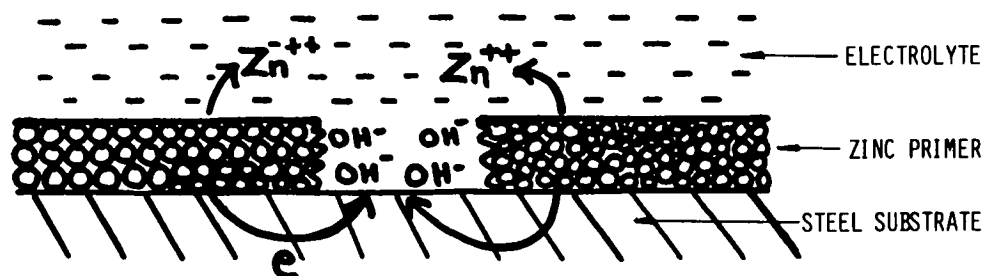


FIGURE 4 Mechanism of steel protection by zinc-rich primers. The presence of strongly electronegative zinc-pigmented coating short-circuits all local cell activity on steel. The steel becomes totally cathodic to zinc anode. The zinc corrodes but the steel will not corrode even at bare spots. It is mandatory that the zinc coating is in electrical contact with the steel surface, therefore the steel must be stripped of all contamination.

### Inorganic Zinc-Rich Primers

Inorganic zinc-rich primers have been produced with phosphates, titanates, and silicates, although the last are by far the most important commercially. Inorganic zinc silicate primers may be categorized by vehicle type, although it seems likely that once fully cured all zinc silicate films are more or less similar in composition irrespective of their composition at the time of application (38).

The two basic types, the alkaline-silicate-based zincs and the alkyl-silicate-based zincs, cure by somewhat different mechanisms, however. The alkaline silicates, typified by the silicates of sodium (39), potassium (40), lithium (41), and quaternary ammonium silicate (42), cure in the presence of zinc by a mechanism that involves the initial evaporation of water and the hydration of the silicate to silicic acid, via carbonic acid from the atmosphere or the application of a post-curing solution (such as a weak acid). The silicic acid then reacts with ionized zinc on the zinc particle to form a three-dimensional zinc-oxygen-silicon matrix, which is further cross-linked over several months by the slow neutralization of residual vehicle alkalinity by additional acidity from the air (38, 43, 44).

In the alkyl-silicate-zinc primers, the solvent evaporation leads to the hydrolysis of the alkyl silicate to silicic acid and the pertinent alcohol (which also evaporates). There follows a reaction between the silicic acid and zinc ion, essentially similar to that described above with the alkaline silicates, and the resultant formation of a zinc-oxygen-silicon matrix (38).

Historically, inorganic zinc-rich primers have been two-component materials wherein the zinc is added to the silicate mix just before application. In the case of the alkaline silicate, reaction between the solvent carrier (water) and the zinc itself mandates the two-pack nature. In the alkyl silicates, however, various techniques have been employed over the last decade to produce single-component, zinc-rich products (45, 46). In general, the industry consensus remains that the two-pack inorganic zincs are rather more reliable for high performance than are the single-pack systems, and cure rates are inevitably faster.

On bridge structures, alkyl-silicate-based zincs are by far the most common inorganic primers. None of the alkaline silicates have achieved the same use, although inorganic zincs based on a colloidal silicate have been used in California (47). If anything,

the alkaline silicates outperform the alkyl silicates, although surface preparation and recoating requirements are perhaps slightly more demanding with these systems than with the alkyl silicates.

The newly formed inorganic zinc-rich film, irrespective of its derivation, is not only cohesively strong but is adhesively extremely secure on well-prepared surfaces. Although some controversy exists concerning the mechanism of such strength and adhesion, the most reasonable explanation seems to be that not only does the primary valency bonded matrix involve zinc ions from the pigmentary surface, but iron ions from the steel substrate (44). Consequently, zinc, iron, and silicate would all be closely bound together in a single large matrix.

Unlike organic systems, the zinc-silicate matrix is itself electrically conductive (38) and the possibilities of highly dielectric encapsulation of some zinc metal in this case are absent. Lower zinc loadings without the switch-off phenomena (brought about by too low a PVC in organic systems) are possible, although performance and longevity of protection (anode life) is undoubtedly directly related to the amount of zinc employed (48).

As the cured inorganic zinc-rich primer ages, zinc continues to react with the environment producing a variety of zinc corrosion products (hydroxides, carbonates, oxychlorides, etc.) depending on the environment (50, 51). As this happens, the resultant corrosion current continues to render the steel totally cathodic and protected. Eventually the zinc corrosion product expanding from the surface of the zinc particles in the film occupies the areas between the zinc particles, sealing the primer film completely and producing a dense, extremely hard abrasion-resistant film. The effect is one of polarization, and protection of the steel is gradually converted from one primarily sacrificial to one with considerable barrier properties. If the coating is in this state scratched, and the steel exposed, sacrificial protection will locally reoccur until the cut is sealed. In this case, however, only the zinc at newly exposed sloping sides of the cut (and not the entire surface) will afford newly bared anode area to protect the exposed steel at the base of the cut. As the ratio of anode area to cathode area is smaller than would be the case were a scribe to be made shortly after application, the intensity of protection is reduced, and where large abrasions occur so that considerable steel is exposed, anode areas may be too small to prevent steel corrosion.

For cathodic protection to be viable, there must be a continuous film of electrolyte across both anodic and cathodic areas. This need only be a thin surface film, but atmospheric service, particularly in dry environments, often precludes this. In this case there can be no protection offered to steel at any bared area.

In more cases on bridge structures, films are recoated relatively quickly after application, long before the primer films are sealed. In this case the penetration of solvents from the topcoat into primer creates a vapor pressure that produces bubbles or "blowholes" in the finish (36). The problem is reduced as the inorganic system ages (becomes sealed), and does not occur in post-cured alkaline silicates wherein sealing is artificially induced during post-curing (although the surfaces require careful cleaning of excess curing residues before coating). With organic systems the problem occurs in the more porous films, and may be related to PVC/CPVC ratios. Several techniques have been explored to reduce or eliminate the problem (49). The most effective technique seems to be the use of a tie coat such as the vinyl butryal wash primer (DOD-P-15328D). Other somewhat less reliable techniques appear to be the use of thin mist coats to seal the zinc before the application of the full topcoats, or the use of "zotcoats" (radically diluted finish coats), applied before the fully concentrated finish. A more complete dissertation on the effects of topcoating of zinc-rich films on performance may be found in the SSPC report on the subject (51).

Zinc-rich primers are often deliberately extended with non-zinc pigments. These extenders have included inert materials (asbestos, mica, or silica) to control application, rheology, mud-cracking tendencies, gassing, inorganics, and PVC/CPVC ratio, or reactive pigments (such as red lead and lead chromate) that improve film formation and prolong pot life (inorganic systems) or improve durability (33). The hexavalent chromates of lead and zinc have also been found to improve durability. It has been postulated that the effect of such inhibitors is to control the rate of anode consumption (52). One of the most common reasons to modify zinc systems with other pigments is to tint the zinc in order to easily differentiate between the blasted steel substrate and newly primed areas during application. As the color of the unmodified zinc primer and white blasted steel are similar, pigments such as lead chromate, yellow iron oxide, lampblack, and red iron oxide have been used. Selection of the particular pigment requires care, especially in inorganic systems (particularly single-pack inorganics), as both stability and performance may be affected. Certain conductive pigments are said to be of value as zinc replacements in sacrificial primers. Careful performance testing of such "extended" systems is advocated, however, with particular attention being given to the levels of zinc replacement, before such primers are employed on a commercial basis.

## BARRIER COATINGS

The barrier coating, unlike the inhibitive primer and the sacrificial primer, is used as both a primer film and as a finish coating over other systems (17). It is typified by an inert pigmentation at lower PVC levels than either of the other two systems, producing a tighter, more cohesive film morphology with significantly lower permeability to water, oxygen, and, in particular, to ionic material (53). The barrier system is exem-

plified by a wide range of coatings, such as the coal-tar enamels, low-build vinyl lacquers, epoxy and aliphatic urethanes, and coal-tar epoxies.

Pure barrier systems are often simple composites of multiple coats of virtually the same product. On bridge structures the coal-tar epoxy system, which has poor ultraviolet resistance, has been used with success on the steel of the expansion bays beneath the road deck, where corrosion control is often the most difficult because of the continual access of chloride solutions from leaky joints (54).

Despite the reduced transmission properties of the barrier system, it has been shown experimentally that normal film thicknesses of even the best barrier coatings used in bridge-paint systems allow more than sufficient oxygen and moisture vapor through their continuum to support the cathode reaction (55). Yet this coating is extremely efficient in maintaining corrosion control even under the most demanding conditions, including immersion in both fresh and salt water, burial in soils, etc., and service under highly corrosive chemical environments.

The mechanism of protection appears to rely on the ionic impermeability of these films (54, 56) (Fig. 5). The property ensures that any moisture that does penetrate the film's continuum and reaches the steel substrate is of so high an electrical resistance that the electrical conductivity of the electrolyte is so low that the transfer of corrosion current between anode and cathode is minimized. In effect, the barrier coating functions by acting like a continuous filter, allowing only pure water through the film but preventing, or at least severely hindering, the migration of all ionic species. It also seems possible that very thick barrier films may so significantly reduce moisture and oxygen transmission that they protect by the simple exclusion of moisture per se.

It is essential in the formulation of the barrier system that all ion-producing pigments are replaced by inert materials. The inclusion of inhibiting pigments, for example, within the barrier film is counterproductive, especially where ionogenic (ion-producing) pigmentations of high solubility are employed in systems for environments of high humidity or fresh water immersion services (53). Under these conditions, osmotic gradients are likely to be set up resulting in film breakdown by excessive blistering (57). Similarly, the entrapment of ionogenic species beneath the film may reduce the necessary high electrical resistance of the moisture that penetrates the film, thereby nullifying the functioning mechanism of the system (58). It is for this reason that surface preparation with true barrier systems must be totally exacting; residual chlorides and sulfates being devastating.

Flat, platey pigments are extremely valuable in the barrier film as they assist in preventing moisture and oxygen penetration by increasing the path of infusion through the film (59). Glass flake, micaceous iron oxide, graphite, and mica are all employed in such coatings. Wide use has been made of aluminum flake in barrier systems, and experimental evaluation of this type of pigment against other lamellar pigments has shown its value (60). High-solids epoxies (61) and moisture-curing urethane barrier systems (62) employing aluminum have recently been achieving an increasing share of the bridge-coating market.

Judicious pigmentation, both in type and amount, must also include some considerations to maximize the electrical resistance of the paint film (63).

Vehicle selection is also important, and is generally best con-

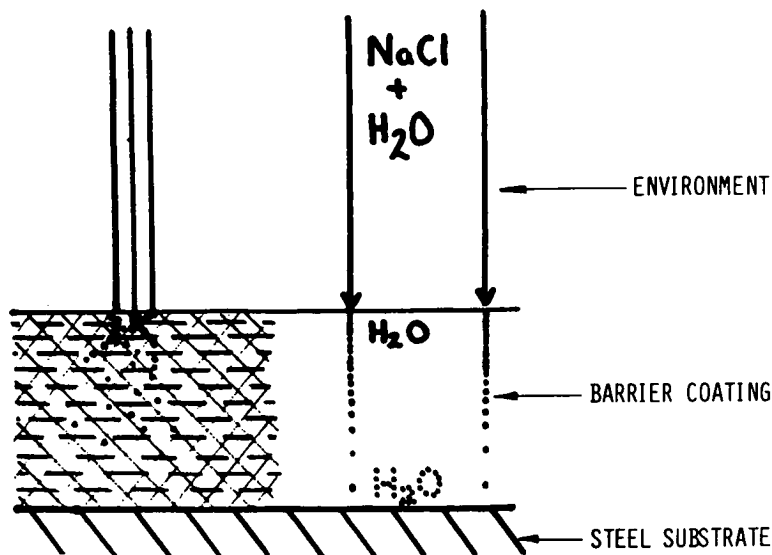


FIGURE 5 Mechanism of steel protection by barrier coatings. Highly impermeable films allow no ionic penetration and only slight oxygen and water penetration. Any water reaching the steel contains no ions and has a very high electrical resistance, hence there is no external passage of current between local anodes and cathodes and no corrosion under the film.

fined to those materials with inherently low moisture and oxygen transmission rates and high dielectric constants.

Vinyls, chlorinated rubbers, and coal-tar systems make excellent barrier vehicles. Epoxies and urethanes, although not having quite the same moisture vapor impermeability as do the above coatings (64), are more conducive to high-build applications and therefore find many applications as barrier systems, particularly when pigmented (65–67). Oil and alkyd systems, with their overabundance of backbone ester groups, do not make good barrier vehicles because of the vulnerability of this group to alkaline saponification. Latex systems, like alkyds, do not make good barrier coatings (68), and are best employed as inhibitive systems. Even then, multi-coat systems are required and their use in snowbelt and in coastal locations will probably be less successful than in drier interior environments.

Film thickness is critical, and, all other things being equal, the thicker the barrier coating system the longer and more successful will be the protection afforded (69, 70). Although economic necessities foster the trend toward fewer, thicker coats, barrier systems in general give better performance when the same film thickness is built up from three or four successive thin coats rather than two coats with twice the film thickness or a single coat with four times the film thickness (R. S. Martell, personal communication, 1988).

In general, high-build barrier systems are of high PVC and morphologically less compact than low-solids barrier systems. This exacts some compromise in impermeability, although this may be made up with increased thickness. High-build systems, used as intermediate coats between zinc-rich primers and low-build finish coats, are quite popular.

#### COMPOSITE COATING SYSTEMS

The system wherein some compromise in impermeability may be acceptable from high-build barrier systems is where such

systems are used over zinc-rich primers, particularly those of the inorganic type. In this case, the finish is no more than the front line of defense, and is supported by the galvanic protection of the zinc-rich system. Properly functioning zinc-rich systems need finish coats for little more than aesthetics, and in consequence high-build “barrier” coats of relatively higher permeability make perfectly sensible finish coats.

In practical circumstances, the tight, relatively moisture-impermeable barrier systems may actually contribute to problems when used over improperly cured zinc-rich systems. Many zinc-rich and other primer films require either water or oxygen to cure completely. If recoated too rapidly with highly impermeable finish coats, the curing process in the primer may be virtually halted by the presence of the topcoat, and the undercured state may be literally locked—precluding the attainment of optimum physical properties in the primer.

It is necessary when using coating systems involving barrier topcoats to verify complete cure (and/or solvent release of the primer) before the primer is recoated, particularly when either the drying of the primer is slow or its cohesive strength is likely to be limited.

The design of functioning composite paint systems is, in fact, often more exacting even than the design of the individual coatings themselves. It is for this reason that individual elements of a complete coating system should be selected from the same manufacturer, who should be aware of the particulars of individual elements (paint films) and should have examined their interactions as a total composite system. In many cases, coating system failure in the field seems to result not so much from a defect in a single element of the coating system as from a failure in one element that has been caused or exacerbated by some aspect of an adjacent element.

Many aspects of such multi-coat design considerations are now well appreciated at the design state, and so basic are the concepts involved that it is difficult to determine whether the original difficulties to which the system design precautions re-

spond were actually predicted from theory, derived from laboratory practice, or first identified as a result of a field problem. Some (usually related to application problems) are revealed so immediately that experimentation would probably isolate their existence before field difficulties were encountered. Such failures are exemplified by the attack of aromatic and oxygenated solvent systems of finish coats on newly applied oxidizing systems, the bubbling of vinyl topcoats over highly porous zinc films (36) or the alligatoring of highly inflexible finish coats over inappropriately flexible primers (57). Other design considerations might be predicted from theory. These might include the necessity of nonmetallic primers to insulate metallic finish coats bearing electro-positive pigmentation (copper or stainless steel) from steel substrates, avoiding possible galvanic substrate pitting; or

the complete degradation of an oleoresinous coating system by cathodic alkali in the areas of expansion bays subjected to continual drenching salt water. Still other design considerations, and probably the majority, undoubtedly result from difficulties originally encountered in the field. These are most often the longer-term problems resulting in failure after the system has been in service for a number of months or even years. These are exemplified by the inadvisability of applying alkyds and oil-based finish coats directly over zinc surfaces (36), or the necessity of using a wash primer tie coat in recoating unmodified phenoxy zinc-rich primers (46). Intercoat adhesion difficulties with epoxy systems resulting from amine carbonate contamination of slow curing (or noninducted) primers when recoated without carbonate removal is another example.

## CHAPTER THREE

## SURFACE PREPARATION

## INTRODUCTION

With the revolution in bridge-painting systems that began in the 1960s, inevitably came a corresponding revolution in surface-preparation techniques. Although oil and long-oil alkyd systems were rather tolerant of the type of surfaces left by simple hand- or power-tool cleaning techniques, the newer high-performance coating systems were not, and, to work satisfactorily, demanded clean surfaces free of contamination. As the emphasis in coating systems gradually changed from straight inhibitive systems to zinc-rich and barrier systems, so the importance of mill-scale removal increased, and the elimination of residual chlorides and sulfates became more critical. As environmental regulations prohibiting the use of inhibitive pigments based on lead and hexavalent chromium spurred on the experimentation with nontoxic inhibitors, the greater sensitivity of these inhibitive systems to chloride ion depassivation again encouraged the abandonment of the older preparatory techniques in favor of those producing a physically and chemically purer surface.

By the late 1960s, some 10 states had abandoned hand- and power-tool cleaning in favor of some form of abrasive blasting (71). Generally this was merely brush-off blasting (SSPC-SP-7), although Louisiana for a while adopted a white blast standard, changing this, after a short time, to a commercial SSPC-SP-6 standard as a more cost-effective procedure. Even so, many states continue to employ oil and alkyd systems and apply these over an SSPC-SP-6 or -7 type surface. By the 1980s (72), almost all states were employing abrasive blasting in some form in maintenance operations as well as in new construction. Many states were employing several alternative coating systems (usually two)—a conventional lead-based oil/alkyd system, and a high-performance system, most often an alkyl-silicate-based inorganic zinc-rich. This dichotomy produced two standards of abrasive blasting, brush-off or commercial for the alkyds and commercial or near-white for the zinc systems (73).

Those states that retained the oil-based systems have found advantage in improved performance with a higher level of surface preparation. This is certainly true in new construction where entire steel surfaces are blasted. Problems still can occur in spot maintenance, where old films around the periphery of a spot-blasted area may be severely damaged without actual removal. Recoating can only further weaken the old paint integrity.

The improved performance cited by many states with the simple oil/alkyd systems on the better surface preparation is hardly surprising. The beneficial effects of improved surfaces on paint-system performance has long been recognized, although

over profiled substrates the application of films of sufficient thickness becomes more critical. Since the early work of Hudson (74), other studies (75, 76) have demonstrated the importance of good surface preparation, so that now the equating of surface preparation with performance has become axiomatic. Data from a Federal Highway Administration (FHWA) study evaluating the effectiveness of a wide range of specialty coatings for use over rusted steel substrates indicate that none is capable of producing a performance profile better than that of most bridge-paint systems on properly prepared steel substrates (77).

## JUSTIFICATION FOR SURFACE PREPARATION

The principal reasons for surface preparation may be condensed into four main points.

1. To ensure a uniform substrate that is in practice as close as possible to a theoretical model originally conceived by the specifying paint system design engineer.
2. To ensure adhesion of the paint system to the steel by removing all loose and tightly adherent contamination and foreign matter (including rust scale and mill scale) from the steel surface, thereby freeing up reactive sites on the metal surface so that subsequent reaction with the paint may take place.
3. To improve adhesion through greater primer/substrate reaction density by increasing the number of reactive sites per given square centimeter of surface area (i.e., by increasing the real surface area per apparent surface area).
4. To ensure that the mechanism by which the paint system protects the steel is neither hindered nor prohibited either chemically or electrically by the presence of soluble moieties such as chloride and sulfate ions on the steel surface.

## SURFACE PREPARATION METHODOLOGIES

Several organizations around the world have established standards for surface preparation (78–86). Some of these are confined to the specifications of blast quality standards only (79, 81), whereas others cover other types of surface preparation (78, 83). A comparison of some of these standards is given in Table 1. None details all the methodologies and most are more concerned with the visual quality of the blast rather than either surface area or freedom from ionogenic material. In many specifications surface area and mil profile are controlled separately



TABLE 1

COMPARISON OF SURFACE PREPARATION STANDARDS

Surface Preparation	SSPC	Description <sup>a</sup>	NACE	Swedish Standard	British Standard	Japanese Standard (Primary)
Solvent Cleaning	SSPC-SP 1	Complete removal of oil, grease, wax, dirt, and other contaminants by cleaning with solvents, vapors, emulsions, alkalis, or steam. Interior environments of low humidity only.	NACE # 5			
Hand-tool Cleaning	SSPC-SP 2	Removal of loose rust, loose mill scale and paint by manual labor with wire brushes, hand scrapers, sanders, etc.	NACE # 6			
Power-tool Cleaning	SSPC-SP 3	Much the same as above but utilizing powered tools such as clippers, descenders, grinders, etc.	NACE # 7	St-2 <sup>b</sup> St-3 <sup>b</sup>		Pt-1 <sup>b</sup> Pt-2 <sup>b</sup>  Pt-3 <sup>b</sup>
Brush-off Blast	SSPC-SP 7	Blast cleaning of all except tightly adhering residues of mill scale, rust, and old coatings, exposing numerous, evenly distributed areas of underlying metal.	NACE # 4			Sd 1 & Sd 2
Commercial Blast	SSPC-SP 6	Sandblasted until at least two-thirds of each element of surface area is free of all visible residues.	NACE # 3	Sa2 <sup>b</sup>	Third Quality <sup>b</sup>	
Near-white Blast	SSPC-SP 10	Blast clean until at least 95% of each element of surface area is free of all visible residues.	NACE # 2	Sa 2.5	Second Quality <sup>b</sup>	Sd 2 & Sh 2
White-metal Blast	SSPC-SP 5	Complete removal of all visible rust, paint, mill scale, and foreign material by wheel or pressure blasting using (wet or dry) sand, grit, or shot. Suitable for all the most severe environments including immersion service.	NACE # 1	Sa 3	First Quality	Sh3 & Sd 3

<sup>a</sup> For complete specification description, see original SSPC document.<sup>b</sup> Misalignment is intentional.

from the control of blast quality. Few U.S. specifications consider the chemical cleanliness of the substrate, and, in general, removal of chlorides and sulfates has not assumed the same importance in the United States that it has in Europe. These deficiencies are considered by McKelvie in a paper reviewing present surface-preparation standards (87). The establishment of a reliable quantitative field test is, however, difficult, and even in Europe viable standards remain elusive. Subcommittee TC35/SC12 of the International Standards Organization is designing a more comprehensive international standard. The scope of the work is described by McKelvie (88).

The preferred surface-preparation technique, therefore, is that which satisfies all four requirements: (a) normalization of the surface, (b) exposing the reactive steel, (c) increasing the real surface area of the steel, and (d) removing all ionogenic materials. Surprisingly, perhaps, few techniques currently in use are totally satisfactory (Table 2).

#### Hand- and Power-Tool Cleaning

There are few techniques that may be described under hand-tool (SSPC-SP-2) or power-tool (SSPC-SP-3) cleaning that satisfy any one of the four basic requirements (Fig. 6). By definition, hand and power tools were never intended to remove more than loose rust, paint, etc. Many hammers, chisels, and other tools do more damage than good as they force as much corrodent into the steel as they remove. They are, however, valuable to remove heavy rust scale before blasting. Blasting through heavy scale to bare steel is extremely time-consuming and impractical.

Hand-held brushes, even when employed correctly, are hardly effective in any respect, and certainly not cost-effective. Power brushes are more effective but leave much to be desired in the quality of the surface they provide and they are less cost-effective than blasting. Power grinders are similarly limited, but serve reasonably well in the feathering of the peripheral edges of paint films surviving spot-cleaned areas. Neither hand- nor power-

tool cleaning methods are suitable for the removal of tight mill scale.

Needle descaling tends to force corrosion product into the steel. Despite these limitations, needle guns are very useful for intricate areas (such as rivet heads, bolts, seams, etc.) and for removing weld spatter.

Some of the newer power tools remove tightly adherent material and provide scarification of the quality of abrasive blasting (89).

#### Dry Abrasive Blasting

Abrasive blasting (Fig. 7) is far more universally effective for most areas of bridges. Although the quality of the surfaces produced will depend on both the type and size of the abrasive as well as the condition of the steel, with the exceptions of the brush-off blast SSPC-SP-7, blasting fulfills requirements 1, 2, and 3 (noted above), and this fulfillment improves as the quality of blasting increases from commercial SSPC-SP-6 through near-white SSPC-SP-10 to white SSPC-SP-5.

In abrasive blasting, one of two principal methodologies is employed: centrifugal blasting (Fig. 8) or air blasting (Fig. 9). Centrifugal blasting (90-93), normally a shop procedure, involves the passage of steel members through a field of high-velocity abrasive particles produced by several electrically driven rotating bladed wheels that hurl the abrasive at the steel. Portable units (94, 95), which themselves move over the steel surface, have been employed in the ship-building industry, but are rarely used on bridge structures in the field because of the complex geometries that are involved. The increased availability of centrifugal blast equipment has played a large part in the increased use of abrasive blasting preparatory techniques, which were a prerequisite to the adoption of the high-performance coatings. As the abrasive is normally reusable, the more expensive blasting media (96) may be employed in centrifugal blasters, and as steel in fabrication is most usually clean, with fewer contaminants

TABLE 2

THE EFFECTIVENESS OF VARIOUS SURFACE PREPARATION TECHNIQUES ON ATTAINMENT OF SATISFACTORY SUBSTRATES

Cleaning Methodology	Normalization of Substrate	Removal of Interference Material	Increase in Surface Area	Removal of Soluble Salts
Hand-tool Cleaning	Poor	Poor-Fair	Poor-Fair	Poor
Power-tool Cleaning	Fair	Fair	Fair	Poor-Fair
Brush-blast Cleaning	Fair	Fair	Good	Poor-Fair
Commercial Blast Cleaning	Good	Good	Excellent	Good
Near-white Blast Cleaning	Very Good	Very Good	Excellent	Very Good
White-blast Cleaning	Excellent	Excellent	Excellent	Very Good
Water Blasting	Good	Good	Poor	Fair
High-pressure Water Blasting	Very Good	Good-Very Good	Poor	Good
Wet Abrasive Blasting	Very Good-Excellent	Very Good-Excellent	Excellent	Excellent

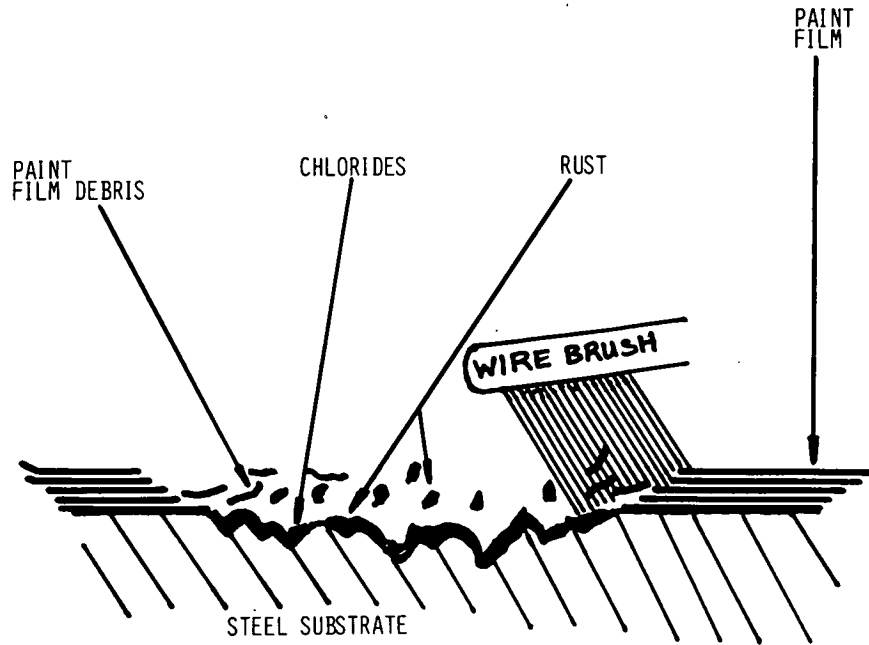


FIGURE 6 Stylized representation of hand- and power-tool cleaning. Wire bristles only partially scarify the steel surface, remove loose paint, rust, and dirt. They do not remove tight paint, rust, and mill scale or embedded ionic contamination. There is little air pollution but it is inefficient and the effectiveness is poor.

except rust and mill scale, metal shot or preferably shot and grit mixes can be employed. Care must be taken to ensure that recycled abrasive is continually stripped of contaminants (oils, etc.), as these can severely affect the quality of the blast and the production. In general, centrifugal blasting saves much time and money compared to air blasting.

In the field, air blasting, where abrasive is propelled at high velocity from a venturi nozzle in a stream of compressed air,

is normally used (97, 98). In such open blasting, collection and recovery of abrasive is difficult, and in consequence lower-priced abrasives are employed. Silica sand, coal slag, mineral slag, garnet, and crushed flint are all used, although silica sand is in some areas prohibited because of toxicological effects (silicosis). In areas where abrasive recovery is possible, steel grit or aluminum oxide may be used.

In field blasting particularly, corrosion of steel in the interval

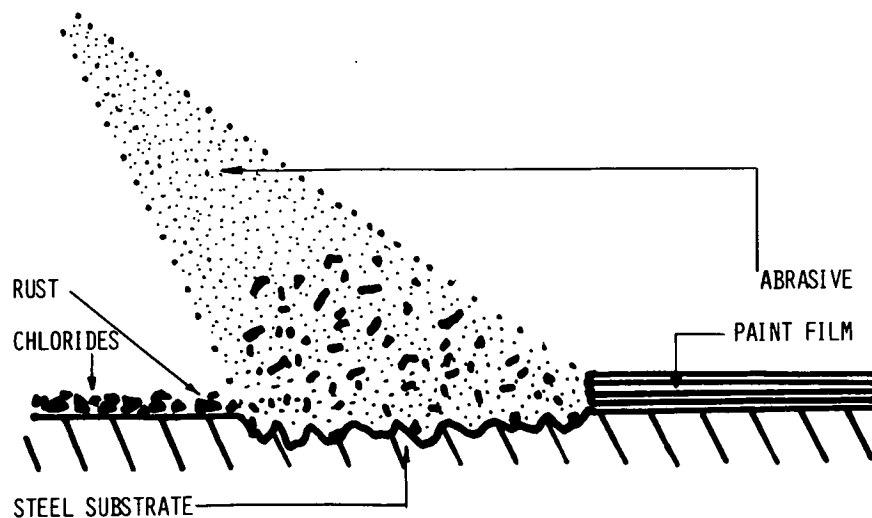


FIGURE 7 Dry abrasive blasting. This method provides an excellent scarification of steel surface removing paint, rust, steel, and most contamination. It may not entirely remove chlorides, particularly from pits. It may produce hazards from blast debris, it is dirty, and much waste is produced.

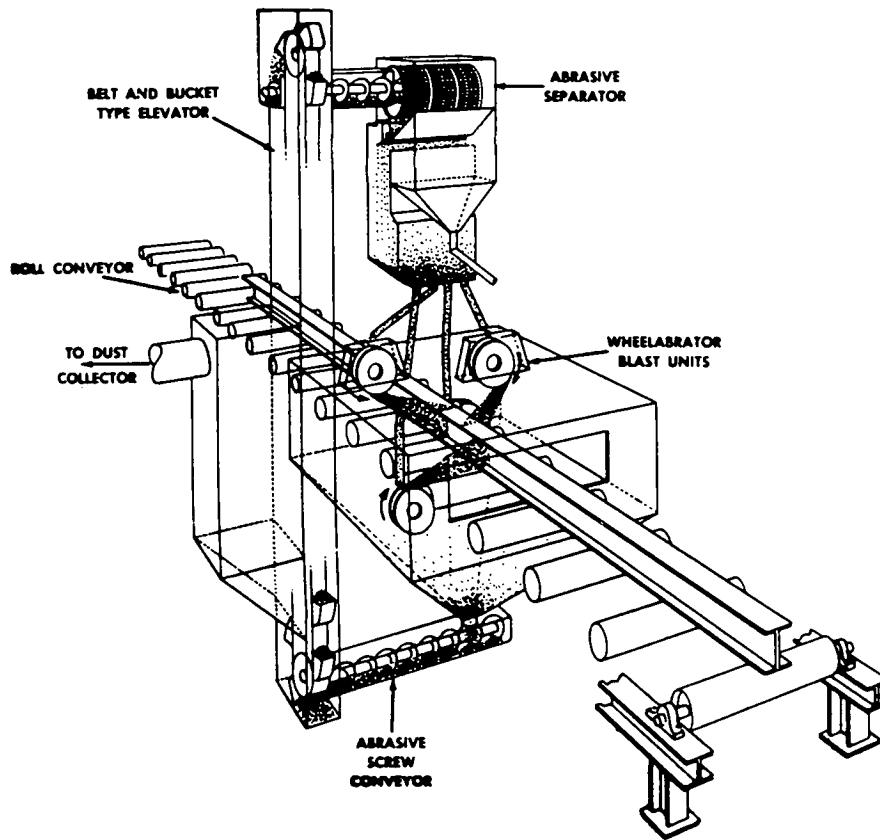


FIGURE 8 Centrifugal blasting methodology. (Courtesy of Wheelabrator-Frye, Inc.)

between the blasting and priming operations is always possible and can be a costly complication. In humid environments, or in areas where fogs or mists can develop rapidly and unexpectedly, blasting/priming schedules can be disrupted by the newly blasted steel "turning." Zinc shot (99) and other abrasives in which zinc is mixed (100), or, more effectively, where abrasives are coated with zinc (101), have been found to provide much longer noncorroded intervals between blasting and priming. The zinc embedded in the steel surface gives a limited but satisfactory cathodic protection to the blasted steel for as long as several days. Adhesion of subsequent coatings is said to be good (102). The major limitation of the zinc-modified blast appears to be cost, which relegates the technique to areas where its advantages are absolutely necessary to solve specific problems.

In a recent study by Peart and Flounders (103), several types of common abrasives were evaluated for a variety of properties including purity, pH, chlorides, and sulfate content as well as cutting rates and breakdown characteristics. The chemical purity of slag, sand, and abrasives in general is of considerable importance, because of the dangers of deposition of impurities on steel surface. Copper abrasives are of concern because of the effects of the deposition of electrochemically cathodic (with reference to steel) copper metal on the steel surface and the possible corrosion that this can cause.

Not only is the type of grit important in abrasive blasting, but both shape and size are directly related to the typical anchor pattern or mil profile that is provided to a given surface (104).

Round shot produces a crater-like surface topology with smooth rims; grit-abraded surfaces are more irregular, particularly when nonmetallic abrasives are employed. Coal slag, for example, one of the widest employed abrasives in maintenance painting, produces highly irregular surfaces compared to those produced by steel grit, which has a more orderly array of superimposed craters (105).

The deficiency of the dry abrasive blasting process to rid steel of ionic contamination is, of course, more severe in the maintenance application than it is in new construction, for on old corroded bridges not only is ionic contamination likely to be greater, but surfaces are less conducive to easy contaminant removal. The limitations of the dry blasting process and the susceptibility of corroded spots to ionic contamination are clearly visible when newly blasted areas of spot-corroded steel are allowed to stand without coating. Here it is always in the old pitted areas (now newly blasted) where the old coating had deteriorated that corrosion of the new surface is first seen (73).

#### Water Blasting

Water blasting (hydroblasting) (103, 106, 107) is very effective in removing chloride contamination and quite effective in removing sulfates (Fig. 10). At 10,000 to 20,000 psi, the technique will also remove old paint, rust, and loose scale. It will not, however, entirely remove all tightly adherent mill scale (except at very high pressures) nor will it mechanically scarify the sur-

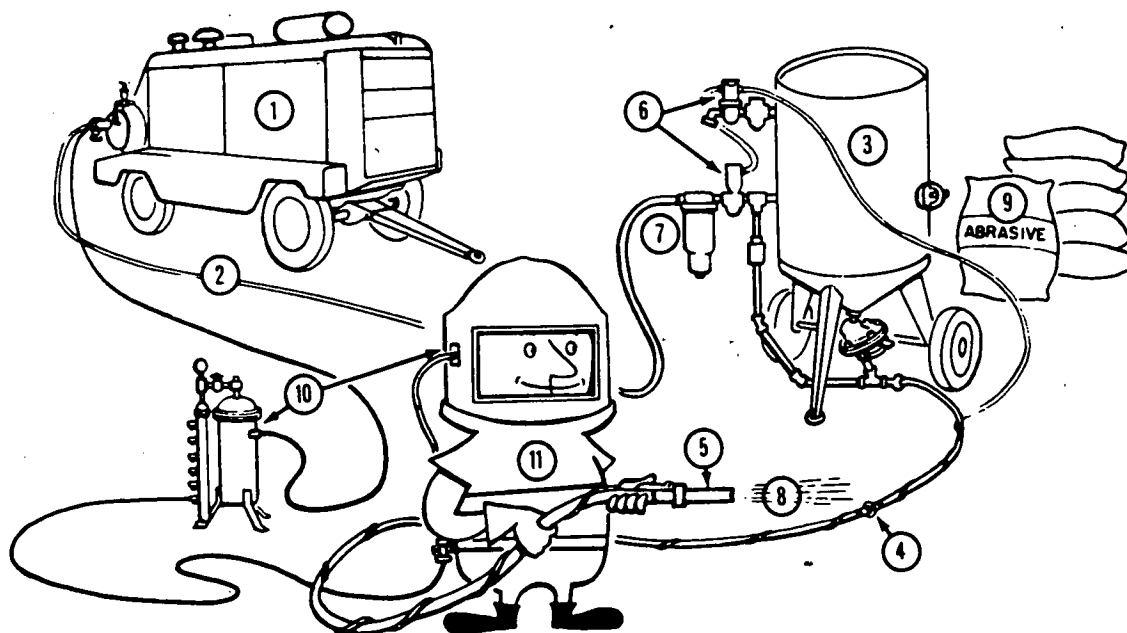


FIGURE 9 Air blasting methodology. The components of a good air pressure blast system are: (1) Compressor giving an adequate and efficient supply of air. (2) Air hose, couplings, and valves of ample size. (3) A portable, high production sandblast machine. (4) The correct size anti-static sandblast hose (with externally fitted quick couplings). (5) High-production venturi nozzle. (6) Pneumatic remote control valves for safety and cost savings. (7) Moisture separator. (8) High air pressure at nozzle. (9) Correct type and size of abrasive. (10) Air fed helmet and air purifier (in good working order). (11) A well-trained operator. (Courtesy of Clemco-Clementina Ltd.)

face. At such high pressures, the technique also involves considerable operator fatigue and it is dangerous. In consequence, pressures nearer 5,000 psi are more nearly the norm in bridge maintenance.

#### Wet Abrasive Blasting

A more satisfactory surface preparation is achieved if abrasives are fed into the water stream (108, 109). These wet tech-

niques satisfy all of the criteria mentioned for good surface preparation (Fig. 11). They suffer only from the messy sludges that result (again increasing the hazard to operators, and, on high structures, to traffic below) and from a tendency of the steel so blasted to corrode before paint can be applied. Although it is often possible to satisfactorily dry the steel before corrosion sets in by either eliminating water or water and abrasive immediately after the wet blast (dry blasting or blowing the newly blasted steel dry as a second step), the wet over-blast contamination of dried areas already blasted often cannot be avoided.

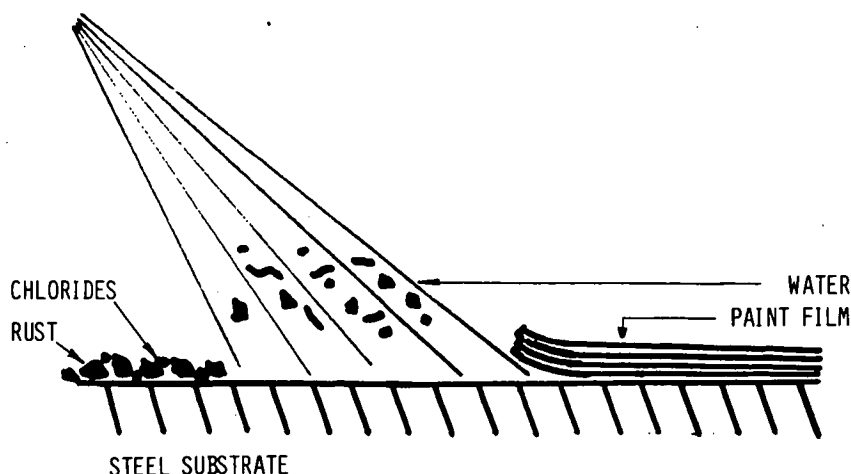


FIGURE 10 High-pressure water blasting. Steel is not scarified by this method. Paint, rust, and ionic materials are successfully removed.

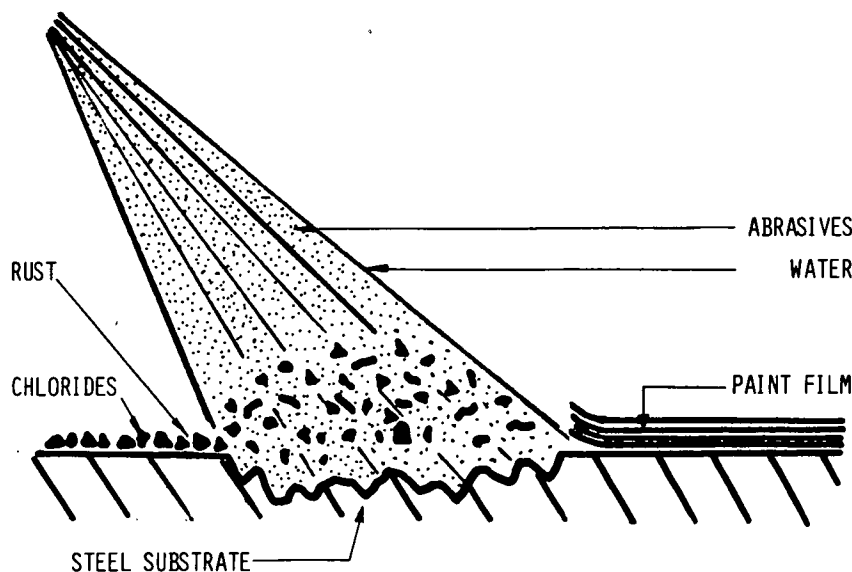


FIGURE 11 Wet abrasive blasting. This combination of water, abrasive, and air removes steel, rust, paint, and all ionic materials effectively. Steel may rust before it can dry off unless care is taken. There is little air pollution with this method, but it does produce a messy residue and there is a safety hazard to operators.

This problem results in a need for constant reblasting and makes the technique less cost-effective. The problem is particularly difficult in areas such as overhangs, open boxes, etc. A general treatise of wet abrasive blasting and of the newer surface preparation techniques may be found in the *SSPC Manual*, Vol. 1, 2nd Edition (110).

Further refinement of the wet-blast method involves the use of inhibitive solutions introduced into the water. This technique results in passivated surfaces that resist rust for several days after blasting. Inhibitors employed may be chromates, phosphates, nitrates, etc., as well as water-soluble amines, and although there exists the theoretical possibility of adhesion problems or osmotic blistering of barrier systems applied to such substrates in areas of high humidity, tests have shown little problems with adhesion of self-curing, water-based inorganic zincs to this type of substrate (111).

The air abrasive wet blasters (112, 113) are described as very efficient (80 to 90 percent of dry blasting) with little loss of visibility and good control of airborne dust. They are messy, however, and somewhat cumbersome, requiring two hoses to mix water and abrasive at the nozzle. Slurry abrasive blasting units (114) are for large production and are more expensive. In these units the water and abrasive are mixed in a control unit, which must be separately manned and which feeds the slurry to multiple operating nozzles. Advantages are high efficiency, low water flow rates, automatic inhibitor monitoring, and greatly reduced dust.

High-pressure water abrasive blasting (115) uses much less abrasive but high water rates. This allows the use of longer hoses but efficiency is reduced (30 to 50 percent of dry blasting). The units are expensive and are probably best employed in the removal of old paint and rust. Visibility during operation is poor and high thrust (6,000–15,000 psi) results in operator fatigue. Less expensive and less exhausting are the low-pressure (2,000–4,000 psi) water abrasive blasting units (115, 116). These units

have much poorer efficiency and are again best used for rust and paint removal rather than surface scarification. They operate at lower water flow rates, use short hoses only, but have the advantage of better portability.

#### Experimental Preparatory Procedures

In recent years, environmental concerns and a greater awareness of the possible toxicological problems that may be associated with the removal of old lead paint systems from bridge structures in urban areas have perhaps motivated the search for alternative preparatory techniques as much as have the more basic engineering concerns. Local control of toxic aerosols from open-air blasting by means of vacuum-blasting techniques, although efficient on flat uninterrupted surfaces, is not as effective on many bridges where the profusion of rivets, angles, and corners reduce vacuum efficiency. The technique is also slow and tiring for operators, which again reduces efficiency. Aside from wet abrasive blasting, little success has been realized in producing a viable, cost-effective option to dry abrasive blasting, and environmentally protective developments involving containment of the dry blast debris have been more successful (9, 117, 118).

There are many new concepts currently being explored in the surface preparation of metal. Many of these are reviewed in a recent SSPC Report (95). They range from space-age variants of flame cleaning techniques, such as laser (119, 120), xenon lamp (121), and high-velocity ice pellets (122), to ultrasonic (123) and bacterial cleaning (124), to citric acid cleaning (125), coating removal via cryogenic techniques, and high-shrinkage strip coatings such as those based on polyvinyl pyrrolidone (126). None of these techniques at this time, however, appears to provide any real practicality in regard to adaptations for the

surface preparation of steel bridges, particularly for bridge steel preparation in field maintenance applications.

Recent experimentation has involved an evaluation of cavitation blasting (127). In this process, air bubbles introduced into a high-velocity water stream collapse against the surface being cleaned producing a severe localized pressure reversal that literally pulls contamination and old coatings from the steel surface. Difficulties have been experienced in achieving practical production rates with this concept, however, and to date a satisfactory cost-effective practical adaptation remains elusive. Stand-off distances are critical to cavitation effectiveness, and the procedure does not scarify the steel surface.

#### PREPARATION OF CONTAMINATED WEATHERED ASTM A 588 SURFACES

A growing concern to the industry, particularly in the snow-belt or along coastlines, is a deterioration of unpainted weathering steel (ASTM A 588). Several studies (128, 129) have shown that in high-chloride-ion environments, weathering steel in the areas of steel bridges that are well sheltered from the washing effects of rainfall is subject to severe corrosion. The mechanism of attack is particularly dangerous as the steel develops a honeycombed deterioration with chloride solutions becoming deeply embedded into the grain structure of the steel. This effect makes cleaning considerably difficult. It has, however, been the subject of considerable study by Tinklenberg at the Michigan Department of Transportation (128) and Raska at Texas DOT (130) who experimented with various water washing and abrasive blasting combinations before coating with a variety of different

coating systems. So deep is the entrainment of chlorides in such steel in these areas (deterioration might be as accurately described as honeycombing as pitting) that the removal of chloride by this technique is never adequate. Once these surfaces have corroded under such circumstances, total rectification of the steel appears to be considerably more difficult (if not impossible) than does the rectification of ASTM A 36 steel. Tinklenberg concludes that simple abrasive blasting is in this case as appropriate a technique as the various blast/water wash combinations examined, and produces results that are quite comparable. Other studies indicate the benefits of wet blasting and/or washing, however. Many of these are discussed in the SSPC State of the Art Review (131).

#### CLEANING OF EXISTING PAINT SURFACES

In the maintenance painting of existing bridges, where funding is restricted or the extent of deterioration is insufficient to justify the complete removal of the existing paint system, it remains a common practice to spot clean and prime deteriorated areas of the structure and apply full coats of conventional oil/alkyd intermediate and/or finish coats over both spot repairs and existing films in good condition. The procedure is widely practiced throughout the United States, and in most states lead-based systems are reapplied. Although not so common, and less advisable, such spot techniques have also been employed with high-performance lacquers and chemical converting coatings such as epoxies (73). In this technique the pre-blast cleaning of the existing paint film becomes more critical, as the existing

TABLE 3

SSPC-SP-1 METHODOLOGIES AND THEIR EFFECTIVENESS IN THE REMOVAL OF SOIL TYPES

Cleaning Methodology	Road Soils	Deicing Materials	Chalk	Bird Droppings	Organic Chemicals	Inorganic Chemicals
Water Washing	Fair	Good	Poor	Fair	Poor Poor	Good
High-pressure Water Wash	Good	Very Good	Fair	Very Good	Fair	Very Good
Detergent Wash/Water Rinse	Good	Very Good	Fair	Good	Good	Very Good
Alkaline Cleaning/Water Rinse	Good	Very Good	Good	Very Good	Very Good	Very Good
Emulsion Cleaning/Water Rinse	Good	Very Good	Fair	Very Good	Good	Very Good
High-pressure Detergent Wash/Water Rinse	Very Good	Excellent	Very Good	Excellent	Very Good	Excellent
Detergent Wash with Mechanical Scrubbing/with Water Rinse	Very Good	Very Good	Very Good	Very Good	Very Good	Very Good
Solvent Cleaning	Good	Poor	Fair	Fair	Very Good	Poor
Steam Cleaning with Water	Good	Very Good	Good	Very Good	Good	Very Good
Steam Cleaning with Detergent/with Water Rinse	Excellent	Excellent	Very Good	Excellent	Excellent	Excellent

film then becomes in effect the new substrate and attention must be paid to ensuring that this film is free of all contaminants.

In some cases, where existing films are hard, old, and highly cross-linked, such as might be the case where old epoxies have been used in the past, it may be necessary to provide mechanical scarification by water or sweep blasting to obtain a reasonable key for adhesion of the new finish. In the majority of cases where such older films are oils and alkyds, for example, such radical techniques are unnecessary (although the removal of oil, grease, road dirt, chalk, and ionic materials from the films to be recoated remains important). In the snowbelt, after winter, or on coastlines throughout the year, the cleaning of accumulated chlorides from such structures before blasting or power-tool cleaning becomes even more important, as does the removal of sulfates from bridge structures in industrial environments. As in painting bare steel, the degree of care in pre-blast preparation will to some extent be dependent on the type of new coating system to be used; oil paints and alkyds being more forgiving than high-energy systems, which require better surfaces for good adhesion.

The several techniques, discussed and grouped under SSPC-SP-1 (132), provide methodologies for such cleaning. Additional information may be found in Volume 2 of the *SSPC Manual* (133). A more detailed treatise on soil removal may be found in Spring's text (134). Not all techniques discussed under SSPC-SP-1 are universally applicable to the removal of all contaminant species (see Table 3), and, those that are, are usually the more expensive. Effectiveness is dependent on the selection and mastery of the correct technique. Water, for example, will remove

ionic contamination, especially chlorides, but will not touch oils or road dirt. Solvent cleaning will remove oils, greases, and road dirt but not ionic species. Neither method, without some mechanical assistance, will remove chalk from existing films. More effective are the use of detergent solutions and steam cleaning (with or without the use of chemical agents such as metasilicates), although in all cases where chemicals and/or detergents are employed a two-stage process is necessary where paint films are rinsed after cleaning to remove chemical contamination. In detergent solution cleaning, it is often necessary to use mechanical assistance, such as brush scrubbing or brooming of the surface, before rinsing. In steam cleaning, it is important to allow the hot detergent solutions to work on the oils, grease, and road dirt before a second clear water pass is used to rinse the coating film. Water blasting may also be employed and, with high pressure and good pressure control, may remove rust and loose scale from the spot-deteriorated areas in addition to old poorly adherent paint. This may eliminate the need for subsequent blasting or power-tool cleaning where suitable low-energy coatings are to be employed in the new system. In many cases, as in subsequent spot blasting, it may be expedient to use hammers and chisels before water blasting to remove highly adherent heavy rust scale. Like water blasting, steam cleaning is also useful for removing old oxidized paint systems. In water blasting, as in both steam cleaning and high-pressure washing techniques, control of dwell time of the process in one particular area is important, as all techniques are capable of removing still viable films of old paint.



## CHAPTER FOUR

## COATING SYSTEMS FOR STEEL BRIDGES

Practical paint systems for bridge structures are designed to employ one or more of the fundamental mechanisms of corrosion control outlined in Chapter 2. The possible permutations of primer and finish coat systems that might be employed to produce viable coating systems for bridge structures are many and increase as each new adaptation of polymer type to coating function is added. Many combinations are, of course, not possible because of incompatibility of polymer properties with coating characteristics (the sensitivity of vegetable-oil-based systems to saponification when employed as vehicles for zinc-rich systems, for example). In other cases, economic considerations discourage adoption (acrylics or aliphatic urethane primers and midcoats), while in yet others the market opportunities have already been more satisfactorily fulfilled by other coatings (vinyls, acrylics, and chlorinated rubbers as thermoplastic finish coats instead of phenoxy-resin-based topcoat vehicles). The vast array of potential candidates is consequently trimmed by a sort of natural selection to a more manageable list, at least from the generic standpoint.

Each new system brings its own particular requirements for surface preparation and application as well as its own peculiarities that relate not only to its film formation methodology and its mechanism of protection but to its resistance to moisture, sunlight, corrosives, and physical abuse. None are as universal or as tolerant of variations from the ideals of preparation, application, and use as were the old lead-based systems, and most are less understood by specification writers and applicators alike. On the other hand, there is little doubt that if properly applied in any given environment (particularly those more demanding environments), the best of the new systems, carefully selected, will produce substantially better and more cost-effective protection than will the systems they replace. Consequently, each year more and more bridges are being converted from the lead- and chromate-based inhibitive approach to zinc and barrier systems.

Unlike the classic red lead/linseed oil systems, formulations of which are well known and have changed little over the past 200 years, or the basic lead-silico-chromate systems developed and marketed so well in the early 1960s, the majority of the newer coating systems have been adopted from proprietary products of individual paint manufacturers who have introduced them directly to the states and bridge authorities. The formulations of even commodity items, such as ethyl-silicate-based zinc-rich primers, have in consequence been closely held and even now for the most part remain inadequately appreciated by the states that specify them. Furthermore, as one product may

radically differ from a generically similar product of another manufacturer, the older compositional forms of specification have given way in many cases to performance specifications that may or may not have a quasi-compositional outline (weight per gallon, minimum zinc content, etc.), but give little real guidance as to the details of the composition.

In consequence, terms such as high-build epoxies and aliphatic polyurethanes are generalizations about large families of products that may not only vary considerably in formulation [pigmentation, pigment volume concentration (PVC), critical pigment volume concentration (CPVC), volume solids, solvent systems, etc.] but may actually be polymerically very dissimilar. High-build epoxies, for example, may employ different types of curing agents including families of resins such as polyamides, amido-amines, aliphatic and cycloaliphatic amines, and aromatic amines, with or without catalysts such as nonylphenol or tertiary amino phenolic materials, not to mention epoxy resins of various molecular weights, and modifications utilizing a variety of mono- and di-functional diluents, acrylic monomers, hydrocarbon resins, butylated urea formaldehyde, and silicone resins (135). Families like polyurethanes, with their rich diversity of available polyols and choice of di- and poly-isocyanates, are still more difficult to categorically specify despite qualifications of polyols as polyesters or hydroxy functional acrylics. The ASTM five-family categorization for urethanes does little more than classify the polyurethane family in terms of curing mechanisms. A similar plethora of formulations are probable for many other systems and in some cases (such as vinyls) an incomplete or erroneous specification of polymer type can lead to severe performance difficulties in service.

Although all vinyl chloride/acetate resins will, for example, adhere to films of other vinyl chloride/acetate lacquers, only the maleic acid modified terpolymer will adhere to bare steel. Unfortunately, this carboxylated vinyl will not adhere to the wash primer (DOD-P-15328D) (136) that is required pretreatment for steel to ensure the adhesion of the hydroxylated vinyls. These and the unmodified copolymers will not adhere well to bare steel (7). On the other hand, certain butyl maleate modified vinyls will adhere satisfactorily to both wash primer and to bare steel.

Because one coating system is found sensitive to a particular failure mode, it does not necessarily follow that all coatings of the same generic type will be similarly sensitive. Formulation effects, pigmentation differences, solvent systems, and differences in the basic polymer (even to differences in the molecular weight of a given thermoplastic) can have significant effects on the susceptibility of a product to a specific failure mode.

## OVERALL TRENDS IN PAINT SYSTEM UTILIZATION ON BRIDGES

Throughout the 1970s, an increasing number of states and bridge authorities experimented with and then adopted many of the newer systems (initially for new construction, but with increasing frequency for field maintenance also). Although some have experimented with one or more of the many new inhibitive pigments, few if any will concede that even the best of these new pigments are a match for the classic lead and chromate materials.

Perhaps the major factor that has retarded the complete abandonment of the inhibitive system has been the number of bridges across the country that now bear these older systems and require maintenance. The funds are simply not available for the complete removal of existing paint from the bridges all at once, and, in consequence, the majority are simply spot repaired and repainted, as they have been for years, with lead- and chromate-based systems. Removal of lead for bona fide environmental reasons has only been a practice in urban areas of the country to date, although this is changing.

It is usual that the inhibitive system is abandoned only when a bridge has deteriorated to the point at which complete paint removal is justified. In drier, more rural climates, a second factor discourages the change. Here, red-lead- and zinc-chromate-based inhibitive systems are found to give long-term protection that reduces the cost-effectiveness of the higher performance systems. Where coatings cure by moisture-activated mechanisms (e.g., alkyl silicate-based zinc-rich primers), there are also problems with drying and recoating in very dry climates. The next single most persuasive factor that appears to discourage some states and authorities from their abandonment of the inhibitive systems has been the failures that have attended the use of the new high-performance systems (36). Although teething problems will inevitably accompany any new technology, paint failures are expensive and embarrassing. The bridge engineer with a million dollar paint failure finds little solace in isolating system peculiarities.

More recently, concern over the difficulties and costs of disposal of the spent abrasive from the removal of old lead-based coatings have also affected decisions regarding the abandonment of traditional finishes.

## INHIBITIVE SYSTEMS

Inhibitive systems now in use by state highway departments may be categorized by five types: red-lead-based systems, zinc-chromate-based systems, nontoxic systems, latex systems, and, most commonly today, systems based on basic lead silico chromate (BLSC). With the exception of the latex systems, all are oxidizing primers and employ oxidizing intermediate and finish coats using either conventional pigmentation (titanium dioxide, chromium green oxide, phthalocyanine blues and greens, etc.) or aluminum. Vehicle systems are either unmodified linseed oil, alkyds (long and medium oil alkyds) with and without linseed oil modification, phenolic varnishes, or modified alkyds such as silicone alkyds and uralkyds. In California, inhibitive latex primers based on zinc chromate/zinc phosphate (137) combinations or zinc hydroxy phosphite are employed in four-coat

systems utilizing, in some areas, latex-aluminum topcoats. The five basic systems are shown in Table 4.

### Red-Lead/Linseed Oil/Alkyd-Based Systems (System Group I)

In its classic form (red lead/linseed oil primer, red lead/iron oxide/linseed oil intermediate coat, and white lead or blue lead linseed oil finish), this system has changed little over the century and a half that preceded the 1950s. The complete system is now hardly employed at all, although versions of the primer and intermediate coat remain the primary maintenance systems in several states.

Red lead/linseed oil primers are generally of the TT-P-86E (AASHTO M 72-74) type employing either straight red lead and linseed oil (Type I) or pigmentary modifications with red iron oxide and alkyd modifications of the vehicle (Type II, III, or IV). The classic 24 to 25 lb per gallon Type I red leads are still the best paints for the poorest surfaces, and there are few benefits obtained from better surface preparation (138). Alkyd modification reduces such tolerances slightly, although all these systems are good for hand- and power-tool-cleaned substrates. Dry times are very slow and two- to three-day recoat periods are usual over the soft films. Increased alkyd shortens these recoat intervals considerably. Film thicknesses of these red lead primers usually vary from 1.5 to 3.0 dry mils although film thicknesses are rarely specified. At very high film thicknesses, skinning and wrinkling become problematic although these defects seem not to have a serious effect on performance, certainly in the short term.

Intermediate coats employ more iron oxide at the expense of red lead and generally introduce more alkyd modification (139). These systems may also employ extenders such as magnesium silicate and even graphite (140). Despite the heaviness of the pigmentation, settling is not often the problem it might be because of the shortness (thixotropy) of these systems (through lead soap formation). Aluminum stearate, once widely used as a thixotrope, has now been replaced by the organo montmorillonites and hydrogenated castor oil derivatives.

Most frequently, red-lead systems today utilize BLSC finish coats (141) [and even intermediate coats (142)] of much the same composition as are used over the TT-P-615 Type I and V BLSC primer based systems. Alkyd or phenolic bound leafing aluminum finishes are also popular (143). Non-aluminum finishes are quite variable in color and range from grays, blues, and greens to beiges, reds, and maroons. Arizona, until quite recently, has used a blue lead topcoat (72) although the use of white lead appears now to have been totally supplanted. Although certain states still retain old lead and oil topcoats in their specifications, the amount of use is probably small. Without lead pigmentations it is virtually impossible to get unmodified linseed oil to dry without severe wrinkling, and most lead and oil topcoats have now been replaced with 100 percent alkyds or heavily alkyd modified vehicle systems pigmented with titanium dioxide, chromium green oxide (144), etc. Longer-oil-length systems are possible when BLSC is employed in the topcoat pigmentation (145), although, in these finishes too, generally the trend is toward slightly shorter-oil-length vehicles. This gives better flow and leveling and better gloss, with some sacrifice to brushability. The lead pigmentation of TT-P-102

TABLE 4

## INHIBITIVE COATING SYSTEMS—UTILITY AND APPLICATION COMPARISON

System Group No.	System Description	Volume Solids (%)	Typical Film Thickness (dry mils)	Surface Prep. (Min.) SSPC-SP	Adaptability to Poor Surfaces	Probability of Early Failure from Deviations in Application	Recoat Times (days)	Solvent Type	Usual Mode of Application	Compatibility with Old Coatings	Ease of Spot Repair	Ease of Cleaning (Salts and Soils)
I	Red Lead/Linseed Oil <sup>a</sup>	95	2.0	2	Excellent	Very low	3	Mineral Spirits	Brush	Excellent	Excellent	Good
	Red Lead-Iron Oxide/Oil-Alkyd <sup>b</sup>	80	1.5						Brush, Roller, or Spray			
	Aluminum/Alkyd or Phenolic <sup>c</sup>	48	1.0				2					
	BLSC/Oil Alkyd <sup>d</sup>	75	1.0									
II	Zinc Chromate/Alkyd <sup>a</sup>	48	2.0	3 or 7	Good	Low	1	Mineral Spirits	Brush	Excellent	Excellent	Good
	Zinc Chromate/Alkyd <sup>b</sup>	48	1.5						Brush, Roller, or Spray			
	Aluminum/Alkyd or Phenolic <sup>c</sup>	48	1.0									
	BLSC/Oil-Alkyd <sup>d</sup>	75	1.0									
III	BLSC/Linseed Oil-Alkyd <sup>a</sup>	77	2.0	3 or 7	Very Good	Low	2	Mineral Spirits	Brush	Excellent	Excellent	Good
	BLSC/Linseed Oil-Alkyd <sup>b</sup>	75	1.5						Brush, Roller, or Spray			
	BLSC/Linseed Oil-Alkyd <sup>c</sup>	75	1.5									
IV	Nontoxic Inhibitive/Oil-Alkyd <sup>a</sup>	63	2.5	6	Fair	Moderate	1	Mineral Spirits	Brush, Roller, or Spray	Good	Very Good	Good
	Nontoxic Inhibitive/Oil-Alkyd <sup>b</sup>	51	2.5									
	Nontoxic Inhibitive/Oil-Alkyd <sup>c</sup>	45	2.0									
	Aluminum/Alkyd or Phenolic <sup>d</sup>	48	2.0									
V	Inhibitive Latex <sup>a</sup>	45	2.0	6	Fair	Moderate	1	Water	Brush or Air Spray	Fair	Excellent	Poor
	Inhibitive Latex <sup>b</sup>	45	2.0									
	Noninhibitive Latex <sup>c</sup> (two coats)	39	3.5									
	Noninhibitive Latex Aluminum/Latex <sup>d</sup>	37	1.5									

<sup>a</sup> Primer coat.<sup>b</sup> Intermediate coat.<sup>c</sup> Finish coat.<sup>d</sup> Finish coat alternative.

and AASHTO M 70-74 (1982) (still on the books of some agencies) has now been replaced with titanium dioxide, and the original linseed oil/bodied oil vehicles replaced with very-long-oil alkyds (146).

It is the fashion today to view these older lead systems as passé and outmoded. Yet they still have a place and probably will continue to have until all existing bridges are totally stripped of old coatings and are upgraded. Some states (Colorado, Montana, Wyoming, Arizona, North Dakota, and South Dakota) even retain these systems for new construction, despite the disruption of shop scheduling caused by the exceptionally long dry times. In these states it is inevitable that lead-painted bridges will exist for some time.

Performance of the lead-based systems, moreover, is hardly marginal; three-coat, 4.5 total dry mils systems are reported in rural Alabama to last 20 years (S. Cauthen, personal communication); in the Dakotas 20 to 30 years are expected (72), and in the valleys of Oregon 40 to 50 years service lives are claimed (147) from 5 to 7 coats of red lead primer/alkyd topcoat systems. Given the low surface preparation requirements, the minimal demands on contractors and inspectors, and the relative freedom from the risks of failure that haunt the newer systems, many state bridge engineers still using these systems are justifiably not motivated to switch to the newer systems.

Linseed oil and alkyds are subject to alkaline saponification, and, in aggressive high-chloride-ion environments, the corrosion process itself may cause degeneration of these oxidizing binders, with susceptible ester groups in the backbone of the polymer. These limitations have led to shorter service lives in the snowbelt states and coastal locations, especially in the Southeast. In industrial areas the service lives of red-lead systems are also severely shortened.

#### **Zinc-Chromate/Alkyd-Based Primer Systems (System Group II)**

The direct inhibitor zinc potassium chromate (ASTM D 478), also known as zinc yellow, zinc chromate, and, in Europe, as basic zinc chromate, has been employed in alkyd and phenolic vehicles for many years. Its use on bridge structures has not been widespread, however, but seems to have increased as lead pigmentation has diminished. The concern over toxicity that has restricted lead pigments has not spread to the chromates despite the concern over the carcinogenic toxicity of hexavalent chromium. In fact, Alabama, which allows the use of either red-lead systems or zinc-chromate systems as both shop and field specifications, reports that for the most part only the zinc-chromate primers are now being used because of worker concern over lead and the extremely slow drying rates of red-lead primers.

Zinc-chromate systems appear to be used more in the South than elsewhere. Alabama, Arkansas, and Florida utilize the systems in one form or another with alkyd topcoats. In Alabama (148) and Arkansas (proposed specification) (149) the first field coat is identical to the shop coat, although Alabama adds black to the intermediate coat to differentiate it from the red oxide colored primer. Alabama uses either an AASHTO M 69 Type I aluminum as a finish, or a green BLSC topcoat with a predominantly alkyd vehicle system. The Alabama primer, like SSPC Paint 11 (150) that it resembles, employs a binder that

is half linseed oil. The use of linseed oil as a binder for zinc chromate has been discouraged elsewhere (151). Alabama, however, reports good service with its system with an estimated 10-year minimum service life for the three coats over an SSPC-SP-6 blast. Alabama does not specify film thickness, but relies on opacity to achieve 1½ mils per coat. Arkansas, using a pure alkyd primer over the same blast quality, specified wet (not dry) film thickness of 3.5 mils per coat. Green or blue finish coats are detailed in the Arkansas specification; or the AASHTO M 69 Type I aluminum is used (3 wet mils per coat). Both states give detailed compositional specifications for all coats and variants.

Florida also relies on the zinc-chromate-alkyd primer when zinc-rich primers are not considered appropriate, and Texas uses a mixture (3:1 to 4:1) of zinc chromate and red lead primer. Alabama, Texas, and especially Florida use zinc-rich systems in fresh or salt water and chemical environments (71).

#### **Basic Lead Silico Chromate (BLSC)/Oil and Alkyd (System Group III)**

This successful system, introduced in several forms in the late 1950s, originally replaced the red-lead systems. Primers are for the most part heavily pigmented with BLSC (iron oxide is added for opacity) and are based on linseed oil and long-oil alkyd vehicles. They are typified by Federal Specifications TT-P-615 Type I through Type V (AASHTO M 229-80, Types I, II, III, and IV). Very-long-oil systems (TT-P-615 Types I and V) are usually employed as primers in most states. As with other lead-based systems, the more alkyd that is introduced into the vehicle the faster are the drying properties but the lower is the tolerance for poorly prepared surfaces. In general, BLSC systems have somewhat more alkyd modification in their vehicles than do straight red-lead systems.

Midcoats are generally shorter in oil length than the primers with lower levels of BLSC and higher levels of other pigments such as iron oxide (152). Typical finish coats (153) may be much higher in percentages of alkyd and range from all BLSC to levels in the 1 to 2 lb per gallon range. Some states employ no BLSC in finish coats when colors are light or when aluminum topcoats are employed. Generally, however, finish coats are pigmented with BLSC that is over-tinted to a variety of colors including greens, grays, etc. with titanium dioxide, chromium green oxide, etc. In Pennsylvania (154) silicone alkyd finish coats are employed as part of the BLSC systems. Formulations and specifications (155) for most states were originally developed as part of an aggressive marketing campaign. Resultant specifications were extremely well documented and have remained essentially unchanged since the early 1960s. Like red-lead systems, the low-energy oil-modified systems were originally applied to new mill scale (later to brush-off and commercially blasted surfaces) but have given satisfactory performance in rural areas for more than 15 years. Like the red-lead systems in the Dakotas, 30-year performances in the rural dry climates of Colorado and Wyoming have been the rule and final service lives of 30 to 40 years are projected. Shorter service lives are seen in the industrialized east, and states such as New Jersey and Massachusetts may realize no more than 7 to 12 years in marine or, particularly, industrial environments.

Like the red-lead systems, the low-energy vehicles make BLSC

paint systems relatively invulnerable to catastrophic early failures caused by compromised surface preparation, although their relatively high solids content and normal three-coat "defense in depth" (155) form provides some insurance against very low film builds. Dry film thicknesses are rarely specified, however, although some states do. Tennessee, for example, calls for 2 dry mils of primer and 1.5 dry mils each of the two field coats.

Unfortunately, manufacturers have been known to take advantage of the low specific gravity of BLSC (approximately equal to barytes) to replace the BLSC with barytes (with or without red lead to maintain the lead content) particularly in finish coats where serious color floatation problems from the BLSC can cause field difficulties. This has often caused problems in drying with the long-oil primers and midcoats, particularly in cold, damp climates at the beginnings and ends of seasons, because of reduced drying catalysis of the low-lead systems. Recent analytical procedures designed by industry are aimed at forestalling such practices (156).

Currently, some 20 states still employ BLSC systems for new construction, although only half regard the system as their preferred system for new work. More (24) utilize the system for spot maintenance in the field (though not necessarily for radical maintenance) and most of these regard this as their preferred system.

A second variant of the BLSC system utilizes an aluminum topcoat instead of the colored finish. The decision to employ this alternative finish coat presumably reflects the somewhat better performance of this type of finish (better UV resistance, increased impermeability). States employing this type of system include Virginia, Wisconsin, and Montana (which employs the system in both new construction and maintenance and considers its results excellent) and to a lesser extent Kentucky and Idaho. New Jersey utilizes a graphite-based finish coat over BLSC primer and intermediate coat on the underside steel of bridge decks (157).

Interestingly, an early advantage claimed as a reason to replace red lead (lower coating weight by virtue of lower specific gravity of the pigment) has been cited as a major reason for the adoption of the BLSC system in the repainting of the Brooklyn Bridge. The system change saved 100 lb per linear foot on the old structure (158). Paint weight can be a considerable factor, especially on older bridges, or on bascule structures where paint buildup must be removed periodically to maintain the counterweight balance.

#### **Nontoxic Inhibitive-Pigment-Based Systems (System Group IV)**

Despite the number of candidates for the replacement of lead and hexavalent chromium pigments, comparably few have found their way into bridge-paint specifications. In response to environmental concerns, in 1979 Massachusetts began to test various new pigments in bridge-paint systems put together by the pigment manufacturers. In 1980 they opted to phase out the BLSC system for a system based on calcium borosilicate (159). After five years of exposure, results are mixed; the same system performs well on some structures, poorly on others. Post-painting inspection has found that the 7.0 dry mils called for in the three-coat specification was rarely, if ever, met, and that surface preparation was generally poorer than specified. The state con-

cluded that for such nontoxic systems to do well they must be given the same sort of care in application and inspection that is called for with the zinc and barrier systems. To counteract the deficiencies in surface preparation and application, a fourth coat was added to the specification, which also was modified to give better distinction between coats. At the same time, the blast requirement was upgraded from a SSPC-SP-7 to SSPC-SP-6. After three years, bridges bearing this system are said to be giving very satisfactory performance. The borosilicate primer is an oil-modified alkyd and one (now two) pure long-oil alkyd intermediate coats are employed. The finish coat is a silicone alkyd, and calcium borosilicate is used in all coats.

The Corps of Engineers used a borosilicate primer and intermediate system with two aluminum topcoats on three bridges over the Cape Cod Canal and has had the same sort of variation in performance associated with the quality of work, with some structures now seven years old looking better than structures similarly painted more recently.

The Port Authority of New York and New Jersey has employed a borosilicate-pigmented silicone alkyd finish coat over lead primers in the maintenance of the Goethals Bridge and the Outerbridge Crossing between Staten Island and New Jersey (160).

A system based on barium metaborate has been authorized as an alternative to the borosilicate system by Massachusetts, although few bridges have to date been painted with this system. Other states, such as California and Idaho (a single instance), have also experimented with nontoxic pigments (zinc phosphate) and zinc hydroxy phosphite in latex paints. California settled initially on a mixture of zinc phosphate fortified with zinc chromate in the first two coats of its four-coat latex system (137), and later adopted a similar primer based on zinc hydroxy phosphite without the chromate.

North Carolina is currently evaluating two nontoxic inhibitive oil/alkyd systems, one based on zinc hydroxy phosphite, one based on calcium borosilicate.

Several zinc-phosphate-based paint systems are approved by the British Department of Transport for use on bridge structures and include systems based on vinyl/alkyds, epoxy esters, chlorinated rubber/alkyds, and epoxies (161). Use of zinc phosphate is not as prevalent in the United States.

Much information from test data on the performance comparison of many of these newer nontoxic inhibitors has been reported by the SSPC in their Project PACE Study. Unfortunately, in this study pigments and paint systems are treated as proprietary materials and not generally identified. Notwithstanding this, the study provides good general data on the performance of this class of system against the more traditional lead and chromate pigments (162).

#### **Inhibitive Latex System (System Group V)**

Apart from oleoresinous oxidizing systems, the only other bona fide inhibitive systems currently adopted on any large scale are the California latex-based inhibitive systems. These systems (137, 163), based on zinc phosphate/zinc chromate (more recently zinc hydroxy phosphite) and a styrene acrylic resin for the primer with acrylic latex finish coats, were introduced in 1979 as a response to the increasingly constrictive limitations on solvent emissions in that state. They are employed as both

spot and full-coat systems. Later variations on these same systems eliminated the zinc chromate from the primer and first coat. Chromate pigmentation tends to promote destabilization of the latex polymer (164), and it is believed that this, as well as environmental restrictions, limited the levels of zinc chromate in the original systems.

In its current form, the primer is applied over a commercial blast in 2 dry mil coats (a red and a pink) over which a latex finish system is applied in two coats of 1½ to 2 dry mils each. In most applications the finish is a simple colored latex paint without inhibitor, although on the Bay Bridge (also bearing the latex system) and on certain draw bridges the finish coat is pigmented with leafing aluminum.

In some early formulations the third coat was based on non-leafing aluminum, but since then this coat has employed an ordinary gray pigmentation. The aluminized latex finish is a relatively simple formulation devoid of surfactants, etc., but, because of stability problems (hydrogen generation), the aluminum and latex are packaged in separate components.

The four-coat Caltrans system is applied over a commercial blast and seems to give service as good as earlier solvent-based systems, although some deterioration at edges, seams, lower flanges, etc. is seen on some structures. These early deteriorations have been associated with such problems as insufficient film build and applications in low-temperature and high-humidity conditions. High chloride-ion concentration of the environment may also play a part because it is in coastal areas where the inappropriate temperatures and humidities have been experienced. In an effort to control the film thickness, the state has now restricted the use of airless spray application because of application control problems. Complaints have been made that it is difficult to get contractors to realize that first coat film thickness is to be measured from the profile peaks, and that additional material must be used to fill the profile before the film thickness count can begin.

Although it remains too early to make a final evaluation on the effectiveness of the California latex system, it is interesting to note that no higher incidence of failure occurs with bridges utilizing this system than other high-performance systems such as vinyls and zincs. A service life of 20 years in the interior valleys may be feasible if the material is applied successfully. In the more demanding coastal applications 5 to 7 years seems more probable. California concludes that location and overall quality of job execution (film thickness, surface preparation, and inspection) are of equal importance to the successful outcome of bridge painting as is the specific nature of the coating system.

## ZINC-RICH SYSTEMS

The zinc-rich primer/barrier finish concept (Table 5) has to a considerable extent assumed the mantle once held by the inhibitive systems for bridge painting. At least 30 states now utilize a zinc-rich system for new construction and, despite the exacting surface preparation and application requirements, more than 25 have employed this type of system in maintenance application. More than a dozen generic variants of the system have been employed ranging from alkaline silicate zinc-rich/vinyls (with a WP-1 tie coat) to uralkyd zinc primer systems with aluminum/styrene acrylic topcoats.

In all zinc-rich systems, the zinc coats are the primary defense against corrosion, and in many instances these (particularly the alkaline silicates) have gone untopcoated in environments of suitable pH and achieved service lives of 20 years and even longer. More commonly, however, both to prolong the coating life and to provide color and the required aesthetics, zinc-rich primers are recoated with simple barrier systems, such as vinyls, epoxies, and urethanes, as one- or two-coat finishes. The results give a more finished appearance to the structure and eliminate the aesthetic drawbacks caused by white rust (zinc corrosion). In some cases coloring pigments have been added to the zinc in an attempt to provide colored zincs in a single coat, but these attempts have been frustrated by color uniformity problems and the inevitable corrosive deterioration of the zinc surface.

The most reasonable categorization of these systems is by the type of primer vehicle, which may be divided into organic and inorganic vehicles. Subclassification within these two categories is again made by virtue of specific vehicle type. Such classifications have been adopted by SSPC (165) and are discussed by Berger (166) and Munger (44).

### Alkyl Silicate Inorganic Zinc-Rich-Based Systems (System Group VI)

The bulk of current inorganic zinc-rich-based systems in use on bridges are two-pack alkyl-silicate-based materials formulated with partially hydrolized ethyl silicate. Commercial offerings of the prehydrolized silicate vehicle have been available for several years (167, 168), and the basic formulations are hardly complex, although thixotropes, extenders, and other pigments (coloring pigments, inhibitors) are not as well documented.

Variations based on zinc content by weight are offered by several manufacturers, but most market an 82 percent zinc (percent by weight of zinc on the dry film weight) version that has served well on numerous bridges across the country.

Single-pack variants are also available, and these are now being adopted by several states that formally adopted the two-component ethyl silicate material. Some sacrifice in performance and in stability has been exacted for the convenience of no field mixing, although studies such as the Mann's Harbor Paint Evaluation have shown some single packs to give performance ratings on a par or better in some cases than the two-pack systems after 33 months of exposure (169). Some authorities, in response to questions concerning the relative merits of one- and two-pack zincs, assert that although the single-pack zincs were not as good as the two-pack systems, bridge service was not so severe that such differences were critical. On the other hand, at least one major manufacturer will not supply single-pack zincs and advocates that no single-pack zinc should be topcoated, citing poor cure response and the dangers of lateral cohesive failure under vinyls, epoxies, and urethanes (170). With some commercial single packs, difficulties with the untopcoated films (mudcracking and delamination) have been noted, whereas with others difficulty with protracted curing rates has been found. Some of these difficulties have been experienced on actual bridge structures. Commercial single-pack resins, if not necessarily as uniform in composition as the prehydrolized resins for two-pack

TABLE 5

## ZINC-BASED COATING SYSTEMS—UTILITY AND APPLICATION COMPARISON

System Group No.	System Description	Volume Solids (%)	Typical Film Thickness (Dry mils)	Surface Prep. (Min.) SSPC-SP	Adaptability to Poor Surfaces	Probability of Early Failure from Deviations in Application	Recoat Times (days)	Solvent Type	Usual Mode of Application	Compatibility with Old Coatings	Ease of Spot Repair	Ease of Cleaning (Salts and Soils)
VIa	Alkyl Silicate Zinc <sup>a</sup> High-build Vinyl <sup>c</sup>	65	3	6	Poor	High	1-7 <sup>d</sup>	Alc./G.E. Ke./Es./ Arom.	Airless Spray	Poor	Poor-Fair	Very Good (Zinc-Poor)
		33	5									
VIb	Alkyl Silicate Zinc <sup>a</sup>	65	3	6	Poor	High	1-4 <sup>d</sup> 0.02- 1.0	Alc./G.E. Alc. Ke./Es./ Arom.	Airless Spray	Poor	Poor-Fair	Very Good (Zinc-Poor)
	WP-1 Vinyl Wash Primer <sup>b</sup>	9	0.3									
	High-build Vinyl <sup>c</sup>	28	5									
VIc	Alkyl Silicate Zinc <sup>a</sup>	65	3	6	Poor	High	1-7 <sup>d</sup> 1	Alc./G.E. Alc. Ke./Es./ Arom.	Airless	Poor	Poor	Excellent (Zinc-Poor)
	Epoxy/Polyamide (High-build) <sup>b</sup>	60	4									
	Aliphatic Urethane <sup>c</sup>	52	2									
VIId	Alkyl Silicate Zinc <sup>a</sup> Epoxy/Polyamide (High-build) <sup>b</sup>	65	3	6	Poor	High	1-7 <sup>d</sup>	Alc./G.E. Ke./Es. Arom.	Airless Spray	Poor	Poor	Excellent (Zinc-Poor)
		60	5									
VIe	Alkyl Silicate Zinc <sup>a</sup> High-build Aliphatic Urethane <sup>b</sup>	65	3	6	Poor	High	1-7 <sup>d</sup>	Alc./G.E. Ke./Es.	Airless Spray	Poor	Poor	Excellent (Zinc-Poor)
		60	4									
VIIa	Alkaline Silicate Zinc <sup>a</sup>	60	3	5	Poor	Very High	1+	Water Alc. Ke./Es. Arom.	Airless Spray	Very Poor	Very Poor	Very Good (Zinc-Poor)
	WP-1 Vinyl Wash Primer <sup>b</sup>	9	0.3									
	Vinyl <sup>c</sup>	17	2				1.0					
VIIb	Alkaline Silicate Zinc <sup>a</sup>	60	3	5	None	Very High	1+	Water Ke./Es. Arom.	Airless Spray	Very Poor	Very Poor	Very Good (Zinc-Poor)
	Vinyl <sup>b</sup>	20	1									
	Vinyl <sup>c</sup>	25	1.5				0.1					
VIIIa	Phenoxy Zinc <sup>a</sup>	38	3.0	6	None	Moderate-High	1+ <sup>d</sup> 0.02- 1.0	Est./Ket. Alc. Ket./Est. Arom.	Airless Spray	Fair	Fair	Very Good (Zinc-Fair)
	WP-1 Vinyl Wash Primer <sup>b</sup>	9	0.3									
	Vinyl <sup>c</sup>	28	5									
VIIIb	Phenoxy Zinc <sup>a</sup>	38	3	6	Fair	Moderate-High	1+ <sup>d</sup> 1	Ke./Es. Arom.	Airless Spray	Fair	Fair	Excellent (Zinc-Poor)
	Epoxy/Polyamide (High-build) <sup>b</sup>	60	4									
	Aliphatic Urethane <sup>c</sup>	52	1.5									
IX	Chlorinated Rubber Zinc <sup>a</sup>	68	3	6	Fair	Moderate	1+ <sup>d</sup> 3	Arom./Alc. Ke./Es.	Airless Spray	Fair	Good	Good (Zinc-Fair)
	Chlorinated Rubber High-build <sup>b</sup>	35	3.5									
	Chlorinated Rubber Finish <sup>c</sup>	36	2									

TABLE 5

## ZINC-BASED COATING SYSTEMS—UTILITY AND APPLICATION COMPARISON (Continued)

System Group No.	System Description	Volume Solids (%)	Typical Film Thickness (Dry mils)	Surface Prep. (Min.) SSPC-SP	Adaptability to Poor Surfaces	Probability of Early Failure from Deviations in Application	Recoat Times (days)	Solvent Type	Usual Mode of Application	Compatibility with Old Coatings	Ease of Spot Repair	Ease of Cleaning (Salts and Soils)
X	Vinyl Zinc Rich <sup>a</sup>	20	2.0	10	Poor	Very High	0.2-1.0	Ke./Es./Arom.	Airless Spray	Poor	Good	Very Good (Zinc-Fair)
	Vinyl <sup>b</sup>	28	3.0				0.2					
	Vinyl <sup>c</sup>	28	3.0									
XIa	Epoxy/Polyamide Zinc Rich <sup>a</sup>	47	3.0	6	Good	High	1.0	Alc./G.E. Ke./Es./Arom.	Airless Spray	Fair	Good	Excellent (Zinc-Fair)
	Epoxy/Polyamide Midcoat <sup>b</sup>	60	4.0				1.0					
	Epoxy/Polyamide Finish <sup>c</sup>	60	2.0									
XIb	Epoxy/Polyamide Zinc Rich <sup>a</sup>	47	3.0	6	Good	High	1.0	Alc./G.E. Ke./Es. Arom.	Airless Spray	Fair	Very Good	Very Good (Zinc-Fair)
	Epoxy Polyamide Zinc Rich <sup>b</sup>	47	1.5				1.0					
	Vinyl Aluminum <sup>c</sup>	14	3.0									
XIc	Epoxy/Polyamide Zinc Rich <sup>a</sup>	47	3.5	6	Good	High	1.0	Alc./G.E. Ke./Es. Arom.	Airless Spray	Fair	Very Good	Good (Zinc-Fair)
	Epoxy/Polyamide Red Lead <sup>be</sup>	49	1.5				1.0					
	Vinyl Toluene/Acrylic Finish <sup>c</sup>	50	1.5									
XIIa	Uralkyd Zinc Rich <sup>a</sup> (two coats)	55	3.5	6	Very Good	Moderate-High	1.0	Arom./Al.	Brush/Airless Spray	Fair-Good	Very Good	Good (Zinc-Fair)
	Vinyl Toluene/Acrylic <sup>c</sup>	50	1.5									
XIIb	Moisture-curing Urethane Zinc <sup>a</sup>	63	2.0	6	Fair	High	1.0	Ke./Es. Arom.	Brush/Airless Spray	Fair	Fair	Excellent (Zinc-Fair)
	Epoxy/Polyamide Midcoat <sup>b</sup>	60	2.0				1.0					
	Aliphatic Urethane Finish <sup>c</sup>	52	2.0									
XIII	Galvanizing <sup>a</sup>	100	5.0	8	Poor	Moderate-High		None	Dip		Fair	Excellent
XIIIa	Galvanizing <sup>a</sup>	100	5.0	8	Poor	High	0.25	None	Dip		Good	Very Good
	WP-1 Vinyl Wash Primer <sup>b</sup>	9	0.3				0.02-1.0	Alc. Ke./Arom.	Airless Spray			
	Vinyl <sup>c</sup>	28	5.0									
XIIIb	Zinc Metallizing <sup>a</sup>	100	5.0	5	Poor	High	0.25	None	Met. Spray	None	Good	Very Good (Zinc-Poor)
	Vinyl (Carboxylated) <sup>c</sup>	20	2.0					Ket./Arom.	Airless Spray			



TABLE 5

## ZINC-BASED COATING SYSTEMS—UTILITY AND APPLICATION COMPARISON (Continued)

System Group No.	System Description	Volume Solids (%)	Typical Film Thickness (Dry mils)	Surface Prep. (Min.) SSPC-SP	Adaptability to Poor Surfaces	Probability of Early Failure from Deviations in Application	Recoat Times (days)	Solvent Type	Usual Mode of Application	Compatibility with Old Coatings	Ease of Spot Repair	Ease of Cleaning (Salts and Soils)
XIIIc	Zinc Metallizing <sup>a</sup>	100	5.0	5	Poor	High	0.25	None Alc. Ke./Arom.	Met. Spray Airless Spray	None	Good	Very Good (Zinc-Poor)
	WP-1 Vinyl Wash Primer <sup>b</sup>	9	0.3				0.02-1.0					
	Vinyl (Hydroxylated) <sup>c</sup>	17	2.0									

<sup>a</sup> Primer coat.<sup>b</sup> Intermediate coat.<sup>c</sup> Finish coat.<sup>d</sup> Critically dependent on attainment of full cure and solvent release.<sup>e</sup> Marine environment only.

systems, are also available from several manufacturers for the preparation of these primers (167, 171).

Some disagreement among manufacturers exists concerning the procedures for touch-up of inorganic zincs and ranges from simply thinning the second inorganic zinc coat to sweep-blasting the original coat before applying the makeup coat. Very often organic zinc makeup coats are applied over hand- or power-scarified surfaces. Epoxy/polyamides and phenoxies have been employed in this way.

The widespread use of organic zincs of high PVC over inorganic zinc films is to be avoided. Over the porous inorganic, some of the vehicle binder from the organic will be absorbed into the inorganic matrix, thus effectively raising the PVC/CPVC ratio of the organic primer and decreasing its cohesive strength. This increases the risk of system failure by lateral cohesive failure of the organic zinc continuum later in service.

As with the two-pack alkyl silicate specifications, however, the single-pack zinc specifications remain vague and reflect the proprietary interests of the various manufacturers of products from which the specifications were derived. Perhaps most seriously lacking is a more complete specification for vehicle systems (including additives such as silanes, borates, etc.), but the manufacturers of the silicate vehicles show little real interest in formalizing specifications such as was done with alkyds, phenolics, and the older vehicle types. Even in the latest specifications, such as that of Virginia (172), the vehicle is often incompletely defined as an organo silicate in appropriate solvents and additives.

In-depth compositional specifications for two-pack alkyl silicates are beginning to appear from some bridge authorities, such as the Massachusetts Turnpike Authority (173). Some specifications such as that of Ohio refer to the Steel Structures Painting Council Paint System Guide PS 12.00 (174), although this does not spell out specific formulations either.

The employment of inorganic zinc dictates a minimum surface preparation quality of SSPC-SP-6 and some specifications prefer SSPC-SP-10. Mil profiles on new steel are preferably 1 to 2 mils, although in maintenance applications involving the removal of existing paint, higher profiles (3–4 mils) are often necessary. Film thicknesses for the inorganic zinc primer usually range from 2.5 dry mils to 5 dry mils, although too high a film thickness (particularly in the single-pack systems) would produce serious film defects such as mudcracking and delayed cure response. These concerns restrict the use of inorganic zinc on structures of complex design with surfaces that are difficult to reach or clean or on which applications of controlled film thicknesses are difficult. Inorganic-zinc-based systems are most ideally suited to the modern, simple rolled-beam designs with large areas of uninterrupted steel surface. Major advantages of the alkyl silicates that are common to all inorganic zinc systems include long service life, reduced application temperature requirements, and a high coefficient of friction (higher, in fact, than that of sandblasted steel). Because of this high coefficient of friction, inorganic zinc can be applied to faying surfaces of steel members in the shop, eliminating the need to mask these areas (an advantage not universally appreciated by bridge design engineers). The coefficient of friction is dependent on carefully controlled application and, for faying surface applications, film thicknesses that remain in the 1 to 2 dry mil range per mating surface are necessary (175).

#### **Alkyl Silicate Inorganic Zinc/Vinyl Systems (System Group VIa and b)**

The most common barrier finish coat for inorganic primers is the high-build vinyl system in films ranging from 3 to 6 mils. The propensity of these vinyl finish coats to bubble during application (49, 51) over the inorganic zinc has in many states encouraged the use of vinyl tie coats or the vinyl wash primer WP-1 (DOD-C-15328D) (136), which, in films of 0.3 to 0.5 dry mils is probably the most effective solution to the problem (System VIb). Although the primer undoubtedly adds to the adhesion of the vinyl topcoats and may improve the curing of the primer, SSPC in a large study of the topcoating of inorganic zinc-rich primers concludes the wash primer neither improves nor detracts from the performance of any topcoated zinc-rich system (51).

In some cases, in lieu of the wash primer, carboxylated vinyls are also used at low solids as tie coats (System VIa). Mist coats have also been used, as have zotcoats (topcoats that are thinned radically with solvent and applied before a full unreduced coat) to eliminate the bubbling phenomenon, although mist coats are not as universally reliable with vinyls and other high-molecular-weight thermoplastic lacquers as with other finishes such as epoxies. Bubbling and the consequent crater formation as the bubbles burst, although aesthetically displeasing, does not appear (in the short term at least) to compromise the performance properties of the system.

A second problem of more serious potential with inorganic zinc/vinyl systems is the lateral cohesive failure that occurs when the vinyl topcoat is applied before the inorganic zinc has completely hydrolyzed. North Carolina has reported numerous failures on bridge structures applied in 1976 and 1977. It is believed that low shop humidity during application of the zinc, rapid topcoating, and a relatively tight (low PVC) vinyl film may all have added to the failure, by first delaying hydrolysis and then preventing further cure with the impermeable topcoat (W. M. Medford, North Carolina DOT, personal communication, 1984). As with all moisture-curing systems, humidity and temperature will affect the curing of the alkyl silicate primer and therefore the necessary recoating interval. Job schedules, particularly in maintenance operations, are often in conflict with delayed topcoating requirements and these differences can lead to serious problems. One manufacturer will only allow rapid (one day) recoating of such alkyl silicate zincs if the WP-1 (phosphoric acid cured) wash primer is employed as a tie coat (believing this to increase the rate of cure). It is interesting to note, however, that in the North Carolina experience, a wash primer was, in fact, employed.

Claims are made that the vinyl butyral modified alkyl silicate primers with fine particle sized zinc greatly diminish both topcoat bubbling and lateral cohesive problems by producing films with more rapid cure and reduced porosity (176, 177). The organic polymer is said to actually chemically combine with the ethyl silicate producing improved adhesion and a denser product. These claims have been disputed elsewhere (178).

By the mid 1980s, many of those states that retained oxidizing systems for spot maintenance in the field were employing inorganic zinc-rich/vinyl systems in new construction. The inorganic zinc is applied in the shop, touched up in the field, and the finish coat system then applied. In some states, where bridges

in the field need complete removal of the old paint, the inorganic zinc-rich approach has been adopted here also, notwithstanding the difficulties in surface preparation and application. Such systems are not generally advocated for older structures with inherently unsuitable design features such as heavy lattice work, back-to-back angles, etc. Even heavily riveted structures should not be attempted unless job control (inspection) can be maintained at a very high level. Some problems with delayed re-coating with shop-applied zinc surfaces (salting, contamination with shop soils, dirt, and oils) have proved to give significant field painting problems, and some states have abandoned the approach in favor of complete shop painting (179).

Like most vinyl systems, either of two approaches to the formulation is employed in high-build vinyl finish coats. The first utilizes a carboxylated system for direct zinc application, the second a hydroxylated vinyl, which necessitates the use of the wash primer as a tie coat. Either vinyl may be used over carboxylated tie coats. In some cases both resin types are employed. Many paint manufacturers would prefer the carboxylated vinyl approach as this not only reduces the number of coats required, but provides for easier formulating (molecular weight for molecular weight), as the carboxylated vinyls give lower solution viscosities than do their hydroxylated counterparts. This allows for higher volume solids (with easier high-build capabilities) or lower cost solvent systems. On the other hand, many believe that the wash primer/hydroxylated vinyl system produces added engineering benefits in improved interfaces and adhesion and rely on thixotrope/solvent systems for high-build capability. Some manufacturers will also use the lower viscosity butyl maleate modified vinyl, which displays adhesion to both metal and wash primer alike, as an auxiliary resin.

In most cases, the service life of these inorganic zinc/vinyl topcoat systems is excellent; even in relatively demanding wet exterior and chemical environments, claims are made of 15 years of service and more. The earliest systems were applied in the 1950s and are still, in many instances, in good shape. Typical are the experiences of West Virginia, which expects 30-year service of the system, and which first adopted a two-coat system in the early 1970s (only later was a tie coat employed). Apart from some early delamination problems before the tie coat adoption, West Virginia has not, so far, needed to repaint any structures. Borrowed almost directly from the proprietary products of a large manufacturer, West Virginia neither specifies the type of topcoat nor the specifics of the finish coat vinyl formulation, but leaves this up to the manufacturer, citing the necessity of compatibility and providing certain performance criteria (180).

One problem that has haunted the West Virginia system as well as several other states, such as Maine, Tennessee, and Missouri (using similar vinyl topcoats), has been topcoat chalking and fading. The phenomena are reported to depend on color and may well be related to specific pigments or pigmentation levels. Other manufacturers note some chalking and fading of the vinyl system after five years or so, but in Maine, West Virginia, Tennessee, and Missouri dramatic color changes have occurred in less than two years. Curiously, Maine, using the same topcoats of the same manufacturer in the same color, has on some occasions seen bridges fade badly, while on other equally exposed structures paint films have retained excellent color stability. Like other performance specifications, the Maine

specification does not control composition, and failure analyses have not been performed.

Review of the high-build vinyl specifications of many states (181–183) reveal the same numbers (27 to 29 percent minimums for pigment, 19 to 21 percent minimums for vehicle solids, 48 percent total solids, etc.) and similar language, betraying perhaps some uniformity of the source. Few provide details of composition beyond references to aromatic/ketonic solvent blends, light stable plasticizers, etc. Most high-build vinyl specifications of state DOTs do not describe either pigment or vehicle make-up in detail, calling for a vinyl chloride/vinyl acetate copolymer or, in some cases, even a hydroxylated vinyl chloride/vinyl acetate terpolymer suitable for direct use over an inorganic zinc. Presumably in this case they rely on the manufacturer to correct the apparent discrepancy and modify the copolymer in some manner using either a butyl maleated vinyl or even to substitute the carboxylated vinyl in spite of the specification. This type of specification generally does not use the wash primer tie coat and is applied directly to the zinc. The danger of this type of quasi-compositional specification derived from a single source is exemplified in the chalking problems described above, although, in fairness, different interpretations of the same specification from other manufacturers have reported similar problems. Other high-build vinyl specifications (184) are even less compositional, but generally call for the vinyl to be manufactured by the manufacturer of the zinc primer. The West Virginia specification allows great latitude in composition, but specifies weight per gallon and viscosities as well as resistance to sulfuric acid and sodium hydroxide. South Carolina (185) specifies that the vinyl shall have been used successfully over an inorganic zinc-rich primer for at least two years in a similar environment. Several states employ lower build systems for topcoating inorganic zinc, and in general these are more definitively specified. Maryland (186) calls for SSPC-Paint 9, Massachusetts (187) calls for a hydroxylated vinyl of specified composition, and Minnesota (188) provides complete formulations for eight separate vinyl paints for use over a wash primed phenoxy zinc. High-build compositional specifications have recently been specified by the Massachusetts Turnpike Authority (173). Martell (189), in a review of vinyl technology, describes a Massport compositional high-build vinyl specification (190) for use over a wash primer. A later variation of the same specification is even more detailed.

In the Mass Turnpike specification, the vinyl is applied directly to the zinc and a butyl maleate-based vinyl resin is used to modify the normal carboxylated terpolymer. The Mass Turnpike specification employs a low-build acrylic (with vinyl modification) as a 2 mil topcoat for the 4 mil high-build intermediate vinyl coat. The modification of vinyls with acrylic thermoplastics is not an uncommon practice to upgrade UV resistance where necessary.

The susceptibility of vinyls to fading and chalking, evidenced by experiences in Ohio, Missouri, Tennessee, Florida, etc., is by no means categorically proven to be a defect in the generic system. Many individuals blame the fading not so much on resin type but on pigmentation selection and specific formulations. The position is given much credence by the significantly better UV resistance of the low-build systems such as those described in the Minnesota vinyl specification (188). As noted in the case of Maine, some batches (and/or products) give better perform-

ance than others. In an unpublished study by Hare (191), severe color deterioration, such as has been seen in Maine, has been shown to result from formulation practices not in keeping with the general guidelines as originally published by Union Carbide Corporation. These formulation guidelines are extremely comprehensive, delineating acceptable types and levels of pigmentations, plasticizers, stabilizers, and solvent systems. Tinklenberg of Michigan DOT reports that color deterioration in exposed vinyl films seems more related to an individual company's products than it seems to be generic (Gary Tinklenberg, Michigan DOT, personal communication, 1985).

#### **Inorganic Zinc/Epoxy/Urethane Systems (System Group VIc, d, and e)**

Somewhat newer and less widely employed on bridge structures at this time are epoxy and urethane topcoats over an inorganic zinc. In general, high-build epoxies (3.5 to 5 dry mils) are used as intermediate coats directly over the zinc primer (if necessary using a mist coat technique) and then 1.0 to 2.0 dry mils of aliphatic urethane are applied as finishes (Systems Group VIc).

At the time of writing, New York State was planning to use this type of system on the Green Point Bridge. Pennsylvania has painted several bridges with the system and reports good early data. Michigan (179) in early 1983 adopted this type of system for a total shop painting program and has painted a number of bridges that show good early performance. The Michigan specification (192) is a performance specification without compositional additions. Several other states are either testing or considering the system (e.g., Ohio, Massachusetts). Wisconsin is now using this type of system. The system has also been selected for the new painting (1984) of the suspended span of the Newport Bridge in Rhode Island. Material costs are slightly less than the vinyl, and the possibility for further cost reductions by specifically utilizing the urethane only on some exposed areas of the structure and replacing this with a further coat of epoxy in those areas with reduced UV exposure may also reduce costs. The Michigan specification (192) at one time eliminated the urethane from areas other than the fascia beams, and simply retained a two-coat inorganic zinc/epoxy system in nonexposed areas (System Group VI d). More recently the state has begun to adopt the three-coat urethane finished system across the entire structure.

The high-build epoxy midcoats are usually applied directly over the zinc. They are somewhat less sensitive to topcoat bubbling than are the vinyls, probably because of their initially lower molecular weight, which tends to result in reduced early surface skins. Bubbling is somewhat dependent on formulation, but in most cases it can be reduced by mist coating techniques. The midcoats are also subsequently recoated with the urethane or another coat of epoxy, although bubbling, and its resultant cratering, once formed, tends to telegraph from coat to coat. Epoxy midcoat solids normally range between 55 and 70 percent by volume. Resin systems at this time are most often based on medium molecular weight bisphenol A type epoxy resins with polyamide cures, although the use of lower molecular weight epoxies is increasing. PVCs are higher than the urethane finish coats, and gloss is often reduced to semi-gloss or eggshell to

improve intercoat adhesion and obfuscate gloss reductions in applications where urethane finish coats are not used.

Two principal types of polyols are used in the urethane systems, a hydroxylated acrylic or a hydroxylated polyester. Although the polyester-based products have the edge in chemical, solvent, and abrasion resistance, the acrylics have slightly better UV resistance, and faster initial drying profiles. They are also less costly. Conventionally, volume solids ranges for the urethane finish coats are between 50 and 60 percent.

Despite the improved dissemination of formulating data (particularly on the polyester urethane system), coating systems of this type are most often purchased from lists of prequalified manufacturers. This technique is employed in Michigan and Florida.

In-depth compositional data on the epoxies are less readily available to the specifying agencies despite the greater maturity of the epoxy coatings. Maine DOT (193) provides a relatively detailed specification calling for definitive parameters for PVC, pigment weight, solids by weight and by volume, and weight per gallon of both components and the mixed material; this provides much assistance to a would-be formulator. Similar requirements are also listed in the same specification for a polyester urethane. Curiously, neither document specifies a required mixing ratio.

A further advance on the above system is the use of a single high-build urethane directly over the inorganic zinc (3 mils of inorganic zinc, 4 dry mils of urethane). This type of system (System VIe) has been employed in the 1985 repairs made to the Neil Underwood Bridge in Hampton, N.H. (194). Although individual material costs of this system can be somewhat higher than either the vinyl or the epoxy/urethane finish systems, the advantages in reduced labor costs of a two-coat system more than adequately compensate for any apparent disadvantage.

#### **Alkaline Silicate Inorganic Zincs/Vinyl Systems (System Group VIIa and b)**

Bridge-paint systems based on alkaline silicate zinc-rich primers are not as widespread as the self-curing ethyl silicates. Florida, for example, has employed post-cured, sodium-silicate-based zinc-rich primers in both two-coat (inland, nonchemical areas) and three-coat (coastal and high-corrosion areas) vinyl finished systems (195). These specifications are detailed, essentially compositional documents, and call for 2.5 to 3.5 mils of primer and 0.75 to 1.0 mils of vinyl aluminum topcoats with or without an intermediate tie coat of 1.0 to 1.5 dry mils of vinyl (pigmented with BLSC). Surface preparation requirements are for a near-white blast (SSPC-SP-10) with a 1 to 1.5 mil profile.

The high levels of performance capable from such sodium silicate zinc-rich systems are exemplified in the performance of an untopcoated 3 mil system on the Port Orange Draw Bridge near Daytona Beach, which gave 10 years corrosion-free protection before a topcoat was applied (196).

A self-curing alkaline zinc-rich-based system has been employed on the Golden Gate Bridge in San Francisco since the early 1960s. In this case a WP-1 wash primer is employed as a tie coat with the vinyl finish. Alkyd finishes have also been used on the structure, the WP-1 tie coat serving as an effective in-

sulation between the zinc and the alkyd, and thereby preserving alkyd adhesion (197).

Other examples of alkaline-silicate-based systems are reported by Munger, and include the 3 mil sodium-silicate-based system on the Batman Bridge in Tasmania (44).

#### **Phenoxy Zinc-Rich/Vinyl Systems (System Group VIIIa)**

Perhaps the most widely utilized organic zinc-rich-based system, the phenoxy zinc/vinyl system was one of the many coating systems to be developed in California DOT Laboratories (198). Like all of Caltrans's specifications, the documents are comprehensively compositional and involve no difficulty in interpretation for any manufacturer. Although the phenoxy resin is essentially a high-molecular-weight linear epoxy thermoplastic, the solvent resistance is such that the normal thermoplastic solvent weld is unreliable. Addressing this, some manufacturers have deliberately modified phenoxy primers with phenolics and polyketone resins with some success. In other applications, including Caltrans, vinyl finish coats based on hydroxylated vinyl chloride/vinyl acetate resins are applied over a tie coat wash (DOD-P-15328D) to guarantee adhesion to the zinc. Generally, commercial blast or near-white blasts are specified for this system,  $2\frac{1}{2}$  to 3 mils of primer being applied. Wash primer and vinyl topcoat film thicknesses are 0.25 to 0.5 mils and 3 to 5 mils, respectively, although in many systems two vinyl topcoats are employed of 2 mils each. Service lives of 10 to 15 years have been achieved in California with a four-coat system, although earlier breakdown has been encountered, especially near the coast.

Several other states have adopted, modified, or simply copied this specification and have had good service with it. The states include New Jersey, North Carolina, Massachusetts, and Minnesota. New Jersey uses two coats of the phenoxy primer. A series of colored compositional vinyl in-depth specifications, including formulations, for the two low-build vinyl topcoats of this type of paint system are included in the Minnesota 3529 specification (188). Louisiana reports reduced success with phenoxies as compared to the epoxy organic zinc-rich primers, as does Florida (195).

The phenoxy vinyl system is often used (as is the inorganic zinc/vinyl counterpart) as an alternative system to conventional lead systems for wet and chemical environments in states such as New Jersey where environmental zoning is utilized for the selection of bridge-coating systems.

Phenoxy zinc-rich primers are sometimes used for touch-up of inorganic zinc-rich systems.

#### **Phenoxy Zinc-Rich Systems with Other Topcoats (System Group VIIIb)**

The recoating difficulties with phenoxies may be reduced by modification with certain other resins such as phenolics. Using the modified phenoxy to improve recoatability, one major manufacturer has employed phenoxy zinc-rich primers as the base coat for a high-build epoxy (4 mils) with a urethane finish coat ( $1\frac{1}{2}$  mils). This system has given almost 15 years of service on

many structures, but its use on bridges is to this point limited; two to three years of service life, albeit reasonably successful, is all that has been recorded so far.

Intercoat adhesion problems are most common with vinyl systems, however, and other finish coats have been used without modification. Such applications include phenoxy zinc-rich primers that have been used on joints, bearings, etc. and top-coated with 16 mils of a C-200 type coal-tar epoxy (199). As with many systems, service life is quite variable from bridge to bridge, but the phenoxy/coal-tar system has given good service for almost 10 years in these applications on some bridges. There is, however, some question as to whether use of the zinc-rich primer beneath high builds of a coal-tar epoxy is necessary or even advisable. The high-build barrier properties of the coal-tar coating, in eliminating the passage of electrolyte to the zinc, severely reduces the ratio of anode area to cathode area at scratches and breaks and leads to reduced protection of the bared steel at the scratch.

California has also used chlorinated rubber/aluminum finish coats over the phenoxy wash primer systems (R. Warness, Caltrans, personal communication, 1984). This system is said to give at least 7 to 10 years performance without problems. Finally, in spot-blast applications over old oleoresinous systems some states have employed phenoxy/vinyl wash primer/alkyd finish coat combinations. Some problems with this system have been experienced with active solvents from the phenoxy attacking the old alkyd in areas peripheral to the blast.

#### **Chlorinated Rubber Zinc-Rich/Chlorinated Rubber (System Group IX)**

This system (200) was selected for use on the five-year painting program on the Tobin Memorial Bridge in Boston and is giving excellent service after seven years. The system consists of a 3 mil application of a two-pack chlorinated rubber-based zinc-rich primer with a 3.5 mil chlorinated rubber midcoat and 1.5 to 2 mil finish of a low-build chlorinated rubber enamel. Surface preparation is a near-white blast. A similar system used as a spot repair of a red lead/chromium green oxide alkyd oil system on the legs of the same bridge is doing better than expected, although some corrosion is occurring after five years around the periphery of the spot blast as the old alkyd continues to break down.

Interestingly, this system, while performing well in the field, does not do well in the salt spray test, and attests to the limitations of this test (201) as a true measure of field performance.

Early difficulties were experienced with the chlorinated rubber primer, which was originally proposed as a one-pack system (TT-P-1046) (202). In metropolitan Boston the solvent systems of all paints must conform to Rule 63, and the early use of acetate-type solvents with lower-than-specified levels of oxirane acid acceptor produced severe dehydrochlorination in this composition, leading not only to reduced stability and performance but fires and explosions both in the manufacturing plant and on the job. In consequence, a two-pack system was implemented (203) where the zinc was introduced to a highly stabilized resin system on the job site. This points out the complexity of coating formulations and the need to test when changes are made.

### Vinyl Zinc-Rich/Vinyl Systems (System Group X)

A third thermoplastic organic zinc-rich system is based on the three-component vinyl zinc-rich primer developed by the U.S. Army Corp of Engineers (204). This rather cumbersome composition is currently being employed in Oregon, where it has been reported to be successful during the first three years. Because of the necessity of zinc-to-steel contact (which precludes the use of the WP-1 wash primer as a steel pretreatment and therefore the hydroxylated vinyl resin), and the reactivity of the carboxylated vinyl resins with zinc pigment, the vinyl zinc-rich primer must utilize the unmodified vinyl chloride/vinyl acetate copolymer having inherently poor adhesion to metal. This deficiency is rectified by the addition of a small amount of suitable organo functional silane, which is introduced as one of the three components (the zinc also being mixed separately) as the paint is prepared on the bridge. Two relatively high-build vinyl coats of 3 mils dry film thickness each are applied over 2 mils of this primer in rapid succession.

Oregon specifications (205) for this system are compositionally thorough and are a substantial improvement over many vinyl specifications. Interestingly, Oregon will not accept vinyl that displays any tendency to chalk, which would again seem to intimate that in this case chalking is not a peculiarity of vehicle type but of the formulation.

Unlike much of Oregon's experience with high-performance systems, which is disappointing, this vinyl system appears to be giving good service in both coastal and inland areas of the state. Advantages are also cited in the reductions of insurance claims from passing motorists during the application of this fast-drying system.

### Epoxy/Polyamide Zinc-Rich Systems (System Group XI)

Epoxy zinc-rich primers are usually polyamide-cured medium-molecular-weight systems, although other curing agent types may be employed and epoxies of different molecular weight used. They are always two- or three-pack systems because of the chemically reacting cure mechanism and concerns over pigment settlement and in-can gassing. Compositional specifications for the zinc-rich primer are typified by the Corps of Engineers E-303 specification (206). In general, epoxy/polyamide zincs have been found to provide some of the best performance of all the organics, but their use on bridge structures in the United States does not seem as widespread as is the use of inorganic zincs or even phenoxies. Florida DOT describes the epoxy/polyamide zincs as outperforming both the chlorinated rubber and the phenoxy thermoplastics (196). Michigan has now adopted this type of primer and is said to prefer it to inorganic zincs over previously corroded surfaces; it advocates its use over weathered and corroded ASTM A 588 surfaces after blasting.

Like most organic zinc-rich primers, the epoxy/polyamide zinc-rich takes on many of the characteristics of the vehicle. The film is hard, tough, and solvent resistant, as well as highly adherent. Tolerance for poorer surfaces is rather better than the inorganics, although poorer surfaces may confound cathodic protection. The dilution of resin components produced by the high PVC/CPVC ratio of the organic zinc-rich primer tends to reduce cure kinetics to some extent and give longer pot lives.

### Epoxy/Polyamide Zinc-Rich Primers/Epoxy/Polyamide Finish Coats (System Group XIa)

This system, although very sensible, appears to have been used less than the analogous systems described below that utilize thermoplastic topcoats. Film thicknesses recorded for various applications are 2 to 4 dry mils for the primer, 2 to 5 dry mils for the midcoat, and 2 to 3 dry mils for the finish. A similar three-coat system (utilizing 2 to 3 mils of zinc primer, 3 to 5 mils of red-lead primer, and 2 to 3 mils of green finish) was applied as a test section against a three-coat red-lead primer/midcoat/green finish (4 to 6; 2 to 3; 2 to 3 dry mils, respectively) on quite extensive sections of the Newport Bridge in Jamestown, R.I. in the mid 1970s. In fact, after 10 years the red-lead system appears to have a very slight edge over the zinc, although both systems are in quite good shape. Some slight pinholing corrosion is seen on the epoxy zinc-rich primed area.

Michigan now reports excellent early success with a variation of this system in field maintenance. The Michigan system uses high-build epoxy intermediate coats with urethane finishes and is being used in the field for complete renewal of old bridges. The Michigan philosophy is that in replacing the old mill scale beneath existing lead-based systems with a good blasted substrate they not only break the lead cycle but eliminate the need for future radical blasting. Although they foresee necessary maintenance of the new zinc-based system, this future maintenance involves attention to finish-coat renewal only and not to the renewal of the entire system (Gary Tinklenberg, Michigan DOT, personal communication, 1986).

### Epoxy/Polyamide Zinc-Rich Primer/Thermoplastic (Vinyl Type) Finish Coat (System Group XIb)

This system is typified by the specification for Louisiana. Originally a two-coat system in which the tinted epoxy/polyamide zinc-rich primer was recoated with a vinyl aluminum, this system proved to have an inadequate service life, deterioration occurring in 6 to 8 years at edges and seams, and the system has now been replaced with two coats of epoxy/polyamide zinc. The first coat is tinted red (207), and the second is tinted green for contrast (208). The epoxy zinc coats are applied in 3 and 1.5 dry mils respectively over a near-white blast. The system is finally recoated with a vinyl aluminum topcoat (208) and now appears to be giving good service (10 years minimum), but problems are encountered with the vinyl aluminum (leafing) specification, a low-build system from which 3 dry mils in a single coat are required. Despite the use of double passes, etc., the build requirements are reported impractical. On new jobs the topcoat is applied in the field after touch-up of the zinc (where necessary) and overall cleaning of the primer. There is a maximum time of four months between the application of the second zinc coat and the vinyl (a lacquer based on a mixture of both hydroxylated and carboxylated resins). Any delay in topcoating beyond four months results in a mandatory application of a WP-1 type wash primer (MIL-P-15328A) before application of the vinyl. Although the specification calls for the elimination of lap marks in topcoat application, the fast solvent system (toluene and butyl acetate) has given problems with this.

The Louisiana specifications are compositional in nature with full documentation of pigment, vehicle, and solvent makeup,

and products are prequalified. In addition, there is a performance specification with requirements for salt fog (1500 hours), sunshine and weatherometer exposure (1500 hours), and fluorescent UV condensation exposure (QUV) with four-hour cycling 60°/45°C for 1500 hours. The test is performed on the total system, which is evaluated (albeit qualitatively) for blistering, chalking, checking, cracking, delamination, discoloration, rusting, and undercutting (209). Interestingly, in this test, paints are applied at dry film thicknesses and over surface preparation qualities required by the paint company, not Louisiana, although the specification is quite specific on blast quality, mil profile, and film thicknesses required by the state.

A similar system is a new primer topcoat system being introduced into Texas (J. Raska, Texas DOT, personal communication, 1985). The system (System XIc), a three-component epoxy/polyamide zinc-rich primer with a vinyl toluene-based finish, was formulated in the laboratory at Texas DOT in the early 1960s. At the time of this writing it has been employed in only one application; its use being discouraged since then because of the three-component mix. Data would now show the epoxy/polyamide system to be slightly better than the uralkyd zinc that was originally adopted by the state instead of the epoxy/polyamide, and plans are now to change primers. (Service lives indicated from the early experimental applications for the epoxy/polyamide system are in the range of 15 to 20 years.) In the years since its inception, the vinyl toluene/acrylic resin of the topcoat has been discontinued by the resin manufacturer, and the new system will employ a styrene/acrylic solution lacquer that has been used more recently over the uralkyd zinc. Film thicknesses for the new system will be 3.5 dry mils minimum for the primer, and 1.5 dry mils of finish. In salt water environments, the system will be fortified with an additional midcoat of epoxy/polyamide red lead (also 1.5 dry mils). Like the original system, the new specification will not only be compositional in nature, but will specify formulas.

#### **Urethane Zinc-Rich Primer-Based Systems (System Group XII)**

Zinc systems based on both oil-modified urethane (uralkyd) and moisture-curing urethane vehicles have been developed.

The oil-modified urethane primer is a unique specification (System XIIa) that was developed by formulators at the Texas State Department of Highways (130) at the same time as the three-component epoxy system, shortly to be introduced. The primer is a zinc-rich product based on a linseed oil modified polyurethane (210). The zinc powder (89 percent minimum by weight of product) is mixed into the vehicle in the field. Two coats of primer are recoated with a vinyl toluene/acrylic finish (211) (more recently a styrene/acrylic) and in some cases an aluminum pigmented bodied linseed oil modified with a hydrocarbon resin (212).

These systems have provided Texas good protection over the past 20 years or so and are now being replaced only because of the greater acceptance of the three-component epoxy (favored by the formulators).

All specifications are quite detailed and are presented not only in formulation format, but individual raw materials are carefully specified and duplicates allowed only after prior laboratory testing. Careful formulation is said to be essential for

good chalk resistance and color control in the vinyl-type finish. Grays and greens based on titanium dioxide and chromium green oxide are used. Phthalocyanine blues and greens and other organic colorants are not allowed.

Originally the primer system was applied at 5.0 dry mils with 1.0 dry mil of finish, but since 1972 the required film thickness has been adjusted downwards to 3.5 dry mils minimum with 1.5 dry mils of finish. The only difficulties with the system that have been reported are application related, primarily a tendency to blister at high film thicknesses of primer that should run no higher than 10 mils. In one case of serious failure of the system, 80 dry mils of primer were discovered in some areas.

New to the market at the time of this writing are single-pack, moisture-curing, zinc-rich, polyurethane systems (System Group XIIb) based on the same diphenylmethane diisocyanate that is the binder for the urethane/aluminum barrier system (System Group XVIII). Although Michigan reports some favorable data from evaluations of these systems, they are essentially too new for definitive comment. Typical of this type of system is the one being specified for two new bridges in Allegheny County, Pennsylvania. In this system the urethane zinc primer is recoated with an epoxy/polyamide intermediate coat and an aliphatic urethane finish.

Other oleoresinous zinc-rich systems (epoxy ester based) have been used in Japan in bridge systems (213), although little use has been made of these materials in the United States. Experimentation with proprietary products (212) of this type were used under the chlorinated rubber finish coats over power-tool cleaned surfaces in local areas of the Tobin Memorial Bridge to avoid difficult blast containment problems, and after three years show no sign of corrosion breakdown. The same system has also been used for galvanizing touch-up, extensively in industry, but only once on a bridge structure, the Peace Bridge in Niagara Falls (S. Willox, Norfolk Corp., personal communication, 1984). After 10 years this system is said to have given satisfactory service.

#### **Other Zinc Systems (System Group XIII)**

Cathodic protection techniques by means other than paints are also increasingly being employed on bridges. Although formal cathodic protection by means of impressed current or solid anodes is not possible because of the noncontinuity of the electrolyte on bridges, techniques such as galvanizing and metallizing have been and are being employed.

For the most part, galvanizing is only employed on small sections of bridge structures because of size limitations of the hot-dip kettles, although several bridge structures have been erected entirely from galvanized stock (214–216). Galvanized sections of bridges are quite common, however, and galvanizing is often a cost-effective technique for the protection of piers, railings, and so on (214). The cables of suspension bridges, such as the Golden Gate Bridge, are often galvanized before erection. Taking the process one step further, a duplex system (217) involving color coated galvanizing has also been employed on overpasses and railings. In this process the galvanizing, pretreatment, and coating are applied in the shop and shipped to the field where nothing more than touch-up is required. By this method the new “suicide control” railings of the Bourne and Sagamore Bridges in Massachusetts were protected with a gal-

vanized/vinyl system (System XIIIa) (218). Newer systems utilizing urethane topcoats are also under evaluation.

A duplex system consisting of a galvanized steel base with 2 mils of a zinc dust/zinc oxide primer and 2 mils of a phenolic finish has been used on the Hood Canal Floating Bridge in Puget Sound (219).

The painting of galvanized surfaces can be problematic, particularly where oleoresinous topcoats are employed (220). As with zinc-rich systems, acidity from the applied coatings forms zinc salts at the interface and this produces adhesion loss in time. For galvanized surfaces, preweathering, acid treatments, and zinc dust and zinc dust/zinc oxide primers as well as primers based on calcium plumbate have been used with variable success. The most universal design approach would seem to be the use of a WP-1-type wash primer (DOD-C-15328D).

Somewhat more applicable to the wholesale protection of bridges is the use of the metallizing or thermal-spray approach (221). In this process metallic zinc (or alloys of zinc and aluminum) is applied from gas or electric arc guns directly onto the white-blasted steel. Thicknesses are somewhat higher than hot-dipped galvanizing films, and average about 10 mils. As the surface of the metallized film (unlike galvanizing) is porous, a sealer (usually a carboxylated vinyl or, in marine or chloride exposure, a wash primer with a hydroxylated vinyl finish) is normally required for protection to reduce field contamination and dirt pickup as well as to add aesthetics. Applications in both field and shop have been made and the versatility of the process has lent its use on galvanized structures where sections are too large for hot dipping.

Metallizing has not been used as much in the United States as in Europe, where several large and many smaller bridges have been coated. These include the Forth Road Bridge (222), protected with 3 mils of zinc, wash primer, two coats of zinc chromate phenolic, and two coats of micaceous iron oxide finish (one applied in the shop and one in the field). The lower surfaces of the girders of this bridge are subject to salt spray and slow dry-off conditions and, after 14 years, have begun to break down, but the upper areas of the structure remain in excellent condition.

The Pierre-Laporte Bridge in Quebec, Canada, was metallized in the field (after abandonment of a BLSC oil/alkyd system) during the late 1970s with 5 mils of zinc, wash primer pretreatment, and two 1 mil coats of vinyl (System XIIIc) (223). Up to 20 years of service are predicted for this structure. New York State has recently experimented with an 8 mil zinc/aluminum (85/15) metallized primer using a urethane finish over a wash primer on the Robert E. Moses Bridge on Long Island, N.Y. Extensive use of metallizing is reported in Scandinavia, France, and the United Kingdom. In rural areas a sealed metallized zinc coat of 6 dry mils is predicted to last well over 20 years; in industrial and sea water splash zone areas something like 10 dry mils is required for the same sort of protection (34).

## BARRIER SYSTEMS

The barrier coating systems (Table 6), which may be the heaviest duty coating systems yet devised, have not been employed to the same extent as the zinc-rich systems in the corrosion protection of bridges. They are exemplified in both thermosetting systems (epoxies) and thermoplastic systems (e.g.,

vinyls), and occasionally in mixtures. Definitions are complicated somewhat by the inclusion of inhibitive pigments in some formulations, but their inclusion will be ignored in the categorization below because it is unlikely that the inhibitors play any major role in the protective mechanism of these relatively impermeable systems.

### All-Vinyl Barrier Systems (System Group XIV)

The all-vinyl barrier system is one of the oldest high-performance coating systems for steel structures. It was pioneered by the U.S. Army Corps of Engineers in the early 1950s, and since then it has been used widely on diverse structures (189). Vinyl coatings are tough, flexible, adherent systems that are highly resistant to moisture vapor transmission, particularly when pigmented with aluminum. They have good resistance to saponification and chemicals. They are permanently solvent sensitive (ketones, esters, etc.), but this allows intercoat adhesion via solvent weld. (A more complete review of their properties may be found in the NACE Publication 6H177.)

Two basic types of vinyl coatings are used. The first employs a carboxylated vinyl in a noninhibitive primer coat, applied directly to the steel over which multiple coats of vinyl intermediates and finishes are built up to the required film thickness. These systems are typified by the Bureau of Reclamations VR-3 and VR-6 systems (224). As intermediate and finish coats, they do not require the 1 percent maleic acid modified polymer for adhesion to steel. Some systems may utilize the unmodified copolymer in coats other than the primer, the solvents of which partially dissolve the vinyl vehicle in the coat already applied, and attain intercoat adhesion by the solvent weld typical of the thermoplastic system. Other vinyls, such as the butyl maleate modified materials and even vinyl chloride/vinyl ether systems, may be employed in these midcoats and finish coats. As in the high-build systems, thermoplastic acrylics and polyketone resins may also be employed. All of these vehicle modifications are rarer in the barrier vinyl systems, however.

Inhibitive pigmentation is rarely built into the carboxylated primer because of reactivity, although some relatively insoluble inhibitive species (e.g., zinc phosphate) may be added with care.

The common alternative approach to the carboxylated vinyl barrier systems involves the use of a WP-1 (DOD-P-15328D) wash primer for adhesion to steel, and a hydroxylated vinyl (a vinyl chloride/vinyl acetate/vinyl alcohol terpolymer) applied over that. As the hydroxylated vinyl is not necessary for adhesion in further coats, and is a more expensive resin, intermediate and finish coats may again utilize the straight copolymer. Although the hydroxylated vinyl primer has been pigmented with both red-lead and zinc-chromate pigmentation, there appears to be little difference in service life between vinyl systems based on this approach and on the VR-3 approach, which utilizes no inhibitor. Much confusion can arise from the specificity of vehicle type to the surface being coated, and in some cases (such as the SSPC-Paint-8) both the carboxylated and hydroxylated vehicles are employed in the same primer giving the product versatility over both bare steel and the wash primer, with only slight compromise in adhesion. The approach is also used in the SSPC-Paint-9 specification utilized by Maryland.

The hydroxylated vinyl is more compatible with other resin systems than is either the carboxylated resin or the straight



TABLE 6

## BARRIER COATING SYSTEMS—UTILITY AND APPLICATION COMPARISON

System Group No.	System Description	Volume Solids (%)	Typical Film Thickness (Dry mils)	Surface Prep. (Min.) SSPC-SP	Adaptability to Poor Surfaces	Probability of Early Failure from Deviations in Application	Recoat Times (days)	Solvent Type	Usual Mode of Application	Compatibility with Old Coatings	Ease of Spot Repair	Ease of Cleaning (Salts and Soils)
XIVa	Vinyl (Carboxylated) <sup>a</sup>	20	1.5	10	Poor	Moderate	0.1	Ke./Es./Arom.	Airless Spray	Poor	Excellent	Very Good
	Vinyl (2-5 coats) <sup>b</sup>	20	1.5(x3)				0.1					
	Vinyl <sup>c</sup>	20	1.5									
XIVb	WP-1 Vinyl Wash Primer <sup>a</sup>	9	0.3		Fair	Moderate-High	0.02-1.0	Alc.	Airless Spray	Poor	Very Good	Very Good
	Vinyl (Hydroxylated) <sup>b</sup> (plus 2-4 vinyl coats)	17	1.5(x3)	6			0.1	Ke./Es./Arom.				
	Vinyl <sup>c</sup>	17	1.5									
XV	Chlorinated Rubber Primer <sup>a</sup>	32	1.5	6	Fair-Good	Moderate	1.0	Arom./Ali. Ke./Es./G.E.	Airless Spray	Good	Excellent	Good
	Chlorinated Rubber Midcoat <sup>b</sup>	35	3.0				1.0					
	Chlorinated Rubber Finish <sup>c</sup>	33	1.5									
XVIa	Epoxy/Polyamide <sup>a</sup>	55	2.5	6	Good	Moderate-High	1.0	Alc./G.E. Ke./Es./Arom.	Airless Spray	Good	Good	Excellent
	Epoxy/Polyamide <sup>b</sup>	60	2.5				1.0					
	Epoxy/Polyamide <sup>c</sup>	60	2.0									
XVIIa	Aluminized Epoxy Mastic <sup>a</sup>	85	5.0	2 or 7	Very Good	Moderate		Arom.	Brush/Spray	Very Good	Very Good	Excellent
XVIIb	Aluminized Epoxy Mastic <sup>a</sup>	85	5.0	2 or 7	Very Good	Moderate	1.0		Brush/Airless Spray	Very Good	Very Good	Excellent
	Aluminized Epoxy Mastic <sup>c</sup>	85	5.0									
XVIIc	Aluminized Epoxy Mastic <sup>a</sup>	85	5.0	2 or 7	Very Good	Moderate	1.0	Alc. Ke./Es./Arom.	Brush/Spray	Very Good	Very Good	Excellent
	Epoxy/Polyamide Color Coat <sup>c</sup>	80	5.0									
XVIIIa	Moisture Cure Urethane Aluminum <sup>a</sup>	50	2.5	6	Fair-Good	Moderate-High	1.0	Arom.	Brush/Roller	Good	Fair	Excellent
	Moisture Cure Urethane Aluminum	50	2.5				1.0					
	Moisture Cure Urethane Aluminum <sup>c</sup>	50	2.5									
XVIIIb	Moisture Cure Urethane Aluminum <sup>a</sup>	50	2.5	6	Fair-Good	Moderate-High	1.0	Ke./Es./Arom.	Brush/Airless Spray	Good	Fair	Excellent
	Moisture Cure Urethane Aluminum <sup>b</sup>	50	2.5				1.0					
	Aliphatic Urethane Color Coat <sup>c</sup>	52	2.0									
XIX	Coal Tar Epoxy <sup>a</sup>	71	8.0	10	Poor	High	0.2-1.0	Arom.	Airless Spray	Poor	Poor	Very Good
	Coal Tar Epoxy <sup>c</sup>	71	8.0									

<sup>a</sup> Primer coat.<sup>b</sup> Intermediate coat.<sup>c</sup> Finish coat.

copolymer. This characteristic has been used in vinyl/alkyds, which have been used widely by the U.S. Navy (225). Newer types of hybrid coatings include vinyl/epoxies and vinyl/urethanes. In the latter case the hydroxylated vinyl acts as a polyol for the isocyanate curing agent (226). Both vinyl/urethanes and vinyl/epoxies are two-package systems and quite new. They have been applied on bridges in both Maine and Florida with encouraging results after three and a half years of service.

The normal all-vinyl barrier system, however, is a lacquer, and its high molecular weight (of necessity) reduces volume solids because of viscosity and application considerations. In consequence, high-build paint systems must be applied in multiple coats. Usually 4 to 7 coats are necessary to build up 7 or 10 mil systems. Vinyls are high-energy systems and require careful surface preparation (near-white or white blast) for best adhesion and good barrier properties.

The use of barrier vinyl systems apparently has not been either as widespread or as uniformly successful on bridges as it has been on other structures such as water storage tanks, locks, ships, and dams, where service lives of 20 years plus are not at all unusual. The lack of use on bridges is probably related to the number of coats required to achieve the desired system film thickness and the difficulties in achieving proper application and inspection in the field. In California and Oregon, seven-coat vinyl systems have been used on a substantial number of bridges, although with mixed success, particularly near the ocean. Oregon reports that a seven-coat all-vinyl system on the Columbia River Bridge at Astoria showed severe deterioration within the first six months, and required extensive repainting after three years. The state complained about the low film builds, and data would indicate that this was the primary reason for such poor performance. Only 1 and 2 mils were realized in some areas from 7 coats of paint. California reports better success with the same 7-coat system in coastal areas where service lives of more than 25 years have been achieved. Even better performance is recorded in the interior valleys. California also reports mixed results, and relates much of the variability to application effects and the different environments. It is possible that despite the number of coats employed, the geometric complexities, angles, edges, etc. on many bridges make the application of adequate thicknesses of such low-build lacquers difficult without constant and careful inspection. High-build midcoats and finish coats (such as those used as topcoats with zinc-rich systems) are also useful in reducing the number of coats required to attain an overall film thickness, although the high-build vinyl does not appear to have the same degree of impermeability (mil for mil) as the low-build lacquers.

Other hybridized systems utilize combinations of hydroxylated vinyl resins and alkyds in shop primers above which are built full vinyl barrier systems (New Jersey). The Connecticut vinyl primer is recoated with an alkyd intermediate and finish coat system. Both New Jersey and Connecticut systems utilize inhibitive pigmentations in the vinyl primers.

#### **Chlorinated Rubber Barrier Systems (System Group XV)**

Other thermoplastics used as barrier systems include the chlorinated rubber resins. Chlorinated rubber barrier systems have a high degree of chemical resistance similar to vinyls. Somewhat

more susceptible to dehydrochlorination, they need more careful stabilization than do vinyl systems; lead compounds and epoxies are employed to this end. Solvent resistance is poorer than that of vinyls, but moisture vapor transmission resistance is probably greater. A lack of ester groups on the chlorinated rubber molecule lends the polymer excellent resistance to saponification and chemicals. Chlorinated rubber resins are usually modified with straight chlorinated hydrocarbon resins and chlorinated hydrocarbon plasticizers. Properties are more completely considered in NACE Publication 6H275. As barrier systems, chlorinated rubber coatings are unmodified and require good surface preparation. Alkyd-modified hybrids are more forgiving as primers but are more susceptible to saponification.

Minnesota (227), California, and Massachusetts have developed chlorinated rubber systems. SSPC Paints 17, 18, and 19 are compositional specifications for a chlorinated rubber system, although SSPC Paint 17 contains inhibitive pigments. Aluminum finish coats have been advocated by California, and Minnesota has specified chlorinated rubber finish coats for use over a variety of primer types including red lead, BLSC alkyds, and phenoxy zinc-rich primers treated with a wash primer. These systems, however, appear to have been used only occasionally.

#### **All-Epoxy/Polyamide Barrier Systems (System Group XVIa)**

Dunn (135) lists more than two dozen different possible curing agent types that are for use with epoxies. Relatively few of these materials are applicable for bridges because of curing difficulties at ambient temperatures, pot-life requirements, applicable viscosities, color, and physical and chemical properties. The principal curing agents for use at room temperature are polyamides, amido-amines, and aliphatic and aromatic amines. The polyamides have the larger share of the market for bridge work, although, as the drive for higher solids increases, the other materials are being used more frequently. The chemistry and properties of epoxy resins for protective coatings has been recently discussed by Brady (228). A more comprehensive, if less specific, discussion of epoxies may be found in the Lee and Neville handbook (229).

Epoxy barrier systems are rigid thermosetting systems having less flexibility than many coating systems. They are, however, tough, hard, and afford excellent protection despite a tendency to chalk badly in some exposed areas. NACE Publication 6H182 describes in detail the properties of this type of coating system in atmospheric exposure applications. Application is not difficult if flow agents, such as butylated urea formaldehyde or silicone resins, are used to offset a slight tendency to crater. Because of the excellent wetting properties of the polyamide resin, the primers are relatively tolerant for application over poorer surfaces, even contaminated with traces of moisture, but, as a rule, SSPC-SP-6 blasts are required. Application seasons may be limited because of the severely reduced kinetics of the normal epoxy/amine (or amide) reaction below 50°F. More recently, lower temperature coating systems have been introduced, which are said to cure at temperatures down to 35°F. Pot lives of these two-component systems depend on curing agent, catalyst, solids, the molecular weight of the resin, and the atmospheric conditions as well as the amount of pigmentation. Medium-molecular-weight epoxy/polyamides are still the most common combi-

nations for this type of service, with pot lives generally on the order of 8 to 16 hours. Newer systems based on lower-molecular-weight epoxy resins, modified amines, amido-amines, or polyamide curing agents with higher solids (75 to 95 percent) have much shorter pot lives, which may be as low as 4 hours unless carefully modified.

The classic low-molecular-weight epoxy barrier system is typified by the three-coat Navy specification MIL-P-24441, although this system is not overly high in solids.

One of the earliest applications of epoxy systems on bridges was the 1966 application of a three-coat epoxy system (bearing red lead in primer and midcoat and utilizing the green finish coat) used on the steel of the Newport Bridge (Rhode Island). The original system was shop applied with only 5 percent field painting. A 25-year service life was predicted, despite the live loading and stress reversals common on large bridges and their effect on the highly cross-linked film. The adhesion failure that subsequently occurred on this structure (even before the steel was erected) is well documented, but seems to be related more to blast quality, profile difficulties, contamination, and film thickness than it is to stress-related effects. The same system applied over newly blasted surfaces in the field (following the original failure) in the early 1970s has done well to date. The epoxy system used was a relatively simple medium-molecular-weight polymer cross-linked with a polyamide resin. The same system with some changes in PVC was used in all coats.

As is the case with vinyl coatings, the epoxy coatings are so impervious to moisture at high builds that it seems doubtful that the inclusion of the inhibitive pigment does as much for the system as does the impermeability of the vehicle. Strontium chromate is a common inhibitive pigment for epoxies, and this type of pigmentation is included in one of the MIL-P-24441 primers and in U.S. Naval Air Development Center primer MIL-P-23377D. In most MIL-P-24441 systems, however, there are no inhibitive pigments and the specification remains a true barrier system.

On the Newport Bridge also, an epoxy system utilizing glass flake was employed on one of the towers in a more exposed zone. This system failed early in the extremely aggressive salt water environment. The towers are now painted with a single-pack inorganic zinc, over which is applied an epoxy/polyamide finish. The article written by Antonino (230) describing the system before the failure provides interesting reading today, especially when compared with later articles on the failure, such as that by Berger (231).

Like all thermosetting vehicles, epoxies are far more easily adapted to the high-solids technologies because of their initially lower molecular weight at the time of application than their thermoplastic counterparts from which films of high molecular weight are cast solely by solvent evaporation. Still lower-molecular-weight bisphenol A/epichlorohydrin-based epoxy variants with alternative curing agents formulated at high solids to reduce solvent emissions have received wider use on bridges in more recent times. For the most part, these materials are discussed under the aluminized epoxy barrier systems (Systems Group XVII). These materials have short pot lives and give less flexible films unless suitably modified (which many of the mastics are). Although properties such as chemical resistance and hardness are improved, these properties seem less important in bridge use than flexibility is.

All epoxies are potentially subject to amine blush, although

many curing agents such as the polyamides are more resistant than others. Because of the required induction time (a 30- to 45-minute period after mixing and before application in which the individual reactants are allowed to "sweat in" or begin to form longer-chained molecules that do not migrate to the surface of the film) the usable pot life may be further shortened in some systems. Amine blush is a troublesome phenomenon, however, and can result in the formation of greasy films of amine carbonate (the reaction product of the stratified amine and carbon dioxide from the air) that can easily go undetected. These films can nullify the adhesion of any subsequent coat. As application temperatures are lowered, lower reactivities extend required induction times and compound the amine blush problem.

Intercoat adhesion difficulties can also occur when old hard epoxies are recoated after several years of exposure. For this reason it is often necessary to mechanically scarify old epoxy films with a sweep blast or a water blast before the application of the repaint systems. It is also normally necessary to remove chalking deposits from old epoxy films before recoating. This can also be done effectively by water blasting.

#### **Epoxy/Polyamide Primer/Urethane Topcoat Barrier Systems (System Group XVIb)**

Because of the chalking difficulties of the epoxy, updated systems often employ urethane topcoats, which have better resistance to UV, and therefore have better color and gloss retention. Two-pack urethane systems, like epoxies, are thermosetting materials and are strong, hard, and almost as chemically resistant as the epoxies. Final properties will depend very much on the individual formulation and particularly on the choice and level of polyol. Two primary polyol types are currently in use on bridges. One is a hydroxylated polyester, which gives excellent chemical resistance, hardness, and abrasion resistance, but is somewhat more sluggish in dry-to-touch times and more expensive than the other, which is a hydroxylated acrylic polyol. The latter material would seem quite chemically resistant enough for bridge applications, dries faster than do the polyesters, seems easier to use, and is somewhat less expensive. Both the polyester and the polyhydroxy acrylic type aliphatic urethanes have excellent weathering resistance.

Lower cost aromatic urethanes based on toluene diisocyanate are possible for use as midcoats, but are not used extensively. They are prone to recoating difficulties, and their color and gloss retention are far poorer than epoxies. The moisture-curing aromatic urethane is based on diphenylmethane diisocyanate and will be discussed under a separate system.

#### **Aluminized Epoxy Mastics Barrier Systems (System Group XVII)**

Aluminized epoxy mastics are two-pack, very high solids, low-molecular-weight epoxy systems pigmented with aluminum and designed for application over hand- and power-tool cleaned substrates as well as brush-off and commercially blasted substrates. They are primarily designed as two-coat maintenance systems for spot-blast applications over old alkyd systems in order to inexpensively upgrade the old alkyd, although other applications have included use as finish coats over zinc-rich

primers and as primers under vinyl, epoxy, and urethane finish coatings. Claims have also been made advocating the use of this type of coating for the repair of old inorganic zinc systems.

This type of coating was first introduced by a single manufacturer in the late 1960s, being advocated for application over rusty substrates with a minimum (SSPC-SP-2) of surface preparation. The idea of applying barrier coatings over a rusted substrate is hardly in keeping with theory, and it seems likely that only high-film-thickness application, preferably with aluminum flake pigmentation (both of which effectively prevent or slow down water ingress), will give reliable performance. Epoxy mastics with their high-build capabilities are perhaps best suited to fulfill these requirements, and they have indeed been found superior to other systems in a controlled study performed by Rensselaer Polytechnic and Avondale Shipyard (232). Better surface preparation, on the other hand, should produce theoretically more viable coating systems at lower builds.

The initial epoxy mastic, still the most widely used, was based on a low-molecular-weight epoxy cured with a proprietary curing agent modified with what appears to be a bituminous phenolic derivative, specific details of which remain undisclosed. The product has a high viscosity (100 to 140 K.U.) and is 90 percent solids by volume. Application is impossible without thinning, and the manufacturer recommends a 10 percent dilution for spray application although some applicators use higher dilutions. Like many of the lower-molecular-weight epoxy-resin-based systems, the material has a short pot life, four hours at 75°F when thinned 25 percent. The modified curing agent is said to add significantly to its wetting properties, but is probably responsible for a marked tendency of the product to undergo a patchy bronzing, particularly when brush applied. This is an aesthetic drawback, which is less obvious when the product is applied by spray and which is said to become more diffuse on aging. Although essentially a barrier system, the particular product once contained inhibitive lead pigmentation. Newer formulations, however, are reported to be lead free.

Despite the low-molecular-weight resin, most aluminized epoxy mastics are relatively flexible compared to other epoxies, probably from resin modification. This serves well in bridge applications. Use of aluminum pigment not only reduces moisture penetration but reflects UV and heat and protects the epoxy resin.

The success of the original aluminized epoxy mastic undoubtedly was influential in the general development of this kind of product. Many of the systems have lower viscosity than the original product, although solids are still in the same range and thinning for spraying is recommended, especially for the first coat. Pot lives remain relatively short ( $2\frac{1}{2}$  to 3 hours at 70°F, but the nonmodified systems do not bronze). The nonaluminized variants are normally formulated with lower solids than the aluminized systems (80 to 85 percent volume solids). The newer variants of this type of coating have not received the same field use on bridges as have the original material, and being newer, the field history is not as securely established.

Aluminized epoxy mastics are usually applied as a two-coat system (5 mils each), although some manufacturers recommend one coat (5 to 8 mils) only. The consensus is that two-coat applications of the aluminized epoxies are necessary for visible long-term performance. Where they are applied in spot applications, the first spot coat is used over the power-tool cleaned (or blasted) spots, and the second coat is applied as a total

topcoat. It is reported that in Iowa this type of system has been used to spot repair older zinc/vinyl systems.

As in the aluminum pigmented moisture-curing urethanes, recent developments utilize similar vehicle systems with zinc dust. This system, although new to bridges, has been used in some offshore oil rig applications, and is said to provide good performance over salt-contaminated surfaces.

The epoxy mastics have been adapted for maintenance applications in several states including New York (Thruway), Ohio, Wyoming, South Carolina, Massachusetts (on railroad bridges maintained by the public works department), and by Virginia. The product is typified by the Virginia specification (233), which appears to be based on the original product. Wyoming uses the aluminized epoxy mastic on overhead structures and for painting bridge railings (234). South Carolina uses the same product as a finish coat over inorganic zinc (235). The Waldvogel Memorial Viaduct in Cincinnati, Ohio, was painted with a single 5 mil coat of this system over a wire-brushed surface. The Fort Steuben Bridge in Steubenville, Ohio, and the Grand Island Bridge in Niagara Falls have also recently been painted with this type of paint system, and the coating is also being employed for added protection on the expansion bay steel of the Newport Bridge (1984 painting).

The aluminized epoxy mastics seem most widely used in bridge maintenance as an alternative to inorganic zinc systems on those bridges where, because of design difficulties (back-to-back angles, latticed features, and heavily riveted or bolted construction), neither blast quality nor film thickness control can be maintained without continuous costly inspection.

The Virginia specification contains a prequalification clause calling for at least two years of service as a one-coat 5 dry mil film in a similar service and environment to that being considered. The Virginia specification does not appear to utilize the epoxy mastic alone, but as a 5 mil primer over a commercial blast and beneath 3 mils of high-build vinyl or as a 5 mil finish over 3 mils of inorganic zinc applied over a near-white surface.

The amount of diversity from product to product in this class gives great difficulty in categorizing these products. Some contain inhibitive pigments, some are straight barrier systems, some employ leafing aluminum, others are based on nonleafing aluminum. Yet others have abandoned aluminum pigmentation altogether, with what sacrifice (if any) in performance yet unknown.

Service-life claims by the manufacturer are as much as 15 to 20 years for the original aluminized product, although other reports indicate more variable success. This variability may reflect either poor inspection or poor application practices or both. Early applications on the Route 290 Viaduct in Worcester, Massachusetts, were disappointing, although thin films were cited and later more controlled applications did better. One Ohio contractor reported poor results with a similar system leading to extensive system rectification. Test data would show that single-coat systems are less dependable than two-coat systems, and it is possible that variable performance observed is directly related to film thickness effects. Difficulties have also been related by the manufacturer to the degree of pitting on steel surfaces, and it is now recommended that highly pitted surfaces receive blasting preparation only. Various caveats are found in many data sheets concerning the effects of variability in the quality of interpretation of the SSPC-SP-2-3 specifications, and the effects of surface on performance. Many of the test coupons

utilized newly rusted white-blasted steel as substrates for the coating. This, however, is not typical of the type of rusted steel found on many bridge structures.

#### **Urethane/Aluminum Barrier Systems (System Group XVIII)**

Few recent paint systems have been developed, as was the BLSC system, directly from raw material manufacturers. One notable example is the aluminized barrier system based on a diphenylmethane diisocyanate moisture-curing resin and non-leafing aluminum pigmentation, introduced in the early 1970s (62). Like the aluminized epoxy mastics, these moisture-curing urethane-type primers are advocated as an alternative to zinc-rich systems on structures where design considerations might restrict the application of zinc systems. Film thickness specification would in many cases seem equally or more critical (as far as the upper limit is concerned) as zinc systems and certainly more so than the epoxy mastics.

Two variants have been used. System Group XVIIIa is a three-coat aluminized moisture-curing system with all coats based on the same diphenylmethane diisocyanate, but bearing slightly different nonleafing aluminum levels in successive coats and small amounts of tinting pigments used to differentiate between coats. System Group XVIIIb, a similar system, has also been developed wherein the final coat of the moisture-curing urethane is replaced with a two-component aliphatic urethane.

These systems (mainly XVIIIb) have been used on several bridges (Patton St. Bridge and Glenwood Bridge) in the Pittsburgh area, and test areas on the Bessemer and Lake Erie Railroad Bridge are now 11 years old and reported to be in excellent condition. Although the two-coat system applied to the railroad bridge was applied over a hand-tool cleaned surface, newer recommendations suggest commercial blasting these surfaces and a three-coat application. In 1978 on Homestead Bridge in Pittsburgh, a spot blast was adopted in which an SSPC-SP-6 blast was used on rusted areas with an SSPC-SP-7 on tightly adhering old oil paint. The bridge was spotted with the diphenylmethane diisocyanate primer system and then given a full coat of the same product. Finally, a full coat of the polyester/aliphatic urethane two-pack system was applied. In a paper by Bracco (236), some ten individual coating systems designed for bridge structures are described.

The above systems are advocated for application by brush and roller only (the manufacturer discourages spray application) of dry film thicknesses of 2 to 2.5 mils each ( $1\frac{1}{2}$  to 2 mils for the aliphatic urethane topcoat). The manufacturer's advocacy of brush and roller for the system may be related to a need to optimize wetting over pitted surfaces on old bridges. It may also be related to difficulties with wind-carried aluminum over-spray, which is a severe problem with all aluminized finishes. Additionally, it appears that higher builds of the aluminum primer tend to develop severe bubbling tendencies on application (probably  $\text{CO}_2$  generation) and brush and roller application may give better control against excessive film thickness. Based on early field data, the resin manufacturer expects 10 to 12 years for this three-coat system, 25 to 30 years if a commercial blast is substituted for the power-clean surface preparation.

Field performance history does not at this time universally confirm these claims and expectations—at least as far as the

XVIIIa moisture-curing system is concerned. The Pennsylvania DOT (R. Davidson, personal communication, 1985) reports relatively disappointing performance with the diphenylmethane diisocyanate primer-based systems and these reports are confirmed by Tinklenberg of Michigan citing delamination problems, etc. On a structure in the Harrisburg area, performance was said to be no better than that of the three-coat, BLSC-alkyd system. Early failures were believed related to application and inspection problems, but a more controlled application under the supervision of the manufacturer in the Philadelphia area did not result in better service. Again, the pitted condition of the steel was cited as the major reason for the failure. Others have reported that the performance variability is related to formulation effects (D. Miller, Tnemec Co., personal communication, 1985).

A further variation of the above systems was qualified by Michigan for use on riveted plated girders and trusses in the field. In this system, two coats of moisture-curing primer are first recoated with a high-build epoxy and then finished with an aliphatic two-component urethane (237). By 1985, however, Michigan had abandoned this system as a result of extensive delamination failures.

#### **Coal-Tar Epoxy Systems (System Group XIX)**

One of the most common corrosion-resistant barrier coating systems, the multi-coat coal-tar epoxy system, finds only limited use on bridge structures because of its color and poor UV resistance.

Coal-tar epoxy systems exhibit both the very low moisture vapor transmission and excellent acid and alkali resistance of the coal-tar portion with the general chemical and abrasion resistance of the epoxies. Resistance properties, moreover, seem synergistically improved by the blending. A more complete outline of the physical and chemical properties of this coating system may be reviewed elsewhere (238).

So good are the performance properties of this system, however, that it has found much success in protecting some of the most demanding areas of bridge structures, such as the expansion bay steel, which tends to be more susceptible to deterioration because of leaky joints, etc. On the Massachusetts Turnpike the coatings have also been employed on the beam ends and bearings, although here the normal two 8 mil applications are applied over a dry 3 mil film of phenoxy zinc rich.

The New York DOT, citing a need to protect both ASTM A 36 and A 588 steel in highly vulnerable areas beneath bridge decks that are repeatedly wet and show slow dry-off characteristics, has adopted the use of a two-coat, coal-tar epoxy system (one coat tinted).

The major drawback to this heavy-duty system is its sensitivity to sunlight. The product chalks and may become quite brittle on exposure to the actinic rays of the sun. For this reason, and because of the product's ugly black color, employment on bridges is almost universally limited to areas that are hidden from view. Some state highway agencies, such as New York, have used other systems as topcoats (even alkyds) but the solvents of the recoat systems must be carefully selected to avoid bleeding of the coal tar. Also, in recoating coal-tar epoxy, care should be taken to ensure intercoat adhesion, and this may be difficult with generically different topcoats.

Even self-recoating is difficult if too long an interval is allowed between coats, and sweep-blasting is often necessary after the first coat has aged more than 24 hours under summer conditions. Powerful solvent softeners, such as the slow-evaporating *n*-methyl-2-pyrrolidone, applied by brush and allowed to sit some 30 minutes before the second coat is applied, have been used in some cases in lieu of the sweep-blast, although this technique is not foolproof.

Because of the tremendous cohesive strength of the super high build of coal-tar epoxy, care must be taken to ensure a good balance between cohesion and adhesion strengths if delamination problems are to be avoided. Consequently, specifications normally call for a white or near-white blast with relatively deep profiles (4 mils or so).

Similar systems have also employed inorganic zinc, but it remains a point of some discussion as to whether any kind of zinc primer is necessary. So impermeable to water is the coal-tar epoxy, that the sacrificial protection of the zinc at holidays or scars is afforded only by the sides of the scar (the depth of the film thickness of zinc film) and corrosion is inevitable at the scribe because of inadequate area effects (51).

Specifications for coal-tar epoxies have been well developed and formulation examples, such as the C-200 specification of the Corps of Engineers, are available (239). Actual formulations may also be found under SSPC-Paint-16 of Steel Structure Painting Council (238), which approximates the specification from the Corps of Engineers. Some manufacturers, although not offering the C-200 specification, have their own specific products that are essentially similar even though they may employ different curing agents or even different epoxy resins.

In certain amine-cured coal-tar epoxies extreme care must be taken to ensure sufficient induction time to prevent amine blush with consequent amine carbonate formation. The slightest interfacial contamination of the coal-tar epoxy system can lead to severe intercoat adhesion problems.

## Wax Coatings (System Group XX)

One type of barrier coating that has been in use for many years is the wax coating. This type of coating is still used in certain states (the Maine Turnpike uses it on the beam ends and bearings of overpasses, for example), and other states (Texas, Oklahoma, Georgia, Ohio) are evaluating newer variations of the same type of materials.

In recent years this type of system has seen some renewed interest in several applications including bridge painting because of the introduction of a family of metal salt dispersions (240). These are blended and used with microcrystalline waxes and other additives to produce a family of coatings with excellent corrosion resistance, unusually high resistivity, and very low moisture vapor transmission. Claims of corrosion resistance (240) have been confirmed in recent studies, and aluminized variants, like epoxy mastics, have even been tested successfully at high film thicknesses over rusty surfaces (241). Lower film builds require better surface quality for the same degree of protection. It may be concluded that performance over poor surfaces is directly related to the product's ability to restrict water access through the film.

Like all wax coatings, these systems do not form hard, abrasion-resistant films, but remain quite soft and even tacky. Their unique cohesive characteristics and self-healing tendencies, however, make them highly resistant to corrosive failures such as peeling, blistering, cracking, etc., which plague more conventional coating films.

Possible applications on bridge structures are discussed in a recent paper (242), which concludes that with judicious utility on nontraveled surfaces such as pans and below-deck areas, application of these systems may well be justified because of their unique form.

## SYSTEM SELECTION AND SPECIFICATION DESIGN

### COATING SYSTEM SPECIFICATIONS

Today, the practical selection of a coating system for a given bridge introduces an entirely new set of complexities. In the past, such selection was not possible. Little else was available but lead and oil from which to select, and steel was either new and uncoated or bore the same basic systems as those to be used for repair. Where alternative coating types were available, these differed in little more than pigmentation, or, in the most extreme cases, in the particular modification of the basic vegetable oil (alkyds, phenolic varnishes, etc.).

The selection and combination of individual components of a paint system specification is a discipline unto itself and fraught with the many uncertainties that arise not only from the complexities of coatings chemistry, but from the effects that numerous factors may have on the suitability of a given paint system for a given structure. Not only is there statistically an increased likelihood of system design error that is axiomatic with increased choice, but today's high-performance systems are higher energy coatings that neither easily tolerate incompetency in job execution nor adapt as well to the variety of design features and surface conditions that may be found on any given structure as did the systems they replaced.

Furthermore, today's system design engineers in maintenance applications are faced with the repair of existing paint systems applied over the past 20 years that may be as varied in type as the systems available for the repainting, and are often incompletely documented. Additionally, many of the newer systems are harder to repair than were the old oil/alkyd types. Finally, the demands of the late 20th century (increased traffic loads, high levels of deicing salts, etc.) on both bridges and paint systems are more exacting.

It is little wonder that, with the increase in use of the high-performance coating system, there has occurred (with greater frequency) failures the likes of which had not been encountered in the lead and oil days.

Nor can such failures be blamed entirely on the system design engineer, who often is following the paint manufacturer, who, in turn, may be incompletely aware of all the nuances of the coating system and particularly of the parameters of what constitutes acceptable application and utility. It is one thing for a coating system to function properly under ideal circumstances, but another to maintain performance under field conditions where the ideal may be compromised either slightly or substantially.

Under these circumstances it is becoming increasingly necessary for the paint specification to be designed to fit a particular structure than for the structure to be "adopted" by any given

paint system. Only on large bridges, however, are paint systems designed for the specific structures. In practical circumstances it is economically infeasible for every simple overpass, for example, to be individually evaluated and a coating system tailored specifically for that structure. It is also unnecessary, for it is more common to find a group of bridges of similar design in the same general location with similar environments having identical existing paint systems. In this case, what works for one structure will most often work for another, and the adoption of a single specification for a group of overpasses is a viable methodology; and one widely employed across the country.

On the other hand, the concept of zoning (71), now used in several states, is a practical approach to specificity in coating-system selection that is both economically feasible and engineeringly sound. A state will employ a totally different coating system in marine or industrial areas than one it may use in rural inland areas. Although this strategy may not consider all factors that may affect the suitability of a given paint system for a given structure, it deals with one of the most important—exposure. Many states in all parts of the country have observed the effects of the environment on the service life of coating systems, and report that coating systems on coastal structures may give less than half the service life of the same system in the rural interior. Similarly, a paint system in metropolitan New Jersey will give no more than half or even a quarter of the service that the identical paint system will give in the desert Southwest or in rural states, such as Wyoming or the Dakotas.

Moreover, states employing multiple types of coating systems, such as California and Oregon, report that in many cases they see fewer differences in the performance of different paint systems in any given area than they do in the performance of the same system in areas of different environmental severity. An all-vinyl barrier system has been seen to fail in about the same time as a conventional red-lead system in coastal areas of the Northwest, but both will give much longer performance in the interior valleys.

On the other hand, it is widely accepted that zinc/vinyl systems will outperform the BLSC and red-lead systems in more aggressive environments. Such states as North Carolina, Texas, and Florida employ both coating systems, utilizing the zinc in marine or other severe environments where it is considered necessary.

Further examples of increased specificity in coating-system selection is the increased use of "specific utility." The concept takes advantage of an understanding of those areas of a particular structure that are most vulnerable to a specific type of deterioration, and addresses these by specific utilization of pertinent coating systems, additional coats, or additional film thick-

nesses in these particular areas. In this way, money that is not needed in the overprotection of less vulnerable areas of the structure can be saved and better spent in areas where more serious deterioration is expected, based on studies of the deterioration patterns of previous paintings on the same or similarly designed and located structures. In its simplest form, one coat of a three-coat system may be saved on less vulnerable areas (e.g., interior webs), while an additional coat is applied to more critical areas (e.g., lower flanges, seams, edges, etc.). More complex examples include the use of UV resistant finish coats (silicone alkyd, acrylics, aliphatic urethanes) on exposed surfaces, while retaining less expensive systems (long-oil alkyds, vinyls, epoxies) in areas having less UV exposure. Similarly, coal-tar epoxies, hardly desirable or necessary on most sections of a bridge, are particularly valuable on expansion bay steel where some of the most severe deterioration occurs. The concept is discussed more fully by Hare (243).

#### DEVELOPMENTS IN COATING-SYSTEM SPECIFICATION

Over the past ten years the quality of the best system specification (if not the specifications for the individual paints) has undoubtedly improved considerably, although in contrast, the majority of specifications remain less than adequate. Modern bridge-paint specifications still seem to pay more attention to the individual elements (coatings) that make up the total paint system than to the overall system and the interrelationships of each of the several elements within the whole. In many ways the typical high-performance specification betrays the considerable confusion and uncertainty with regard to composition (if not utility) that exists among many of the state specification writers. The dependence on the manufacturers of the high-performance systems in many states all too often shows through.

In many cases specifications today (especially the compositional specifications) have less definition than in the past. Even performance specifications could be improved. Greater attention might be paid to those factors known from past service to be of criticality: post-blast priming intervals, cure verification, re-coat times, etc. Better definition of criteria of acceptability and nonacceptability might be given, and a methodology for correction of common deficiencies, if delineated within the specification documents, would eliminate many legal hassles and claims for extra work orders, and perhaps even serve to prevent the deficiencies before they occur.

Notwithstanding the above, over the past ten years there has developed a greater awareness of the importance of accurately specifying surface quality, film thickness, volume solids, sag resistance, a more scientific control of those climatic parameters under which painting can take place, and more detailed performance test procedures. The use of control instrumentation is now specified in more detail, as are in some cases those less quantifiable coating and coating film defects that will not be tolerated (244).

There seems to be increased emphasis on prequalification, not only for the paint manufacturer and the contracting firm, but for materials and individual operatives who do the work. Increasingly an awareness is growing that not only should the paint manufacturer and contractor be experienced with the type

of product specified, but that there be evidence of a particular paint system's past performance on similar jobs. The new specification for the inorganic zinc/vinyl/vinyl acrylic system for the Mass Turnpike Authority demands that actual operatives have at least five years of experience using similar coatings and equipment, and requires documented resumés for each applicator (173).

Modern specifications often call for continuous inspection and limit the number of work areas in which the contractor may work at any given period, so that inspection will be adequate and cost-effective. The specification for the Tobin Bridge not only required a team of experienced inspectors on the job, but called for field consultants in coating technology and environmental science (244). Many specifications now call for technical field service representatives from the paint manufacturer to be present for some period at the start of any job to teach both contractor and inspector the nuances of a particular system.

#### SHOP AND FIELD SPECIFICATIONS

Paint system specifications for shop-applied new construction are inevitably less complex and technologically more definitive documents than are specifications for the repair of aged coating systems in the field. The uniformity and predictability of the new substrate, the ease of access in the shop for application and inspection, and the control of climate and contamination makes for a cleaner, more certain specification. In effect, the specification writer is more assured in shop specifications that the actual product will closely duplicate the conceived model.

Not clearly differentiated are the advantages and disadvantages of the various options that exist in new construction alone. NACE Task Group T-6H-23 (245) has recently completed a study comparing the various possible sites and procedures for painting structural steel. It cites four major options: (a) job-site application before erection, (b) job-site application after erection, (c) painting at the applicator's yard site, or (d) painting at the fabricator's plant. These options are multiplied when one considers a three-coat system specification, as each of the above alternatives (except the first) applies in the application of the intermediate coat and the finish as well as the primer. There are, in effect, 10 different options for a three-coat system. The specification writer must select which methodology most satisfactorily fulfills the requirements. In bridge construction, not surprisingly, preparation and painting after erection is rarely adopted. It has few advantages, is the most costly procedure, and introduces many of the usual field painting difficulties one experiences in maintenance. Similarly, job-site application has few advantages compared to work done either in the fabricator's yard or the applicator's shop. Handling damage may be minimized, especially if intermediate or finish coats are applied in the field, but costs are higher, and job quality will probably be poorer because of the more erratic application resulting from access difficulties and because of climatic effects.

Advantages and disadvantages of work performed in the fabricator's shop versus the applicator's yard involve cost savings and quality of preparation afforded by centrifugal blasting (most fabricators use centrifugal blasting methods, most applicators use air pressure blasting). Also, application by the fabricator is often performed in-shop (under cover), whereas most paint ap-



plicators have historically worked without cover. On the other hand, a painting contractor will probably be more skilled in the use of coatings than will a fabricator, who, aware of the cost overruns and scheduling problems that historically haunt painting operations, may actually refuse painting services, particularly those involving the application of coats other than the primer.

Various options as to which coats to apply in the shop and which coats to apply in the field remain and revolve mainly around difficulties of field touch-up and the greater vulnerability of multi-coat systems to handling distress. The recent experience of the Michigan DOT (179) would indicate that it is indeed possible to apply all coats in the shop with little difficulty, good control, and extreme cost-effectiveness. Although there are data (246) to support cost savings in the use of inorganic zinc as a shop primer coupled with deferred (five-year) topcoating programs (including the treatment of topcoating as an expense instead of a capital outlay), the data refer to plant construction and would not hold true for bridge work because of the high cost of access alone. For both aesthetic and engineering considerations, the field touch-up of a prime coat or even a midcoat may be more satisfactory than the touch-up of a finish coat (especially a thermosetting system), but field application is inevitably more costly and less secure than shop application. Tinklenberg (179) observes that a greater awareness of the criticality of handling finished pieces in itself fosters greater care in handling, which in turn reduces the amount of field touch-up of finish coats actually necessary in full shop-applied systems. Michigan reports remarkably little field touch-up of its shop-finished system, and is now firmly convinced of the approach. Bayliss has discussed the practicalities of lifting, transportation, and storage of shop-applied finished steel as well as the use of temporary applications (247). Single-site applications will also save money on inspection fees.

Montle (248), in discussing the problem of lateral cohesive failure of inorganic zincs through premature topcoating, observes that jobs calling for primer and topcoat application in-shop are more suspect than field jobs because of the fact that the fabricator, motivated by logistics, is often too eager to topcoat the newly applied primers and get them out. Gelfer and Vandorsten (249), on the other hand, in an attempt to reduce the difficulties of long recoat times of alkyl silicate zinc-rich films in the shop, have produced experimental data indicating that ultra rapid recoating intervals are possible with conventional (vinyl, epoxy, chlorinated rubber, etc.) topcoats, hydrolysis and solvent release of the inorganic zinc primer apparently occurring through the topcoat. These data still require field confirmation, however. Inorganic zincs based on the high  $\text{SiO}_2\text{:K}_2\text{O}$  alkaline silicates are reported by Schaffer (250) to withstand rapid topcoating (two hours) without zinc film splitting.

Although there is a gradually increasing field practice of radically blasting a bridge to totally remove all old coatings and renew the metal/primer interface, this is expensive. Most field maintenance must utilize coating systems over surfaces consisting of old paint, at best spot blasted to an SSPC-SP-6 or 10 and very often only power cleaned or brush-off blasted. Furthermore, the condition of the surface immediately presented to the new paint (which can be normalized to some extent by cleaning) should often be of less concern than the condition of

older interfaces within the existing composite (which are inaccessible for attention). With an old paint system that must, in part at least, perform as the substrate for the new coating system, the specification writer assumes the legacies of prior specifications, surface preparation, application, recoating intervals, and the buildup of paint film thickness. Paint systems for many older structures are written without careful analysis of the structure and the condition and type of existing paint. In the past when such structures were recoated with the older lead and oil systems, the universality of these coatings, their initial flexibility, and the mildness of their solvent systems caused few problems. With newer paint systems, stronger solvents, harder vehicles, and greater initial shrinkage on drying, these older composites are more severely strained with new applications, often to the point of breakdown. Early adhesive and/or cohesive failures at one interface or another within the continuum of one film or another can result in system delamination, particularly in those areas peripheral to a spot blast where the old paint system was damaged almost to the point of failure during spot blasting. As old paint films gradually increase in film thickness with each additional application, as less and less use of the more conventional lead and oil systems is necessitated by increasing environmental restrictions, and as the mixing of newer systems and old systems increases, it is probable that this type of coating failure will become more commonplace until these older structures are totally stripped of their original paint composites.

## GENERAL PAINTING SPECIFICATIONS

A procurement specification for bridge painting is a relatively complex document that is designed to both define the work to be accomplished and to ensure the execution of the job within a set of acceptable parameters. The specification (Table 7) is usually divided into several separate sections, many of which are boiler plate in nature and apply to all contracts issued by the pertinent bridge authority. These sections set definitions, proposal requirements, and conditions, and give general information on the award and execution of the contract, including bond requirements and penalties, insurance requirements, and permits and other legal requirements. These sections may also describe the scope and control of the work, its progress and prosecution, as well as describing the procedures for the measurement of quantities and payments.

Sections of the contract documentation are job specific, normally nontechnical, and usually itemize special job considerations. They provide detailed requirements of the specific job and include the drawings, minimum wage requirements, insurance, and necessary indemnification clauses. They may describe such requirements as traffic control, sanitation, utilities, debris removal, interference with adjacent work, interpretations of contract document, and so on. They may outline process control mechanisms (including inspection and sampling procedures), rigging requirements, pollution control, prequalification requirements for the contractor, and any extraordinary requirements that may pertain to the particular job.

The technical documents are contained in a separate section of the specification and are primarily concerned with requirements for cleaning, blasting, and painting, although quality con-

TABLE 7  
 FORMAT OF TYPICAL BRIDGE PAINTING SPECIFICATION

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GENERAL PROVISIONS

Standard requirements for contracts with Authority.

Definitions and Interpretations of Contract Documents.  
 Proposal Requirements and Conditions.  
 Award and Execution Dates.  
 Bonding and Insurance Requirements.  
 Legal Requirements, Permits and Responsibilities to Public.  
 Penalties, Incentives and Liquidated damages.  
 Indemnification  
 Variances

SPECIAL PROVISIONS

Detailed requirements of specific job.

Scope and Definitions of Work.  
 Drawings  
 Measurement of Quantities and Payment.  
 Minimum Wage Requirements.  
 Utilities, Sanitation, and Clean-up.  
 Traffic Control and Interfacing with Adjacent Works and Other Contracts.  
 Police Service  
 Quality Control, Inspection and Sampling of Materials.  
 Guarantees

TECHNICAL SPECIFICATIONS

Cleaning, Surface preparation and Painting Specifications.  
 Paint System Specifications.  
 Individual Paint Specification.  
 Other Materials Specifications - Sealants, etc.  
 Repairs  
 Environmental Provisions and Disposal.

SAMPLE CONTRACT FORMS

Corporate and Individual Contract Forms.  
 Performance Bond  
 Payment Bond  
 Sub-Contractor Forms  
 Extra Work Forms

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trol provisions and environmental protection (if appropriate) may also be found here. The heart of this section, however, delineates the paint system and the material specifications for the individual paints making up that system.

The technical content of this section will depend on the particular system used, not only in terms of the individual coating specifications, but also in terms of the associated specifications for cleaning, surface preparation, and job execution that are necessitated by the choice of such coatings. Once very simplistic, technical specifications for cleaning, surface preparation, and

painting have, since the late 1960s, evolved into very detailed documents that continue to be refined as more is learned of the parameters of successful and unsuccessful application of each paint system. As experience with a particular paint system grows, process controls are continually redefined and expanded to ensure the quality of the applied system. Where once only the control of thinning, brush technique, and number of coats were important criteria, now a multitude of quantifiable requirements (typified by those items in Table 8) are often included.

TABLE 8

## COATING SYSTEM CONTROL CRITERIA

Specifications	Criteria
Surface Preparation	Allowable climatic conditions (temperature, humidity, dew point, wind speed, and where applicable wind direction) Surface preparation methodology Media type and size range (for blasting) Inhibitor type (wet blasting) Equipment type (for power-tool cleaning) Solution types and concentrations, equipment and rinsing schedules (for washing) Required surface quality Mil profile Blast prime interval
Coating Preparation	Homogenization Mixing (of components) Thinning (solvent type and amount) Induction time requirement
Coating Application	Allowable climatic conditions (temperature, humidity, dew point, wind speed, and where applicable wind direction) Allowable application methodology Wet film thickness (minimum and maximum allowable) Dry film thickness (minimum and maximum allowable) Recoating intervals (minimum and maximum allowable) Pot life limitations Description of required appearance Itemization of nonacceptable conditions and required rectification
Coating Materials (Compositional specifications)	Nonvolatile content Pigment content Nonvolatile vehicle content Weight per gallon Vehicle type as determined by I.R. Spectra Zinc content (where applicable) Quantitative determination of key pigmentary elements (Pb, Cr, etc.)
Coating Materials (All specifications)	Viscosity Dry time - touch Dry time - hard Dry time - recoat (may include coin test and solvent rub tests for zinc primers) Pot life Color Gloss Flexibility Sag Resistance Salt Fog Weatherometer or fluorescent UV condensation exposure Immersion salt water Immersion fresh water Bullet hole
Coating Materials (Complete system)	Adhesion and cohesion Salt fog Weatherometer or fluorescent UV condensation exposure Immersion salt water Immersion fresh water Hot/cold/UV/salt cycling environment
Field Evaluation of Finished System	General appearance Dry film thickness Adhesion Touch-up procedures

## THE SPECIFICATION WRITER

It is important that those whose responsibility it is to produce specifications be familiar not only with the selected paints and paint systems and with the typical day-to-day operations involved in the execution of the bridge-painting process, but also with the strengths and vulnerabilities of the coating system selected and its field history. It is also important that specification writers appreciate the demands that the design peculiarities of a particular bridge may have on these strengths and weaknesses.

Many of the individuals responsible for the generation of bridge-paint specifications have little practical experience in the areas of paints, paint systems, or the painting process itself. This often results in a "scissors and paste" approach to specification design.

An additional complication is that often those individuals responsible for the initial definition of the painting requirements and those responsible for coating system design and final specification are not the same individuals. In some cases, where individual paint specifications are prepared by those other than state employees, there may be little or no communication between such parties. Moreover, there is often too little communication between field engineers and inspectors and those responsible for producing the specifications. It is in the field where specification deficiencies and required refinements are established. Formal channels wherein this type of information can be discussed directly between field representatives and specification writers (if not formulating chemists) are imperative to the refinement of paint system specifications.

## SOURCES OF INSTRUCTION FOR THE PREPARATION OF COATING SYSTEM SPECIFICATIONS

No courses have been identified that deal specifically with the preparation of bridge-paint specifications, and few books and papers seem to address the subject. The best are probably the *SSPC Manual* Vol. 2; Weismantel's "Paint Handbook" (251) (particularly sections in Chapter 4, 6, 7, and 14); and NACE Publication #6J162 (252). Data may also be found in the FHWA study on Best Current Technology by Ray, Henton, and Rideout (36). Some general requirements for specification content are discussed by Baker (253), and valuable material can be found in Standard Specifications of AASHTO (254) and the Construction Manual for Highway Bridges (255).

Although not specifically for bridge-paint systems, the three articles on guidelines by Baldino (256–258) for writing coating specifications have much valuable data and insight on the form and language of the boiler plate and general technical provisions of the specification.

Equally as important as the composition and language of the specification is some understanding of the underlying technology, the materials used, and the job execution process itself. Some practical field experience is invaluable to the specification writer, as is direct contact with residents and paint inspectors and others familiar with the operations of the painting contract. Again, the various publications of SSPC, particularly the Man-

uals and the *Journal of Protective Coatings and Linings*, may be of great assistance here as may be those of NACE (including the journal *Materials Performance*). Other specific articles (10, 27, 259, 260) that discuss paint systems for bridges (among other structures) in some detail do not consider either the form or language of the specification but the discipline in general. Still more basic are those texts that are more concerned with corrosion, surface preparation, application, etc. (10, 104, 261, 262). Many application equipment manufacturers also provide detailed booklets on technique, etc. The one published by DeVilbiss (263) on conventional spray application is an excellent example of this. Introductory texts that deal with basic coatings science and formulation (264–267) are rather more technical, but provide invaluable background support.

Finally, much additional data may be absorbed from existing specifications, although it is important that the would-be specification writer uses these materials as data sources rather than as fixed models, and views a sufficiently wide selection of these documents to become acquainted with all views and approaches. It is well worth remembering that many of these documents themselves are imperfect. The specifications of states such as Florida, California, Louisiana, and other authorities such as Massport, however, are well worth review.

## INDIVIDUAL PAINT SPECIFICATIONS

Today's specifications (268) for individual paints may be loosely grouped into one of three types: the compositional specification, the performance specification, and what is best described as a quasi-compositional specification.

### Compositional Specification

The compositional specification is undoubtedly the most definitive as well as the most restrictive document. This specification both leads and polices the manufacturer. The compositional paint specification is restrictive in both raw materials and composition, and consequently is not conducive to creative formulating. Its value is that it gives the specifying authority the greatest control over what goes onto the bridge, but it limits the quality to that specified and slows the implementation of improved technology.

The compositional specification is generally divided into four sections. These define the raw materials that may be employed, provide an itemized formulation breakdown in terms of both pigment and vehicle, and list a group of quantifiable parameters that may further channel the formulator toward the required product. These quantifiable parameters serve also as a list of requirements against which a testing agency may qualify the product. The fourth section adds performance controls.

The use of compositional specifications has declined. This decline has apparently been encouraged by the FHWA, which has advocated leaving formulation technology to the paint companies (to avoid duplication of effort) and has concentrated its resources on evaluating coatings and developing test methods

and criteria for performance characterizations (269). The prediction of field performance from accelerated laboratory tests on a consistent basis remains elusive at this time, and thus the reliability of high-performance systems should not be evaluated by these tests alone. Some authorities insist that a strict compositional standard, locking in the attributes of well-proved formulations, is the more reliable approach. No matter which type of specification is used, tests must be incorporated to ensure the quality of each batch and to identify it as the same composition as the qualified formulation. As proprietary products become similar and specification writers learn more of the newer systems, their formulations and their performance history, the compositional specification could eventually return.

### Performance Specification

The performance specification is a much less exhaustive document than the compositional specification and is primarily a policing specification. In its purest form, the specification may not even specify the generic type of material to be used. The thrust of the performance specification is to qualify the product by a series of qualitative or quantitative tests that are keyed to the required function of the coating and not to its composition. Thus a large coatings manufacturer, reluctant to manufacture a special specification paint of fixed composition (and contend with fierce competition from smaller manufacturers), is more easily accommodated by the performance specification. This allows a manufacturer to offer a line coating without special manufacturing and at higher profit as long as the coating provides the necessary performance.

The trick is to come up with a group of accelerated tests with pass/fail criteria that can accurately be correlated with a minimum required level of performance in the field. There is much difficulty in correlating any specific accelerated test with field performance, but resolution is generally possible by using several different test criteria to qualify the product. An evaluation of test results against field performance for high-performance systems derived from such specifications would show that enough correlation exists for useful specifications to be designed by this method. Where system failures that are not predicted by test results occur, they occur most often for reasons not associated with a defect in the paint but from deficiencies in other areas (low film thickness, poor surface preparation, etc.). With time and experience with the system, better correlation of accelerated test results with field performance is acquired, and the adjusted specifications become more accurate and meaningful. Performance specifications are typified by the West Virginia Department of Highways specification for an inorganic zinc-rich/vinyl system (270).

The performance specification requires significantly more control through accelerated testing than does the compositional specification. As many of the accelerated tests required in performance specifications take weeks or even months to complete there are impracticalities in correlating testing requirements with job schedules. It is often necessary therefore to tag specific formulations with easily determined quantifiable constants at the time of coating approval and to use these to monitor batch-to-batch consistency. Furthermore, as noted by Ray et al. (36), attempts to ensure material quality with laboratory performance

tests are bedogged by those same variables in test design, surface preparation and application of panels, and changes in test ambient conditions that haunt more formal studies that attempt to correlate performance in lab testing with that in the field. Other (less satisfactory) techniques of quality assurance involve certifications from the manufacturer. Another major deficiency of the performance specification is that it assumes complete compositional conformity between individual batches of the product. This is not always the case, and, intentionally or unintentionally, formulations may vary. Manufacturers may have alternative sources for raw materials and may, for reasons of cost, availability, delivery, or in-plant control, vary formulations. The existence of two or more quite different formulations may be utilized to produce the same product. Whereas most compositional specifications of the Qualified Products List (QPL) type require the manufacturer to notify the specifying authority of any changes in formulation, this is not always done because of the cost of resubmittal. The term "formulation change" is also quite relative. It is rare that some slight modification of formulation is *not* required in quality control, particularly for color, gloss, or viscosity adjustment, and work-offs of past batches are by no means unusual in the paint industry.

One aspect of the performance specifications that might be improved is the misdirected emphasis of testing individual products and not the complete paint system; for so many failures, particularly with zinc-rich systems, seem to result from the effects of the environment on the coating system as a whole and not on the individual elements. The comment is true not only for performance specifications but perhaps for all paint specifications except where single-coat systems are to be employed. Recoating criteria are most critical in many of the high-performance paint systems (zinc-rich, coal-tar epoxy, wash primer systems, etc.), and specifications for total composite thickness and intercoat adhesion must consider control of the total system and not just an individual paint.

Although the realization that all elements of a given coating system should be purchased from the same manufacturer is now a cornerstone of good specification design, the manner in which midcoat, topcoats, and primers interact with one another viscoelastically is not as well considered nor perhaps even understood.

### The Quasi-compositional Specification

The quasi-compositional specification employs elements of both the true compositional form and the performance form, although the latter predominates and the specification is rarely so compositional that a given formulator without prior knowledge could easily create a coating solely from the requirements of the document. This type of specification is typified by many of the aluminized epoxy mastic specifications, such as that of South Carolina (235). This type of specification primarily polices, whereas it leads the formulator only very broadly. The specification will channel the formulator not only by stipulating such things as general vehicle type (alkyl silicate, epoxy, alkyd, etc.) or pigment type (zinc dust, silicates, inhibitive pigments, etc.), but may quantify certain parameters ("weight of zinc in dry film shall be 81% minimum," etc.). It may specify one or

two less critical constants, such as viscosity, dry time, weight per gallon, etc. (which may be used with other determined constants to tag the product for batch-to-batch variations), but the bulk of the specification does much the same sort of thing as does this pure performance specification, and often in as much detail. Quality assurance difficulties are much the same in the case of the quasi-compositional specification as they are in the performance specification. Whether or not quantifiable tags are published with the specification or assigned in a QPL approval process, these are again more successfully used to monitor product compliance than are the long-term accelerated performance tests outlined in many specifications.

Additional discussion of quality control programs of all three types of specifications will be found in Chapter 7.

## GUARANTEES

The practice of guaranteeing jobs (in all industries) is increasing. The guarantee not only offers the owner advantages in improved quality assurance and establishes an exact cost per year, but allows alternative methodologies to low price in evaluating bids. The guarantee may also assist both reputable manufacturers and painting contractors by further qualification and thus may eliminate the less reputable competition. For the paint manufacturer and contractor, guarantees are powerful (if dangerous) public relations and advertising tools.

Guarantees appear more common in Europe and Japan. In Germany, for example, large painting contracts have been underwritten by insurance companies as part of a "Protocol" methodology (271). In this, a trial section of the job (representative of the whole) is painted according to the requirements of the manufacturer of the coating system (under the supervision of the manufacturer's representative) by the contractor establishing a standard of quality. The contractor must then execute the remaining bulk of the contract according to this standard. In the event of system failure, responsibility is judged by weighing the deterioration of the trial section against that of the bulk of the job. Jobs are underwritten by insurance companies and premiums are said to be about 3 to 5 percent of the total contract price (1980).

In the United States, guarantees are becoming more common in other industries where environments are more predictable and applications and inspection are easier. They are discussed by Moore (272). They have been offered between manufacturer and owner, manufacturer and applicator, between applicator and owner, and between manufacturer, applicator, and owner with split financial responsibility between manufacturer and applicator. Guarantees may be written over a set number of years and may be extended by prorating over the final years.

Recent experiments in "turn-key" or single-point responsibility contract approaches (similar to those used in off-shore oil drilling markets, or in the maintenance of chemical processing plants) have been attempted. In this approach, one organization, usually the paint manufacturer, assumes total responsibility for the job as the general contractor. This concept is discussed in detail by Hower (273). The manufacturer hires and trains both the painting contractor and the full-time inspectors in the application of the specific products to be used and provides spec-

ification writing services, contract bonds, and other details. The paint manufacturer also assumes contract management responsibility and provides the bridge authority with a blanket guarantee with assured maintenance for an extended set period. Such a system (based on an inorganic zinc/epoxy midcoat/aliphatic urethane finish) has recently been implemented on the Newport Bridge in Rhode Island (M. Kulick, R.I. Bridge and Turnpike Authority, and T. Calzone, Carboline Co., personal communication, 1984). The only formal parameters of the job dictated by the bridge authority were that the existing paint be removed to the metal and that the new system last at least 10 years.

Several manufacturers bid this job, and the authority and its consultant evaluated the bids for the theoretical soundness of the paint system, the warranty, and the job cost. On award, the paint manufacturer became solely responsible for the quality of the paint system for the next 10 years.

There are many advantages to such single-point responsibility contracts, although it still remains to be seen just how well such guarantees will hold up under test. One advantage of this type of contract is that in the event of problems, inter-party disputes that haunt coating failures are eliminated. In selecting the paint manufacturer as general contractor, there is also presumably some advantage to be gained from the manufacturer's intimate knowledge of the product and, if the inspectors are trained employees of the manufacturer, from the fact that the inspector has applied the paint system in the past and is familiar with the parameters of its employment. Aware of the responsibilities, the manufacturer is also more diligent in training the painting contractor in the correct execution of the job, and training sessions are usually conducted before the job starts. As materials are supplied directly by the manufacturer, the painting contractor realizes no advantage in keeping down the film thickness, although there is no real incentive against the application of film builds that are too high. Perhaps the most important advantage of this type of contract is that application bids are evaluated by the manufacturer who is not bound to select the lowest bid (nor for that matter to advertise the bid generally) but selects the painting contractor from a carefully selected list of qualified concerns with which the paint manufacturer is comfortable in terms of work expertise, cost, and ability to satisfy the contract requirements within the allotted time frame. In general, the paint manufacturer is better equipped than most parties to make such evaluations and to make prudent choices of contractor.

The advantages and disadvantages of single-point responsibility coating specifications are discussed in the Problem Solving Forum of the *Journal of Protective Coatings and Linings* (274). In this discussion the advantages of the concept are advocated by Kimball for large complex jobs and difficult environments (which would seem to qualify most bridge projects), although the author sees less cost-effectiveness over the traditional less expensive contract methodologies for simpler work. Brock points out that the contractor's allegiance in single-point responsibility contracts shifts from the owner to the manufacturer, and this shift may engender significant mark-ups for labor and extra charges for added efforts normally absorbed by the contractor to satisfy the owner and ensure good will for future contracts. Ashbaugh suggests that a third party, such as an engineering-based organization rather than a paint company, should conduct the program. This allows maximum utility of the widest selection of paint systems available, while moving

the control of the program to a knowledgeable third party. The financial strength to support a guarantee may be more problematic on large jobs for an engineering company than a large paint manufacturer, however.

The role of the independent consultant in the management of coating programs with or without the "turn-key" approach has been discussed in more detail by Trimber and Hull (275). Pinney (274) points out that despite the obvious advantages of the "turn-key" approach, the methodology in many respects merely puts the manufacturer in the same position that the contractor has historically been in, and to get the job the manufacturer's prices will have to be cut as inevitably the lowest-total-bid-price scenario will remain. With the "turn-key" approach must come an awareness that not only initial costs are

important, but the strength of the warranty is important as well as the record of the paint manufacturer in these types of jobs and the qualifying procedure for inspectors and applicators.

The major disadvantage to the traditional bridge-painting methodology would seem to be that guaranteed contracts will be confined to large paint manufacturers who can muster sufficient financial capability to back the long-term guarantees. It is possible that in the future some kind of insurance on the guarantee, such as found in Germany, may become available in the United States, although the recent reluctance of the insurance industry to underwrite engineering risks is not encouraging in this regard. It does seem, however, that there may be some future trend toward this type of contract, particularly on large bridges.

## CHAPTER SIX

## JOB EXECUTION

## CONTRACTING METHODOLOGIES

Bridge-painting contracts are normally in a fixed-price format, resulting from an invitation to bid with specifically advertised requirements. Although several possible alternative contracting methodologies are possible, fixed-price contracts are usually the rule. In special circumstances, time and materials and labor hour contracts may be used, but these are often confined to extras, etc. Other forms of contracts, such as cost plus fixed fee, seem rare in bridge painting, although they are used in other industries. Single-point-responsibility contracts have also been used, and two-step formal advertising methodologies involving technical proposals that are evaluated and accepted before invitation to bid would also seem possible in bridge painting, particularly where complex containment methodologies are required.

## THE PAINTING CONTRACTOR

Bridge-painting contractors range from large and medium-sized organizations that are well equipped and staffed by schooled and experienced superintendents, foremen, and operatives (all with good reputations and long records of successful work with many and varied coating systems) to small two- and three-person operations that are, in many instances, in and out of business on a relatively frequent basis. Furthermore, this divergence appears to be widening, although it is possible that the apparent widening reflects changes in the paint systems as much as it does actual deterioration in the expertise of the smaller contractors. The tolerant lead/oil systems could accommodate most insufficiencies of application much better than the high-performance systems.

Although distinctions of competency do not necessarily coincide with size, the larger, successful bridge-painting concerns are generally reputable and skilled, and familiar with the newer coating systems, whereas many of the smaller contractors may be neither as experienced nor as reliable for quality workmanship. Large concerns with bonding abilities in the \$5 million to \$10 million range, who employ several hundred painters on multiple jobs nationwide at any one time, are generally (although not always) employed on larger bridge structures. This is probably because the bonding restrictions of the smaller firms preclude their access to the larger jobs. On the smaller jobs the small firms are more competitive and therefore displace the larger contractors.

If most failures are related to application error (including surface-preparation deficiencies), then the above should indicate

that the smaller structures are more vulnerable. Unfortunately, meaningful correlations of this type are difficult to establish. There are many more smaller structures than larger ones, although coating failures on larger bridges are more publicized. Compounding the difficulties is the fact that the majority of smaller structures are still painted and repainted with lead systems, which are both more familiar to the small bridge-painting contractor and more tolerant of those application deficiencies that would produce certain failure with "high-performance" systems. Finally, as noted by Ray et al. (36), there remains a conspiracy of silence concerning coating failures, and the extraction of data is difficult and sometimes misleading.

## THE CONTRACTOR AND THE PAINT SYSTEM

Data from the contractors confirm the growth of the inorganic zinc and vinyl systems, and most of the larger firms seem quite comfortable with this type of system, although specific concerns (such as the tendencies of certain primers to dry spray in field applications especially during high-wind conditions, or the difficulties in surface preparation, etc.) are still voiced. Smaller contractors do not generally prefer zinc, citing application problems and too much chance of error. Most contractors like alkyd systems and cite their tolerance for application error. Similar surveys also indicate a definite increase in the use of the aluminized epoxy mastic, which some contractors describe as more forgiving than many of the other high-performance systems.

The type of paint system has limited and indirect impact on the cost of the job in the opinion of most contractors, and impact relates more to mandated surface preparation and application costs than to material costs. Although oil and alkyd systems are perhaps only half as costly to apply as inorganic zinc, surface-preparation costs are much more significant than application (276). Differences are, however, magnified by other factors. Most contractors usually report that factors such as the design and location of the structure and, in field maintenance, the type and condition of the existing paint system, all of which may have significant impact on job production rates, have the most impact on the cost of the job. The condition of the steel itself in field maintenance is also critical to job costs. Old corroded steel that is heavily pitted will require much more time to clean than will steel that is newer and still bears coating or mill scale. Certain coating systems, such as inorganic zinc, will not penetrate and wet these pits easily, and residual contamination within the pit will tend to hold moisture and may lead to premature breakdown of any paint film. A red lead/oil primer, on the other hand, readily wets all surfaces, blasted or



not, and is most forgiving. Inorganic zinc films are relatively intolerant not only of poor surface preparation but of film thickness variations, resulting in mudcracking in high-film-thickness areas and runs that require scraping, wire brushing, or even spot blasting.

Few large contractors consider the amount of inspection to be a significant factor in job costs, although smaller contractors, from whom response was poor in the surveys, might not agree in this case.

Nor is skill the only origin of observed divergences. Even the best contractor or fabricator is primarily concerned with the profit motive and may take short cuts if allowed.

Although few if any painting contractors or fabricators can boast an altruistic regard for quality, the better ones would as soon do a job properly as badly. It is as much in the applicator's interest for a job to go well as it is in the interest of others responsible for the job, for on the success of past jobs rest an applicator's reputation. This is beginning to be recognized as more important as there is an increasing use of prequalification clauses, which require the contractor to supply a list of jobs of similar size and complexity using similar paint systems that were completed.

#### IN-HOUSE PAINTING CREWS

Comparatively little painting appears to be done by means other than contracting. Few states now extensively employ their own painting crews, except for touch-up work or for small structures with easy access. In most states these activities represent less than 10 percent of all bridge painting, although some states, such as West Virginia, do use their own crews more extensively, and at least one state (Maine) utilizes state-employed crews almost exclusively.

States, such as Louisiana, Connecticut, and Ohio, that employ practically no state crews, cite a reluctance based on the high cost of wages and equipment necessary to maintain in-house crews, whereas other states, such as Massachusetts, cite the high insurance premiums, pensions, etc. as important dissuatives for the state-employed crew. Most state crews appear to be used for touch-up maintenance of small existing structures and serve to prolong the service life of existing paint systems between major repaintings, which are contracted out.

It is not unusual for authorities operating large bridges to employ a maintenance painting crew for similar duties, although again major painting is almost always contracted out. In areas where painting is seasonal in nature, the problem of "what to do with the state painting crews over the winter" has also been cited as an obstacle to the retention of this mode of maintenance.

#### THE BID PROCESS AND AWARD

After the job is advertised, interested bidders will purchase specifications and drawings, and, in the case of field work, they are invited to examine the structure to be painted. On some jobs such prebid inspections are mandatory and potential bidders not attending are disqualified from bidding. The prebid conference is arranged to outline the job to potential bidders, highlight important aspects, interpret specifications, and address the bidders' questions. In most instances, attendance at a prebid con-

ference is not a prerequisite for bidding, although the prebid conference is most valuable to the contractor and to the bridge authority alike. The prebid conference ensures that bidders are fully cognizant of all aspects of the specification and can in consequence tender a proposal that accurately addresses the job requirements at a price that is both competitive and sufficient. Additionally, potential bidders may use the prebid conference to raise factors for resolution that may not have been fully appreciated at the specification design stage. Response, often in the form of a specification addendum, inevitably improves the overall specification and contributes to the betterment of the job. The prebid conference is also used by contractors to discover and evaluate their competition, for the competition in itself can markedly influence their own quotations.

Several weeks after the prebid conference, tendered bids are opened publicly and the low bidder is announced, although the actual award may not be made until later. Bid openings may be attended not only by the bidders but by paint manufacturers seeking to supply the materials for the job to the successful contractor. It is not unusual for paint manufacturers, with an eye to providing material cost estimates to contractors, to actually take out copies of specifications themselves, although in soliciting a supplier, contractors or fabricators will usually supply manufacturers copies of the technical specifications.

#### MATERIAL SOURCE OPTIONS

Paint may be produced directly by the bridge authority and provided to the contractor who is then responsible solely for the execution of the job, or, more usually, the paint is supplied through the contracting company itself whose bid reflects the price of the material. There are advantages and drawbacks with either technique. If the painting contractor is responsible for the purchase of the material, he or she thereby becomes a customer of the paint manufacturer, who is in turn obliged to satisfy the contractor if the manufacturer is to get paid.

Problems that may arise in situations where the authority itself buys the paint include job delays and shut-down problems occasioned by delivery, testing delays, and application problems. Inevitably a contractor may make a claim against the authority, which must seek reimbursement from the manufacturer.

In the event of short-term application problems or long-term performance failure, the bridge authority may be caught between manufacturer and contractor, both of whom will disavow responsibility. A qualified inspector, independent to all parties, can do much to interpret such problems for the authority and may even help to resolve the difficulties by either technical assistance or arbitration.

#### JOB PREPARATION

At the time of the award the contractor will be formally notified of the earliest start-up date. By inference, from the specification, this will also establish the required completion date, after which the contractor may be assessed for liquidated damages.

Samples of the paint materials intended for use on the job may be requested for testing by the state or bridge authority before work commences. Early delivery of such materials be-

comes essential if a paint manufacturer or a product is not qualified and performance specifications are employed. Performance testing may take several weeks, and tags for the control of future batches must be set. Compositional specification materials will be sampled during manufacture at the paint plant or preferably on the job from actual stocks.

## **MOBILIZATION AND PRECONSTRUCTION CONFERENCE**

After notification of the award, the contractor will begin to mobilize and staff the job. A preconstruction conference will be held to allow all parties an opportunity to evaluate each other and to discuss the project in detail. On small jobs such meetings may be very brief, informal affairs; on larger jobs they can be most important for all parties and for the job in general. Those present may include the specification writer, the paint manufacturer, and the inspector; but certainly the engineer, the contractor and/or the fabricator, and the contractor's job superintendent.

Schedules, logistics, and equipment to be used are normally discussed, as well as the interfacing of the project with other projects on the same structure or in the same shop. The various parties will voice their specific concerns and while difficulties may or may not be resolved, they should be identified and, where possible, quantified. The contractor may require additional interpretation of details of the technical specifications or information concerning access, traffic patterns, lane closings, equipment placement, and so on. The engineer may need details from the contractor concerning equipment, crew size, rigging procedures, containment, etc. In new construction, specifics on delivery schedules, erection, and disruptions to road, rail, and water traffic may be discussed. In field jobs, a contractor may discuss concerns over specific practical aspects of the application with the engineer, specification writer, and/or manufacturer who may in turn stress areas of concern over the technical provisions of the specification with the contractor and inspector.

Although not all potential problems will be identified and dispatched in such preconstruction conferences, if properly conducted and attended by all parties, many of the difficulties and delays that can plague a job can be minimized by address in this forum.

## **RIGGING**

The rigging of a structure is a vital prerequisite to any paint job and is a skilled practice in itself. Proper and adequate access to all bridge surfaces without over-reaching or endangering operator safety is basic to the job process. Several excellent references are available that discuss in detail the many safety considerations in the design and use of scaffolding and rigging systems (277-282).

Although standard rigging features such as swing scaffolds, single-point staging, spiders, boatswain's chairs, and so on are used from job to job, bridge design features invariably require some adaptation or another. Many bridge-painting contractors employ crews specialized in rigging structures and some advertise their services to bridge authorities and engineering concerns requiring rigging expertise for inspection and non-painting main-

tenance (George Campbell, George Campbell Painting Co., personal communication, 1985). For many years these contractors have designed their own equipment, or at least modified that equipment available on the market. Occupational Safety and Health Administration (OSHA) regulations noted by Fox (283) have encouraged more standardization, however, and more recently scaffolding companies have started to market a greater variety of equipment including many pieces of equipment first conceived of by contractors. All manner of apparatus is now available to all contractors.

Devices such as modular suspended staging decks, supported from the flanges of longitudinal I beams, can travel the length of longitudinal beams without disassembly or leaving the working deck (284). Cable-mounted sections of a similar type have been used by Caltrans with considerable savings in production time (285). Permanent cable connections securely anchored into concrete abutments or via beam anchors serve after initial installation for repeated maintenance operations using cables that are slung and tightened using turn-buckle assemblies (284).

Scissor lifts, hydraulic boom lifts, and "Snooper" type devices have also extended easy access. Snooper devices such as those manufactured by Paxton Mitchell in Omaha, Nebraska (286), can put a worker 40 feet in under a bridge deck from the roadway itself. Scissor lifts controlled by an operator from the working platform can raise a worker and 400 lb of equipment 40 feet in the air. Hydraulic booms similarly controlled can reach more than twice that height, although with reduced loads.

Smaller structures with lower clearance (overpasses, etc.) are often painted from the ground by pipe staging rigs. These versatile assemblies are easily modified to any height and shape and may be fitted with wood or metal decking complete with adjustable out-riggers if required. Casters (which lock during painting operation) add portability. In some cases the assemblies may be mounted on vehicles. Pipe staging may also be used on bridge legs, bent supports, and columns and can serve as tarpaulin frames for containment methodology. High supports, legs, and suspension towers are more often than not painted using boatswain's chairs or spiders or power hoist staging. Ladders (used for access) are rarely used on bridges as painting platforms.

A more detailed review of this technology is beyond the scope of this synthesis. Additional valuable data may also be gleaned from the literature of those scaffolding companies specializing in systems designed for bridge work.

## **START-UP PROCEDURES**

At the inception of any job, there is inevitably a period during which the job team (engineer and specification writer, contractor, fabricator and crew, inspector, and manufacturer) becomes acquainted with both the paint system and the specification, the bridge or piece design, and with each other. With the more common paint systems in shop work or on relatively simple structures, the process may be rapid and the learning curve short. On more complex structures, particularly in the field, or with new paint systems, or with an inexperienced crew, the education may be more protracted and involve several false starts. Rigging and scaffolding methods are tried and revised, containment methodologies are debugged, and traffic patterns are verified.

It is during this period that the presence of the paint manufacturer's experienced technical representative is invaluable. This person must demonstrate and train the applicator in the use of the system and educate the inspector to the nuances of good and bad application. The quality of this type of service may be good or bad depending on the individual manufacturer and the contractor receiving assistance. In general it seems that technical service of this type from the larger manufacturers is of a higher caliber than similar service (if available at all) from smaller manufacturers. In other service respects, delivery and response, the smaller manufacturer often seems better. Recent constrictions on profits of many of the larger manufacturers may result in some future cutbacks in the extent of this type of extensive field support.

Interpretations of surface quality and mil profile are made during this stage and the applicators gain the feel of the coating, determine the equipment necessary (pumps, hoses, tip sizes, etc.), and the type and levels of thinner required for satisfactory application. They develop a familiarity with application procedures required to produce reasonably constant ranges of surface quality and of film thickness on all features of the structural design (webs, edges, riveted and bolted sections, etc.). Interpretations of the specification are assessed for both compliance and practicality, and, where necessary, adjustments in techniques or even in the letter of the specification may be made (with the input of the paint manufacturer, specification writer, engineer, and painting contractor) to most effectively resolve difficulties and secure the best job. At this stage of the job some degree of flexibility is important, and closed minds on the part of the engineer and specification writer can be counterproductive. Application of all elements (coats) of the complete system are made (with particular regard to practical recoating schedules) and results are assessed for quality, film thickness, and adhesion.

In effect, in the first weeks of the job, the rhythm of the job will be established and during this time the input of all those responsible for the job is essential. All elements of the design should be evaluated, but especially critical areas such as heavily bolted connections, recessed and back-to-back angles, boxes, seams, and so on should be evaluated for methodology. Striping techniques by brush, by conventional spray, or other application methods should be determined and schedules practiced so that the technical requirements of the job may be accomplished with a minimum of rigging and the least delay. Specific problems, such as the use of mist coats and zotcoats, for example, are evaluated at this time.

## **JOB MEETINGS**

On large jobs, in particular, the regular job meeting can be an invaluable tool through which the engineer, contractor, inspector, paint manufacturer, and consultants can keep track of job status, schedules, and procedures. They may interpret specifications, report on the appropriateness of existing procedures, discuss problems, and resolve most difficulties through this forum. Rarely, if ever, will a specification accurately anticipate all conditions that will be met in practice, and often such conditions cannot be anticipated at the preconstruction conference. Often, to maintain quality and production, some interpretation and modification of the specification will be necessary. Rather than informally on the job, these are best discussed in open

meetings wherein all parties may represent their own position and the consensus be noted. Here the discussion may be recorded, procedures clearly delineated and, where necessary, formal requests for extra-work orders made.

In the event of serious difficulties after the fact, including job claims, coating system failures, and litigation, the minutes of such meetings may be an invaluable aid in resolution, discovery, and settlement. The minutes may also be of great value as part of the technical job record in the post-painting monitoring process.

## **THE MODERN PAINTING PROCESS**

Like paint systems, the painting process (including surface preparation) has over the last decades evolved from what was very much an art to what is, if not a science, a relatively complex technology requiring both practice and understanding. For the most part, the spray gun has replaced the brush and roller, and the centrifugal blaster and blast nozzle have replaced the scaling hammer and wire brush. In itself, however, such a summary is simplistic, for both brushes and scaling hammers are still used as auxiliary equipment and, on some jobs, hand- and power-tool cleaning and brush and roller application remain. Today their employment is, however, more selective and judicious, and responds not only to the economically induced preferences of the contractor but to real engineering dictates of a quality job, factors that are not necessarily opposed to each other.

The modern applicator, therefore, has not so much abandoned the old practices as enlarged upon them. The applicator must not only now be familiar with an ever increasing diversity of coating types, but with the many specific types of equipment that their employment demands, and the fine points of application techniques that these systems require for optimum results.

One neither applies an oil paint by brush with the same technique that one would use for vinyl touch-up, nor would one apply wash primer with an airless gun in the same manner as one would apply an epoxy finish. The application of high-build vinyls or coal-tar epoxies at acceptable uniform film thickness in touch-up or in restricted or intricate areas is all but impossible without care and experience. Primers, tie coats, and high-build mastics all make their individual demands on any applicator as do individual systems within the same type of generic product makeup. One zinc-rich primer with a fast solvent system, for example, will require utmost gun control if dry spray is to be avoided, a second may require a continual balance of speed and gun motion and distance from the work if an overly wet film is not to sag. Adjustment of tip sizes and pump pressures and selection of types and quantities of thinners to be used are essential in today's application if satisfactory control is to be maintained. As the realization that the parameters of acceptable film thickness require maximum as well as minimum values, so the demands on the applicator's knowledge and skill further increase. Design and steel configurations will also influence the methodology of application; large, flat, continuous areas require the long, continuous sweeps possible from airless equipment, whereas edges, bolts, and intricate sections can only be successfully coated with short, restrained gun motion and careful trigger control, more easily accomplished with air spray techniques than airless.

Climatic conditions and work locations, especially in field

painting, will have a significant effect on application technique to the point at which they may preclude application. Effects of this type are not necessarily limited to the often quoted temperature or dew point restrictions, but include wind speed and direction problems.

Along with the selection and use of new equipment has come the necessity for familiarity with support equipment, not only the obvious compressors, heaters, agitators, traps, etc., but metering devices and controls, cleaning equipment, scrubbers, and so on. In the shop application of specialty features (fasteners, gratings, railing sections, lighting fixtures, etc.) electrostatic applications, powder coatings, and even newer methodologies may be employed. Thermal-spray-applied zinc and aluminum systems, now enjoying increased use on bridges, utilize their own equipment, oxy-fuel and electric arc (wire fed) guns, plasma (power fed) guns, power sources, etc., which call for even more exacting application experience than does conventional equipment.

Abrasive blasting has widely replaced hand- and power-tool cleaning not only where high-performance systems are employed, but even in spot maintenance where lead systems are still employed. Rideout et al. in their 1982 survey (73) report that almost all states have now adopted blast preparation (usually SSPC-SP-6 or 7) and only in the rural desert Southwest are any major holdouts found. This is also confirmed by Leyland (287).

Engineering considerations relating to abrasive blasting have been reviewed extensively in Chapter 3. Dissertations on equipment and techniques are found in Chapters 2.0 through 2.9 of Vol. 1 of the *Steel Structures Painting Manual* and in many other sources (91, 98, 107, 288, 289).

## PRACTICALITIES OF THE JOB PROCESS

### Washing and Cleaning

Although the theory and techniques of surface preparation are discussed elsewhere in this synthesis, certain practical aspects should also be included. On spot-cleaning jobs in the field, for example, where old films will inevitably become the substrate for the new coating system, pre-blast cleaning is an important precursor to actual surface preparation (either blast or hand or power cleaning). The process is vital on jobs in industrial areas or in the snowbelt states where salt contamination of paint films can cause serious problems if not removed. Gross (290) demonstrated the amount and variety of chemical deposits that can accumulate on bridge structures, and has shown these to vary with bridge geometries, geographical location, and the type of crossing.

Blast containment of large areas with tarps may also introduce a need for a post-blast washing of primed steel before finishing. Where large containments of structures require several days of work within the same enclosure, blast debris from one day's work can severely contaminate surfaces primed earlier. The debris on such films is so heavy that it becomes cost-effective and certainly technically wise to wash the primed steel after containment is removed.

## Surface Preparation

The practical difficulties in blasting and cleaning often relate to problems of access or of steel condition. On many structures, certainly the older ones, there are invariably areas of poor access. Certain design features of expansion bays, small boxed members, column interiors, steel near abutments, etc. may restrict access. In these areas it is better to utilize a less demanding paint system (e.g., bituminous material or possibly a wax coating) laid on heavily over whatever surface preparation is possible.

On older structures in the snowbelt states and in industrial areas (particularly in expansion bays or lower flanges, etc.), the steel can be very heavily pitted, and such extensive deterioration may not be visible until after the scale has been removed and blasting commences. Cleaning by blasting is difficult and slow, and results even then may be questionable. Although the contractor may balk at the production rates of this type of work, there can be no compromise in blast quality and the steel must be cleaned. Wet blasting with water/abrasive mixtures may give the best results.

Such steel may also bedevil the application of primers, for its very porosity will produce the same bubbles and pinholes that are seen in topcoats over porous zinc films. Furthermore, such holes may telegraph from one coat to another. Uncleaned debris from the pit bottoms may hold on to water after rain and this may result in premature breakdown of even zinc films.

### Priming

The more common problems of priming involve the maintenance of production and job schedules, and balancing these with the weather. As surface preparation is virtually always the rate-determining step of any operation, the contractor will blast for as long as possible in any single working day, leaving the last two hours or so for reblast, blow-down, and priming. In good weather there is little difficulty. In high humidity or where rain threatens, the scheduling of this blast/priming operation can become quite difficult. Under these conditions steel turns more rapidly, and the contractor may lose large sections of blasting before they can be primed. Although the reblast of such areas is never as difficult, production rates are inevitably reduced. Similarly, newly primed films may be overblasted or compromised by contaminating abrasive if not dry. Problems may be compounded as the use of water-base systems grow. These are prone to flash rusting, rain removal, and/or protracted drying times in high humidity.

Other weather-related factors that may confound the contractor's operation relate to temperatures, particularly in areas of the country where the painting season is shortened in spring and in fall. Applications of latex paints, oil and alkyd systems, and particularly epoxies are badly compromised by cold weather, and the contractor must judge the application schedules carefully if cure is to be maintained. The contractor must not only adhere to temperature limitations at the time of application, but estimate the expected delays in surface temperatures achieving minimums in early mornings, and assure enough time for cure before evening temperatures again drop below minimum. When two or three coats of epoxy must be applied and cured

within a set recoating schedule, the judgment of weather conditions over two and three days can become particularly exasperating.

In the practical application of all primers, holidays, skips, thin areas, and areas developed by over-blast are unavoidable. With the older paint systems these required little more than simple field touch-up. With the new systems things may not be so simple and touch-up procedures for inorganic primers, etc. must be established before the fact. Here there is some disagreement. Some manufacturers of inorganics require sweep-blasting of the original coat before a second coat may be applied (291), other manufacturers require little or no preparation but a heavily thinned touch-up coat (292). Additional opinions regarding touch-up of inorganic zinc involve the use of touch-up with an organic primer compatible with the inorganic zinc and with the midcoats and finish coats to be used. This may require the specification of a special touch-up organic zinc-rich primer in the actual specification. Application of an organic touch-up primer is best done after local scarification of the zinc-primed steel by at least power cleaning. Areas of ferric corrosion on zinc-primed surfaces are probably best reblasted and reprimed with the inorganic. Care should be taken not to build up the inorganic in the areas peripheral to the reblast however. Heavy single-coat builds of inorganic zinc will also mudcrack and should be removed by reblast. Isolated runs, however, can be scraped, wire brushed, and touched up with an organic.

Spray techniques with zinc films having critical film thickness requirements need careful development by the crew. These techniques must be adjusted for both the material and the job in order to coat both intricate areas (bolts, rivets, etc.) and large unbroken sections (webs) with enough paint to afford protection—but not so much that mudcracking or total cohesive failure of the topcoated system is possible.

Contamination of primers (particularly alkyl silicate-based zinc-rich primers) before recoating can also be a problem. In maintenance applications the dichotomy between the requirement for adequate cure of zinc-rich primers and the avoidance of surface contamination can be vexing. Some delay in the recoating of such inorganic zinc-rich systems will reduce the possibility of incompletely hydrolyzed films being trapped beneath the finish coat, and therefore mitigate the possibilities of lateral cohesive failures in the partially cured film after topcoating. In certain organic zinc-rich systems, slow solvents (e.g., cellosolve acetate) may be retained in the film for months. Unfortunately, delays of even a week can, under certain conditions, result in surface contamination. On dark zinc-rich films this may not be readily apparent. Heavy zinc corrosion product resulting from heavy rains can usually be removed by washing or water blasting the zinc. Certain organics with thermoplastic vehicles may be broomed free of loose material and recoated readily if good solvent welds are possible between the subsequent coat and the applied primer. More difficult scenarios are created when inorganic zincs or thermosetting organic zinc films are so contaminated. Difficulties are also created by the contamination of partially finished structures with deicing salts late in the season when zinc-rich films can be impregnated with chlorides. In these cases, even water blasting will not totally remove the chlorides and other contamination of the porous films, and intercoat adhesion problems, osmotic blistering, and the early corrosion breakdown of the system are possible.

## Tie Coats and Midcoats

Application of tie coats and midcoats to primer films should be made only after primer cure is completed (although they should be made before surfaces become too contaminated with road dust, etc.). Cure is not generally a problem with thermosetting systems unless temperatures have been misjudged, when epoxies give more problem than urethane primers. Lack of induction time or application at too low a temperature can produce sweating, blushing, and amine carbonate formation of many epoxy systems, which, if recoated, will inevitably cause intercoat failure. The removal of such exudates with isopropanol or some other recommended solvent may be necessary before topcoating. The recoating of coal-tar epoxy systems may be particularly difficult at both temperature extremes. Not only will low-temperature applications produce exudate, but high-temperature applications may catalyze the cure so much that intercoat adhesion may be difficult because of the hardness of the surface. Twenty-four hours may be the maximum possible recoat interval between coats under certain conditions. Beyond this, sweep-blasting or solvent softening may be required before recoating. In the application of new paint systems directly over old, hard epoxy coatings, sweep-blasting of the old coating may also be necessary.

With thermoplastic primers, solvent release may be slow where large amounts of high boilers are employed either in the formulation or in field reduction. Zincs may be problematic because of their weakly cohesive nature and because of their porosity and their propensity for contamination. Coin hardness tests and MEK (methyl ethyl ketone) rub tests are most important with inorganic zincs before recoating, particularly single-pack systems (293).

Where mist coating techniques are employed, detailed procedures should be established (by the manufacturer's representative, if necessary) before widespread application begins. Care should be taken to establish correct gun technique, appropriate schedules for the mist pass and for the full pass, the appearance and opacity of the mist coat, and the degree of cure or set-up between the two coats. Similar procedures are necessary in zot-coat applications, although here the amount and type of reduction solvent must be carefully controlled. It is not unreasonable to find that changes in reduction solvents may be necessary (with all coats) as temperature conditions may vary from day to day, and contractor, engineer, and inspector should be aware of what conditions dictate which reducer is to be employed.

Tie coats of the WP-1 wash primer type require even greater control, specific attention being necessary in agitation of the base component (settling may be heavy), in mixing (too slow or rapid a combination of components may result in premature gelation), and in use. The application of low film thicknesses from an undiluted mix may be difficult with airless application, particularly in tight areas or around intricate configurations, and substantial post-mixing thinning may be required using one of the lower alcohols. Around bolts and rivet heads brush application may be preferred for additional control of film thickness. Thickness may be controlled by monitoring the opacity of the applied wash primer. Very thick films on galvanized surfaces have been observed to result in subsequent delamination of the wash primer and total system. It should be stressed that the

wash primer will not jell, but its effectiveness will lessen progressively after mixing. It may be very difficult to convince an inexperienced contractor of the need to dispose of a still-liquid wash primer left over after a previous day's application. Recoat schedules must also be carefully controlled after wash primer application. The wash primer film becomes very hard, and the recoating of films after 24 hours may produce intercoat problems between the finish coat and the wash primer.

### Finish Coats

The finish coat must not only provide protection but aesthetics also, and considerations such as uniformity of gloss and color become particularly important. Poor gun techniques can result in pinholes, overspray, and patchy, blotchy, and uneven films, even in relatively flat finishes. Difficulties such as these are often more of a problem with fast drying systems than with slower ones, although nonuniformity in film thicknesses resulting in sagging, color float, blushing, and windblown contamination can compromise slower systems.

High-build midcoats and finish coats, even with a mist or zotcoat, may still give application problems—bubbling, frothing, and pinholing over porous zinc primers. Many coatings tend to telegraph craters in midcoats through to finish coats. Excessive frothing and pinholing will not only reduce the effectiveness of protection, but will undoubtedly compromise the gloss and color uniformity of the system. Curiously these difficulties may vary with the same product from job to job, application to application, and may even vary in intensity from day to day depending on wind conditions, temperature, etc. In these situations, *input from*

*the manufacturer in the redesign of the reduction solvent system may be essential.*

Urethanes (particularly the slower drying polyester type) are also very sensitive to humidity variations, and their applications on certain structures (where sudden mists are prevalent) can result in loss of gloss and in surface bubbles.

Wrinkling of oil-based finish coats may produce an apparent patchiness when viewed from a distance, as may the results of application in late fall and early spring. Although these observations rapidly become less objectionable as the films age and chalking sets in, they may certainly compromise the aesthetics of the newly finished job.

Epoxies must be very carefully controlled when applied under border-line temperature conditions. In temperatures much below 50°F, reduced cure will tend to leave films sticky and easily contaminated until cure can again resume at normal temperatures. Although amine carbonate formation caused by reaction of the uncured epoxy film with moisture and CO<sub>2</sub> from the air will not cause recoat problems (as it does in primers and midcoats) in the case of the finish coat, the resultant yellowing and discoloration will badly compromise the appearance of the job. Although such carbonate formation is not generally a problem in bridge work, in shop-painted steel where artificial heat with CO<sub>2</sub>-producing devices is used to maintain temperature, or in the field where artificial heat is used within enclosures to prolong the painting season, such discolorations can compromise the overall finish-coat aesthetics.

A more complete discussion on the practicalities of the application process may be found in several sources including Vol. 2 of the *SSPC Painting Manual* (294), and in references 295–297. Dissertations on application defects may be found in references 26, 297–302.

## CHAPTER SEVEN

## QUALITY ASSURANCE/QUALITY CONTROL

In this chapter only those aspects of control that are directly associated with job execution—shop and field inspection, and the quality assurance/control of coatings—are considered. Pre-specification (systems option) inspection is considered in Chapter 5, and in-service inspection is discussed in Chapter 8.

## JOB INSPECTION

Consistent, quality inspection of the painting process is the most vital component in the entire process whereby the specification as conceived by the engineer, specification writer, and/or the paint manufacturer is transformed into a well-executed job. Many states as well as the federal government have embarked on various education programs and training courses designed to better acquaint bridge inspectors with their job (the monitoring of surface preparation, paint application, etc.) and the tools of their trade, as well as providing some background in corrosion science and the way coatings function.

The best inspectors are often found to have been painters (303), painting foremen, or blasters at some time in their career, and these individuals are probably most valuable because they know the tricks, devices, and foibles of those they must control.

California Division of Highways (as early as 1953) realized the value of such individuals and actively sought to develop inspection crews from bridge painters. As Woods (304) states, "not only could such individuals relieve resident engineers," but they "know what to look for and where to find it."

Paint inspection is often a part-time occupation (particularly in northern states) because of the seasonal nature of the painting practice. This means that the inspector often has other duties calling for other unrelated skills. Even during the painting season, it is common for paint inspection duties to make up only part of the state inspector's total job assignment.

In shop painting, inspection must again often be performed by those responsible for the inspection of other aspects of overall fabrication (welds, etc). Although the importance of the expertise of these individuals in their primary function is often well appreciated, skills in painting inspection are neither acknowledged nor encouraged.

## Inspection Training Courses

Dunkley (305) suggests that

the inspector should have an appreciation of the fundamental aspects of corrosion and factors affecting its control, together

with a basic knowledge of the nature of the materials employed as well as the influence of the environment and conditions at the time of application. His training should be progressive, and linked with career structure, which in turn implies the principle of continuous long term employment.

More on-the-job training of apprentice inspectors by skilled individuals is probably essential, and greater care in the selection of apprentices is warranted. To attempt to motivate the typical paint inspector solely by means of classroom sessions on corrosion science and paint technology and without a balance of practical consideration is probably rather futile.

Although several courses exist for the training of paint inspectors, few at this time deal specifically with bridge painting. Limited courses have been offered by individual states (e.g., California, Florida, Louisiana, and Massachusetts), and in some cases inspection methodologies are actually built into state DOT standard specifications (306, 307). Texas has an in-house bridge-painting course for inspectors that covers all phases from plan preparation to completion of project. Some texts are available (308), and a revised FHWA course (309) is currently under implementation. Inspection courses are also offered by NACE (310), the Institute of Applied Technology (311), British Gas, and the Institution of Corrosion Science and Technology (312), although these are not specifically directed toward bridge work.

The NACE Inspection Course (310) may be the most comprehensive general course, and is divided into three separate courses, each about one week long. Most of the important curricula as far as bridge painting is concerned are found in the first session (1985 cost \$1500.00 per participant). The two other courses (1985 prices \$750.00 per course per participant) are more concerned with other aspects of inspection such as the newer application methodologies, powder coatings, linings, and substrates other than steel. Some of the subject matter in Course II, such as centrifugal blasting, human relations considerations, safety, and certain testing methods, is, however, very relevant to bridge painting.

The Institute of Applied Technology Course (311) is good, but seems quite heavily directed to nuclear power generation. Nevertheless, there is much in the course that is relevant to bridge inspection, and its text makes a valuable reference.

The original FHWA Bridge Paint Inspection Training Manual (313) has recently been rewritten. Although directed at bridge-paint inspectors, the original course seemed to consider the processes of surface preparation and application more generally than it did the particulars of inspection. The totally revised course, which is inspection oriented, has been accepted by FHWA and is available to state highway agencies through the National Highway Institute.

The ASTM Guide for Painting Inspection (currently also being rewritten) is another very valuable text (314). Other reference texts with valuable training data are also available (315-317).

There is a tendency in some inspection courses to emphasize those concepts that are more easily taught (basic corrosion science, coatings technology, etc.) and to demonstrate the range of instrumentation available, rather than to discuss those aspects of inspection that relate to the recognition and detection of untoward conditions and practices on actual structures [the kind of practical treatments noted in the recent article by Bayliss (312)]. Perhaps the most valuable aspects of such courses are the familiarization of the apprentice inspector with surface preparation techniques and qualities, with the use and misuse of application equipment, and with much of the terminologies of both corrosion science and paint technology. Discussions of coating deficiencies (particularly those occurring during application or just after), their recognition, terminology, causes, and rectification are also particularly important.

Some specific treatises on paint film deficiencies are available (26, 300-302, 309). Pictorial representations of various types of coating failures may be found in relevant specifications of ASTM, Federal Standard Test Methods # 141A, and in other specific sources (318, 319). Possibly the most comprehensive coverage is to be found in the original and revised editions of *Hess's Paint Film Defects* (26, 300), which segregate failures that occur during application from those failures that occur in service. Excellent glossaries (320, 321) of terminology may be found in several of the above references, although the most authoritative reference in this respect is probably the *Paint and Coatings*

*Dictionary* (321). Spray equipment manufacturers also publish reference materials on finish problems related to spray application (322-324). Munger also discusses application problems (297).

Compared to treatises that detail the actual practice of bridge-painting inspection, there are many excellent sources of data on the types of instrumentation used for inspection (317, 325-327), and in some cases excellent in-depth scientific treatments for specific aspects of inspection [film thickness determination (328), mil profile (329), etc.] are available. A list of essential inspection tools is shown in Table 9.

#### Private Inspection Companies

In some cases the state highway department or bridge authority may utilize outside inspection for painting bridges, although this seems more common in shop application than it does in the field. Even in those companies offering such inspection services, the "paint inspector" may be primarily skilled in other disciplines, with checking paint and surface preparation as only one part of his or her overall responsibilities.

A handful of companies specialize in the inspection of coatings and the coating process. Unfortunately field rates for this type of inspection are high (generally \$25.00 to \$35.00 per hour plus expenses) and beyond the current budgets of most state highway agencies. Although the rate for paint inspectors is in itself perhaps no higher than for steel inspectors, the need for both types of inspection in effect doubles the rate.

TABLE 9  
THE INSPECTOR'S TOOLS

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1.	Psychrometer, Surface Thermometer, Anemometer,
2.	Mil Profile Comparator, Photo. Standard of Required Surface Preparation, Ion Indicator Papers,
3.	Wet Film Thickness Gauge,
4.	Magnetic Dry Film Gauge, Tooke Gauge,
5.	Holiday Detector, Flashlight, Mirror, Moisture Meter,
6.	Utility Knife, Testape <sup>®</sup> , Painter's Hammer, Chisel, Marker,
7.	Paint Remover, Solvent, Cotton, 4 oz. Jars, Distilled Water, Clean Pint Cans,
8.	Camera (35mm and/or Polaroid Type), VCR Camera, Binoculars,
9.	Safety Gear, (belts, hats, boots, etc.)
10.	Walkie Talkie or C.B. (large multi-level jobs),
11.	Cassette Recorder, Notebooks, Envelopes (for samples).

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Even fewer paint inspection companies specialize in the inspection of the bridge-painting process. Compared to job assignments in other industries (nuclear power generation, offshore drilling, water tanks, etc.), the opportunities for work in bridge-painting inspection have been less than widespread. Although it is claimed with some justification that painting inspection is much the same whatever type of structure is involved, this holds true only for the basic process. The experienced bridge-paint inspector is more aware of the relationships of bridge design to deterioration and better appreciates those areas of greater and lesser criticality (i.e., flanges of floor beams near end connections and bearing points, expansion bays, horizontal surfaces of lower chords, rocker pins and rollers of bearings, anchor chain gallery hardware of suspension spans, etc.).

### Value of Inspection

The value of paint inspection is well exemplified by Kaminski and Allen (330) who represent the cost (less than 2 percent of the total job) as a premium on the insurance against the cost of rectifying a premature paint failure. Much the same position is taken by Roebuck and Brevoort (331), who quote inspection fees at a higher percentage of job costs, generally 3 to 8 percent. The analogy is not unreasonable. The primary role of the inspector, however, is not only to ensure that a premature failure does not occur, but that the projected service life of the coating system is realized. Inspection ensures that a bridge authority gets as close as possible to a dollar's value for every dollar spent in job execution, and measured with the cost of the paint job itself on a cost per year of service basis the cost of inspection becomes insignificant compared to its return.

Kaminski and Allen (330) demonstrate the cost advantages that are realized with professional inspection and show that over the life of the job the savings in additional service may amount to as much as the original cost of the job.

### Duties of the Inspector

The inspector's role is multifold and has been discussed elsewhere (27, 305, 312, 317, 327) as well as in the inspection training texts (309–311). Inspection is necessary at every stage in the painting process, pre-blast cleaning (if necessary), blasting (or other surface preparation), priming, midcoating, and finish coating. The contractor must satisfy the inspector at each stage of the process before proceeding to the next.

The exact duties of the painting inspector will vary with the paint system being applied. Peculiarities of the job may also affect both duties and their scheduling. The various inspection requirements of the typical job will necessarily follow the specification, and may be classified according to the individual job processes that make up the specification. Appendix A details many of the inspection requirements in today's best practice. The inspector must certify that all activities are within the parameters allowed under the specification.

In the field, particularly on high structures, inspection is even more critical than in the shop, for it is here that many contractors see an opportunity for short cuts. For this reason, one of the primary requirements of the painting inspector is familiarity and comfort in climbing on high steel structures, and an

ability to move with as much agility as the paint crew. The basic requirement must be supplemented by a knowledge of coatings, their application (including the equipment used), surface preparation, and an experience of the painting process. On smaller structures, a single inspector may alternate between several different crews on bridges that may be several miles apart. There is some disagreement as to whether continuous on-site inspection is necessary, or whether a single inspector may adequately control several different crews. The latter may be feasible if procedures call for the prohibition of progress from one process of the job to the next without inspection and approval of the previous process.

It may be argued that an inspector can assess the quality and anchor pattern of a blasted steel section after the fact as well as by standing over the operation. With good record keeping and close attention to each job, even recoat times might be controlled by noncontinuous inspection. In such a case, however, difficulties with oil and water contamination of the surface during or after blasting (from blow-downs, etc.) may go unnoticed. Paint handling techniques, including mixing solvent additions, constant agitation of zinc, insufficient induction time, or applications beyond the limits of the effective pot life, may escape detection as may inconsistent spraying procedures such as excessive over-reaching, etc. Without the on-site monitoring of wet-film thicknesses at the time of application it may be difficult, in some cases (soft thermoplastic films, for example), to assess film thickness properly before the second coat is required, although the use of shims can help in this respect. With instruments such as the Tooke gauge, it is now possible to discover many irregularities after the fact, although it is necessary that specifications be so designed to facilitate such instrumentation (tinted zinc primers, obvious color differentials between coats, etc.). In some cases the spot use of paint removers may be necessary.

Difficulties with the contractor because of noncontinuous inspection practice are also possible. These may involve claims of production losses (e.g., repeat blasting necessitated by inspection delays of blasted areas that result in the "turning" of steel before priming). Claims may be made that it is the responsibility of the bridge authority or the inspector (as the authority's agent) to bring specification deviations to the attention of the contractor immediately and without delay, and certainly before such deficiencies are compounded by the application of additional coats, the removal of which would cause unnecessary hardship to the contractor. Certainly, despite the cost, the most efficient way of controlling the paint job is to have the inspector on the job continuously, although he or she may control with ease several full crews if they are in close proximity.

### Record Keeping

A daily log of job progress and activities is kept by most inspectors, but the completeness of such logs seems to vary widely. The daily monitoring of weather conditions is not unusual [although there is often confusion concerning ambient and (the more important) surface temperatures and where exactly they should be taken]. There is also too little concern with dew point, which is as important as relative humidity (if not more so).

The inspector's log may, however, be a most important doc-

ument in the event of a claim or a premature failure, and should contain many other data from which job progress and difficulties experienced may be recreated and studied as part of the post-painting monitoring of the paint system's service. Consequently, it is necessary for the times and dates of application of the various coats to specific areas of the bridge to be recorded and keyed to batch numbers of the materials used. Recoating delays, surface contamination, and difficulties in surface preparation and application (including equipment difficulties) should all be recorded as well as pump and tip size and condition, air pressures, condition of traps, etc. The type and amount of solvents employed in thinning should also be recorded. Notes concerning the skill of the operative employed may also be useful. Changes in operators of spray guns and blast nozzles can have a significant relation to job quality.

Such records of the everyday job process may be done almost routinely, and with little experience on the part of the inspector.

Cameras (Polaroid shots are very convenient) can be used to record job progress, with shots being dated and, if necessary, witnessed every day. Tape-recorded notes from the field may be transcribed easily later, and this makes good practice except where excessive traffic noise confounds the recording.

More recently, the advent of video cassette recorders (VCRs) and video cameras (with close-up attachments) has added significantly to control documentation.

## **MATERIALS ASSURANCE AND CONTROL**

### **Internal Laboratory Control**

Control of the quality of the paint is in most cases significantly more refined than the control of the job execution. For the most part, the laboratories of state DOTs are well equipped with all the instrumentation required for the control of the basic compositional constants (total solids, pigment content, nonvolatile vehicle content, and weight per gallon) and regularly maintain a close check on these as well as such physical characteristics as viscosity, dry time, fineness of grind, color, gloss, etc. Because many state laboratories are responsible for not only paint, but soils and water analysis, asphalt, and concrete, etc., the analysis and testing facilities are more complete than would probably be the case were separate paint laboratories employed. Relatively advanced analytical facilities (infra-red spectroscopy, gas chromatography, atomic absorption, etc.) are in many cases available. In consequence, with the necessary software (spectra libraries, etc.) it is possible for most state DOTs not only to control paint composition but to analyze composition, and where formulating skills are available, to reconstruct the specific coating.

### **External Laboratory Control**

Some states utilize external independent laboratories for testing purposes. Where such labs specialize in paint chemistry, the levels of expertise in all aspects of testing, analysis, as well as formulation, can be of a very high standard (well beyond that of most highway laboratories and even some paint manufacturers).

## **Laboratory Expertise**

Formulation skills are not necessary to control coatings. Control involves the testing of the coatings and/or coating systems against a set of predetermined parameters that, theoretically at least, reflect the formulating extremes that will provide coatings that will give the required performance. In view of this it may be argued that it is the analytical testing skills alone that are necessary.

In practice, however, sound knowledge of paint chemistry allows the chemist (or technician) to interpret findings in terms of their effect on the formulation of the system, its application, and consequently its performance.

## **MATERIALS TESTING METHODOLOGIES**

The several different types of specifications used by bridge authorities across the country require different quality control approaches. The most straightforward format is the compositional specification wherein analytical procedures evaluating specific quantitative compositional and physical parameters may be performed on each batch as it gets to the job. Tests are not overly time dependent and decisions as to suitability or non-suitability can be rendered relatively quickly.

### **Compositional Testing**

The testing of compositional specifications relies almost exclusively on the comparison of determined values of certain key compositional constants of a sampled product with specific values derived from a given formulation that produces acceptable performance. Most compositional testing is done on a weight basis, although all the vital parameters of the paint formulation (PVC, CPVC, volume solids, etc.) are volumetric and more difficult to determine experimentally. Armed with the standard compositional parameters, percent total solids by weight, percent pigment by weight, and weight per gallon, with atomic absorption for elemental inorganics, infra-red spectrophotometric scans for organic and inorganic vehicles, and gas chromatographic analysis for solvent makeup, the essential formulation can, if necessary, be virtually recalculated by the experienced chemist having knowledge of raw materials and their constants (weight per gallons, oil absorptions, etc.). Although minor ingredients such as driers, stabilizers, and thixotropes may remain elusive (even plasticizers may be readily separated by vehicle precipitation techniques), it is quite possible to recalculate the important volumetric parameters from such rebuilt formulations. In less experienced hands, control of the compositional specification by means of the weight parameters themselves is also quite straightforward, and only marginally less effective.

Despite this, the compositional analysis of a paint is itself no guarantee of field performance unless the viability of the compositional specification has been firmly established beforehand, and here this type of control breaks down. Where a specification results from years of trial and error in the field, the viability is proved and compositional control is simple and effective. With newer untried systems, the in-depth compositional control will not necessarily equate with satisfactory field performance.

## Performance Testing

Performance testing takes much longer to carry out than does compositional testing (1500 salt-fog hours is approximately nine weeks), and to avoid job scheduling delays, such tests are usually performed before job commencement. Some state DOTs will prequalify coatings (332), testing the performance properties on a specific sample before allowing the use of the coating. Some tagging of an original sample (known to provide the required performance profile) with compositional tests (percent pigment, percent total solids, percent nonvolatile vehicle, weight per gallon, IR spectra, etc.) along with the physical tests (dry time, cure time, pot life, viscosity, etc.) may provide some reasonably rapid quantitative control mechanism without having to resort to elaborate performance testing on every batch.

Batches of incoming material are thus compositionally evaluated against such tagged tests to ensure against product changes from batch to batch during the job. Long-term performance tests may be repeated, although if the tag tests look good the product is usually employed before performance testing is complete.

Other authorities will prequalify certain manufacturers (usually large national companies) before the job and may not perform batch-to-batch testing during the progress of the job or even subsequent jobs. Typical programs are described in several references (333, 334).

The testing of performance specifications is discussed in some detail by Tinklenberg (335).

## Full-System Performance Testing

It makes more sense to conduct performance tests on the total system rather than on individual coats (unless the individual coat represents the total system). The importance of purchasing all elements of a total paint system from a single manufacturer is now well established, and although specifications often have catch-all phrases such as "the finish coat shall be compatible with the primer," much of the performance testing is still done (at least partially) on individual coats. Laboratory testing of the total coating system is exemplified by procedures used by Louisiana DOT (336) and Michigan DOT (335), as well as in some other newer specifications. Although multi-coat systems respond less rapidly to the effects of testing, they are subject to severe internal stresses that are absent or reduced in single-coat systems. In multi-coat systems, each coat will respond somewhat differently to any given applied stress, and these differences themselves may compound the strain in the system as a whole. Many potential failure modes such as lateral cohesive failure of zinc, bubbling tendencies, intercoat adhesion loss, and certain blistering failures are predictable only from tests on the total system.

Because of changes in the availability of zinc for galvanic protection at cuts, scrapes, and holidays (effects of topcoat on the catchment area ratio of the zinc anode to the steel cathode),

the scribing and testing of untopcoated zinc film tells nothing about the susceptibility of the system to galvanically protect such damage in topcoated systems with much less available anode.

An important corollary of this is that prequalification should be done on the total paint system instead of a single primer or topcoat. Any change in either primer or topcoat or in their relative film thicknesses would require renewed prequalification of the total system.

## Sampling

Irrespective of the type of quality control, effective control of materials is totally dependent on the care and accuracy of sampling. In the field it is normally the job inspector's duty to sample paint, and although there seems to be more awareness on the part of the inspector of the necessary methodology of sampling practice, the accuracy of this type of sampling is still apt to be inconsistent. A sample retrieved from an incompletely homogeneous pail is no more meaningful than a sample of the wrong paint, and can cause unnecessary costs and job delays. To eliminate these difficulties many bridge authorities will sample materials in the manufacturer's plant, immediately after batch completion, or remove unopened containers from the job site for mechanical homogenization in the testing laboratory. Frequently, a state DOT will request the actual batch ticket from a supplier and will send an inspector to the manufacturing facility to observe the manufacturing process and to sample both raw materials and the finished products from the plant. An excellent example of this procedure is one set up by the Texas Highway Department.

There is also a difficulty where a contractor working in one state will purchase materials from a manufacturer in another, necessitating the dispatch of an inspector over long distances at considerable expense. To resolve this situation, several states have collaborated in a reciprocal system whereby the inspector from the highway department of the state wherein the paint is made will perform in-plant sampling duties for the state in which the work is performed.

Although Ray et al. (36), citing Law and Anania (337), consider one sample per batch insufficient to judge conformance, it appears rare that more than a single sampling per batch (or per delivery at least) is employed in practice. Law and Anania suggests a 500-gallon batch of paint packaged in 100 5-gallon containers requires 8 separate samples for a statistically based acceptance sampling. Most individuals in the paint industry interviewed on this point considered so many samples both too expensive and unnecessary.

The most effective point for sampling is in the fabricator's shop or in the field, if possible from the painter's bucket itself. This precludes many cheating methodologies, including "difficulties" that might occur between the manufacturing plant and the contractor's yard or between the opening of the can on the job and the application of the product to the bridge steel.

## IN-SERVICE MONITORING OF SYSTEM PERFORMANCE

### INTRODUCTION

The evaluation of the applied coating system in service is a necessary procedure not only to determine the suitability and efficiency of the system, assess the mode and rate of its deterioration, and establish service life and long-term costs, but also to signal recoating schedules and procedures.

The constant feedback of data on the performance of the newer coating systems from the field is invaluable assistance to the system design engineer in refining the paint system and the parameters of its employment (acceptable surface preparation, film thickness ranges, etc.). By such means both the claims of the manufacturer and the promises of laboratory and test panel data may be checked and modified. Weaknesses may be highlighted and responses developed through formulation changes (vehicle molecular weight changes, PVC adjustments, pigmentation alterations, etc.) or specification adjustments (additional film thickness, revised recoating schedules, etc.). The coating system is thereby continually fine-tuned to produce maximized dependable performance where possible, or alternatively, it is eliminated from applications where data reveal inherent insufficiencies.

Additionally, the year-to-date recording of the gradual deterioration of the coating system on a given structure allows semi-quantification of deterioration, and, through extrapolation of resultant deterioration curves, permits reasonable predictions to be made of the intervals wherein the various recoating (maintenance) options retain viability and cost-effectiveness.

Not all areas of a given structure deteriorate in the same manner or at the same rate. Careful examination of the rates and patterns of deterioration and the correlation of these patterns with bridge design peculiarities, exposure, traffic flow, drainage and dry-off characteristics, etc. can reveal those areas of a bridge more vulnerable to attack where protection should be increased in future specifications and those areas with less susceptibility to deterioration where savings may be afforded by reduced coats, lower film thicknesses, and so on.

Data such as these have far wider applications than solely on the particular structure from which the data were generated, as patterns of deterioration are often duplicated on similar structures with the same design configurations in a given geographic area. With enough data from enough structures, an accurate correlation of cause and effect and patterns of vulnerability may, with some difficulty, be predicted on totally different structures with different exposures.

### EXISTING PRACTICES OF IN-SERVICE MONITORING OF SYSTEM PERFORMANCE

Often there is little or no data exchange between those who are responsible for the collection and recording of the year-to-year data of paint system condition and those who are responsible for the conception and design of the specification. In many cases, records of coating system service are buried in files and are rarely reviewed by the specification design engineers. In many instances of bridge-paint failures, the lack of good inspection and post-painting data means that it is often easier for the failure analyst to reconstruct the failure from direct observations and interpretations of data available at the failure site (substrate quality, mil profile, film thickness, etc.) than it is to rely on inspection and post-painting records.

Only where severe and obvious failure occurs soon after job completion does it seem that the specification design engineer has occasion to monitor the performance of the system.

In less extreme cases, it is not unknown for experimental paint systems to be left and forgotten. Quality monitoring of experimental paint systems in many states and bridge authorities is often related to the dedication of a particular individual rather than to the success of any formalized official post-painting control program. Unfortunately, personnel replacements and promotions, and changes in the requirements and marketing philosophies of manufacturers, have a markedly negative effect on such individualized monitoring.

In Britain (338–340) failures are categorized by the British Department of Transport in terms of the severity of the problem. Their categories I and II represent failures of a local nature, or where the finish coating only has succumbed to the natural effects of weathering. Categories III and IV represent those instances where finish coat (Category III) or the general system (Category IV) has deteriorated before the expected term of successful performance. In the latter categories inspection of the condition and a determination of the causes of the deterioration by qualified paint technologists is mandated before a new specification is considered.

It appears that panel-testing programs and more formalized span-testing programs receive much better attention with continual careful monitoring of systems than do actual full-scale applications on bridges. Keane (341) discusses many such limited evaluations. There have been many other test programs and these are reported widely in the literature (31, 73, 169, 342–345). These test programs are more formalized with more com-

panies and individuals having interest in their outcome, and perhaps more importantly are evaluated by the same departments and individuals that had input into their design. Programs such as these provide system design engineers with much valuable and precise data concerning UV resistance (gloss and color retention), corrosion resistance, film embrittlement, intercoat security, and so on from which rust and/or deterioration curves may be compiled and extrapolated. Limited span- and panel-testing programs are not as representative of actual service as are the trial applications of systems on entire structures, and the relevance of both patterns and rates of panel deterioration (and their extrapolation) may not hold for the system's performance on a complete structure under actual conditions. Panel tests are rarely applied in the field by contractors, and even short-span tests are often weighted in favor of the system by the presence of manufacturers, better-than-normal inspection at the time of application, and often better-than-average conditions. In some respects, a system may be particularly vulnerable to certain bridge work service that is not necessarily present on a particular span exposure.

Even less representative are panel tests of systems designed for spot maintenance or for use over rusted surfaces. Rarely are panels available that are truly typical of these types of substrates, and available substrate uniformity is inevitably problematic. Finally it is rare that panel tests can duplicate the stress conditions (vibrations, etc.) that are always present on real bridge structures. Full structure trials done on a bid basis with conventional inspection, with all the details and intricacies of difficult areas, etc., and without the constant presence of manufacturer's representatives are more in keeping with the real bridge-painting world.

#### **FEDERALLY ENCOURAGED IN-SERVICE MONITORING PROGRAMS**

New efforts to formalize in-service monitoring are now being encouraged by the FHWA in the form of federally funded programs. Such programs include situations where new paint systems being tried by state highway departments are monitored in the field both during and after job execution. In these studies the evaluator makes a pre-painting evaluation of the structure, noting its location, design, and environment including details of the exposure (proximity to marine and industrial pollutants, extent of the use of deicing salts, nature of the crossing, etc.) as well as details of the type, history, and condition of existing paint systems. Patterns of existing deterioration are noted and correlated with obvious causes, and the type of deterioration (corrosion, cracking, blistering, etc.) is recorded. The evaluator then examines the specification, and if necessary the coatings to be employed, and is present on the job to monitor the performance of applicators, inspectors, engineers, and the paint manufacturer. As the job begins, observations on the readiness with which the theoretical specification is translated to practice are made and the operator's and inspector's learning curves are noted. Records are made of equipment employed, unit prices, surface quality and mil profiles, film thicknesses, dilution solvents, time intervals before recoating, etc. Difficulties related to job execution are noted and related to materials, bridge design peculiarities, or personnel. Several unscheduled inspections are made during the course of the job, and on completion the eval-

uator makes the first of several inspections that will document the service produced by the coatings over the next several years. In this manner it is hoped that performance will accurately correlate not only to the coating itself, but to the quality of both job execution and inspection as well as to exposure and bridge design considerations. More importantly it is hoped that the mechanisms and causes of any subsequent painting failure will be more accurately defined to facilitate rectification of specification design, application, or formulation, or in the extreme case (with reasonable authority), to abandon the coating system.

#### **DIFFICULTIES WITH PROPRIETARY SYSTEMS AND PERFORMANCE SPECIFICATIONS**

The value of in-service monitoring is, of course, reduced somewhat with performance specifications based on proprietary products. Unless substantial formulating data are made available to the bridge authority by the paint manufacturer, it is impossible to correlate the observed deterioration with formulation, and in these cases the monitoring benefits the paint manufacturer more than anyone else.

A typical example of this sort of difficulty is found in the chalking failure seen with certain high-build vinyl coatings in many states. Maine, for example, while observing substantial differences in the early chalk resistance of several bridges painted with different batches of the same color of the same product, had no way of correlating these data with formulation, unless they initiated substantial and costly failure analytical procedures (D. Leyland, Maine DOT, personal communication, 1984).

The paint manufacturer, on the other hand, can learn much from the failure records, and if cost considerations allow, can revise the formulation for use on future structures. Depending on the type of problems and specifications, such formulation revisions may or may not be reflected in a specification change, but proprietary considerations do not favor the dissemination of such data.

#### **QUANTIFICATION OF DETERIORATION**

Even in experienced hands, the accurate quantification of paint system deterioration and the establishment of deterioration patterns is not easy. The problem is typified by considering one aspect of deterioration—rusting. Although several organizations have attempted to organize scales of deterioration (ASTM D 610, SSPC-PA-4, Fed. Std. Test Methods # 141A Method 6451), application of such scales to the assessment of real situations is somewhat difficult. Rarely are rust patterns uniform across an entire structure, and while significant value may be afforded by the reporting of patterns section by section (i.e., interior webs of support beams, exterior girder plates, flanges, etc.), patterns are rarely uniform across even a single beam. Appleman (346) proposes a scheme for total area rating that considers the structure in terms of individual elements, and then subdivides such elements into individual sections that may themselves be more definitively rated. This approach fits well with the "specific utility" concept of system design discussed by Hare (243). Evaluations are at best subjective, however, and differences between observers may add to the difficulties. Photographic monitoring, which provides a visual record of the same

section of the structure over a period of years, and from which a more accurate rust curve may be prepared, is valuable. Although it resolves many of the rating difficulties and provides a more satisfactory record of the rates of system deterioration that may be studied at any time, photographic recording is expensive, cumbersome, and appears to be rarely used at this time.

Compounding these difficulties is the fact that rusting is not the only form of deterioration. Oxidizing systems, subject to autoxidation and chain scission with age, embrittle, check and crack, and lose adhesion (particularly over old mil scale). Whereas rust curves might indicate that spot repair would be possible, such paint films would not make suitable substrates for new paint systems, particularly where spot repair involves blasting. Damage to the areas peripheral to the spot blast will weaken the old system resulting in loss of adhesion after re-coating, especially where the recoat films are strongly cohesive. Similarly, severe topcoat chalking, delamination, or erosion, without accompanied corrosion may be reasonably considered criteria for repainting, especially where aesthetic requirements are important. In consequence the evaluation of the condition as a whole, and not just the individual components of deterioration (i.e., rusting), is essential in the assessment of system performance and in the determination of required procedures for rectification and renewal. Quantitative representations of such overall patterns are much more difficult, although rough qualitative ratings have been attempted by the British Standards Institute (347).

## SYSTEM SERVICE LONGEVITY

Perhaps the most important long-term benefit of the in-service monitoring process is an accurate establishment of system longevity. The lack of a more definitive appreciation of coating systems service life at this time may be related to the disorganized state of the in-service monitoring process, and the consequent dearth of measured mean-deterioration curves. Sound scientific principles exist to establish the optimum time for repainting in terms of rate and extent of deterioration and the consequent cost of repainting at any specific epoch (346, 348). In practice, repaint maintenance decisions appear to be more arbitrarily based. As the availability of maintenance dollars have never kept pace with the maintenance requirements for steel bridge painting, the overall tendency has been to protract the interval between paintings well beyond the service life of the system. This practice tends to inflate expectations of service life based on past experience, as well as making rectification more difficult and expensive.

There are many other factors that confound good quantification of system service, not the least of which are the wide divergences in the quality of specifications, job execution, and inspection. Bridge design (especially in maintenance painting), the quality of the substrate (steel, rust grade, old paint condition, etc.), and the appropriateness of the degree and type of surface preparation are also important factors.

It is the environment in which the coating system must do its job, however, that has the most profound effect on service life and the mode of deterioration. The SSPC environmental zone approach is helpful in the semi-quantification of the type of environment, although within these general classifications

there are inevitably degrees of exposure, not only from one part of the country to another but from bridge to bridge and even from section to section of a particular bridge depending on location, type of crossing, bridge design, condition, and traffic volume.

It is in consequence with some misgiving that the performance range (service life) estimates included in Appendix B are offered. They are based on numerous interviews with highway departments, paint manufacturers, contractors, engineers, and other specifying authorities across the country, together with data from a few available published sources (344, 348, 349). Unfortunately, many such sources reflect the use of these coatings in industries other than bridge painting, and some considerable divergence is very apparent. The service life values given in Appendix B are consequently much less conservative than those offered by Brevoort and Roebuck, which are based on in-plant service. The current figures represent for the most part the time to first maintenance of newly applied systems on new bridge steel, maintenance being performed at 10 to 15 percent system deterioration, which may be conservative in many states. Somewhat reduced figures (proportionately) may be expected from the same systems reapplied as in field maintenance. Many of the values, especially for the newer systems, have had to be projected. This is indicated with a letter P, and the maximum 1B environment values of 40 years with some systems (e.g., System XIIIa) may be even too conservative here. Inevitably such figures will invoke criticism, especially among those whose products are typified. Any attempt to refine them is to be both applauded and solicited, but only by consistent and accurate data collection from an ordered in-service monitoring process can such figures be properly modified and their credibility refined.

## COATING SYSTEM FAILURE

In the extreme case, in-service monitoring may, in effect, become the documentation and analysis of a paint system failure. Unfortunately, the definition of paint failure is both elusive and variable and dependent on the expectations and standards of the particular observer. Theoretically, any paint film deterioration mode other than the gradual erosion of the paint system over a number of years might be considered a failure. Certainly, modes of deterioration that involve intercoat delamination, lateral cohesive separation, excessive cracking, blistering, or widespread pinhole-type corrosion, etc. and that dictate special procedures (e.g., total removal of the existing paint system) in subsequent repainting specifications might with justification be considered failures of the paint system. Certain types of failure (bubbling in topcoats over inorganic zinc, excessive early chalking, etc.) are often not considered failures at all, but are accepted as a "characteristic of the coating" to be tolerated. Assessments of this type are in some respects quite arbitrary, however, and although excessive chalking in an epoxy topcoat may be allowed, in a vinyl or silicone alkyd such deterioration would not.

For their definition of failure, Ray et al. (36) adapted criteria involving a failure to achieve an expected or designed service life. Designed service itself, however, is difficult to quantify, and in practice it seems to be only the catastrophic deteriorations of the paint system that occur within a few months or at most a few years of application that are universally classed as failures.

TABLE 10

## APPROACHES TO FAILURE ANALYSIS

The following procedure is typical of the progression of analysis of cause and mechanism of coating system failure on bridge structures. It can be divided into six principal steps:-

1.) Failure Definition:- The failure must be first defined with accuracy. This may be done by itemizing:-

- a.) Manifestations of deterioration.
- b.) Extent and location on structure.
- c.) Patterns of failure that may be related to bridge design, exposure, traffic patterns, etc.
- d.) Methodology of initiation and propagation (if data is available).

2.) Data Collection:- Data relative to the failure must then be collected from the following typical sources:-

- a.) Visual inspection of the failure in the field.
- b.) Laboratory analysis of failure (microscopic examination, film analysis, analysis of interference materials, corrosion products, etc.)
- c.) Materials batch testing data.
- d.) Specification
- e.) Job inspection and post-painting inspection records.
- f.) Climatological records of location during and after application.
- g.) Prior history of specification on other structures.
- h.) Comparison of data pertinent to this structure with that to other successful structures.
- i.) Pertinent change orders, approvals, extra work orders, and general correspondence related to the job.

3.) Isolation of Anomalies:- All anomalies, differences and inconsistencies that set the job in question apart from the basic system specification, from good painting practice as it applies to this system, or to the past use of the system on successful structures are then isolated and reviewed against known susceptibilities of this or similar systems in light of the observed manifestations of failure and data from field and laboratory studies. Areas signalled may be related to:-

- a.) Specification and change orders.
- b.) Applicator expertise and quality of job execution.
- c.) Bridge design and location.
- d.) Applied system film characteristics (determined substrate quality, film thicknesses, etc.)
- e.) Climate and season.
- f.) Paint materials.
- g.) Inspection
- h.) Traffic density and flow.
- i.) Local environment.

4.) Identification of Specific Areas of Concern:- From the above data (2 and/or 3) one or more areas of concern, if not a possible failure mode, will condense as being most suspect. The analyst must then seek to establish which area, if any, fits a sensible failure mode that could be supported by that combination of data that applies to the particular painting. To do this he will draw from the following sources:-

- a.) Basic scientific principles.
- b.) Experience of researcher.
- c.) Published data of failure manifestations of similar description.
- d.) Literature surveys.
- e.) Consultation with other authorities and experts.
- f.) Consultation with paint suppliers and raw material suppliers.
- g.) Experimentation.

5.) Postulation of Possible Cause:- The above exercise should provide one or more most likely failure scenarios. Each will then be reviewed and attempts to deal with apparently non-supportive or contradictory data will be made by further review and analysis of the particular areas of difficulty. Rectification of such difficulties will ideally lead to a single most probable cause.

6.) Verification:- As a final step the analyst may seek to either duplicate the failure in the laboratory or even in the field. In some cases it may be possible to predict the incidence of yet non-apparent failures on structures painted (with similar deficient materials or methodologies) after that on which the analysis was performed. Success in either respect is tantamount to proof of the proposed failure mechanism. Inability to duplicate the failure by laboratory model is not necessarily indicative of an inaccurate analysis, and care should be taken to review the appropriateness of test methodology before returning to re-evaluate the failure for cause.

## Failure Analysis

Failure analysis may be carried out by in-house inspectors or engineers, but more often it seems to be contracted out to private engineering companies and specialists employed specifically for the purpose. As was noted by Ray et al. (36), hard data on specific cases are not always readily accessible, and the details of many coating system failures even after litigation remain poorly documented. Pitfalls of formulation, application, specification design, etc. made evident in such cases seem to gradually diffuse into the technology by word of mouth, rather than become available through widespread publication or more formal distribution of data, and this practice seems to be embraced by bridge authorities as much as by paint manufacturers and applicators.

An excellent overview of many of the analytical techniques, including some of the latest instrumentation available for use in failure analysis, may be found in the Gardener/Sward *Paint Testing Manual* (350). An ordered treatise on the what, the where, and the how to do it of failure analysis, however, does not seem to be available in the literature at this time.

Ray et al. (36) conclude that the best failure analysis practice is to list possible causes of the observed failure and then reduce this list of possibles by a data collection process. They conclude that in practice a cause and effect may not be unequivocally established, and a "most probable mechanism of failure" is the more likely outcome of this failure analytical process. They cite several sources for the generation of possible causes and discuss several bridge-paint system failures. Other sources of assistance in failure analysis include technical service departments of coatings manufacturers and manufacturers of cleaning and spraying equipment as well as materials and maintenance engineers. Added might be the input of other experts and engineers in the field.

Although a comprehensive treatise of the failure analysis technique is well beyond the scope of this synthesis, in view of the relative deficiencies of published material on this aspect of the discipline, Table 10 delineates an alternative approach to analysis (and is based on techniques developed by the author and others in the field).



## CHAPTER NINE

## COSTS

## INTRODUCTION

Perhaps the most elusive element in the entire discipline of painting bridges is the normalization of costs. Notwithstanding the instabilities produced by factors such as inflation and geography, many other obvious and less obvious factors affect the costs involved. There are several sources that are indicators of the basic costs of paint materials, their application, and that of surface preparation techniques (351, 352). These indicators are rarely treated as more than guidelines by most contractors (especially for field maintenance work). Material costs, although dependent on formulation, quantity, and manufacturer, are probably more dependable than either the cost of application or surface preparation, which not only vary with location, design, height, access, intricacies of steel, and the type and condition of existing paint films, but vary widely from contractor to contractor. Furthermore, nontechnical considerations will often affect the bid. Overall bid prices will reflect the makeup of the bidders' list and the manner in which each contractor views the competition. They will also be affected by the bidders' current work load, by the availability and proximity of equipment and facilities, and by the economic outlook and the amount of work being let in the same area of the country.

Difficult as the task may be, therefore, attempts have and are being made to bring some order to costing from both viewpoints (contractor and bridge authority), and progress has been made. Many fabricators and contractors are now beginning to utilize complex and not-so-complex computer programs to assist their estimation processes. The bridge corrosion cost model, designed to assist the bridge engineer in making cost-effective decisions concerning the when, how, and with what of bridge painting, is, for example, being refined into a practical tool.

## COMPARATIVE COST CONSIDERATIONS IN THE SELECTION OF BRIDGE-PAINTING METHODOLOGY

Intelligent and soundly based decisions are needed not only with regard to what paint system should be used, but when to paint and whether painting is preferable; or whether alternative techniques, such as metallizing or galvanizing, should be used.

As noted by many authorities, including Appleman (346) and Frondistou-Yannas (353), there is, in the life of all paint systems, a well-defined epoch relating to the extent of deterioration when value in delayed maintenance changes to added cost. It is consequently important that maintenance painting schedules are correlated with such epochs if maintenance dollars are to be employed effectively.

## Available Studies

Given the number of variables that affect the cost of any job, attempts to make general quantification of the cost of the different processes and materials that make up the total job price are condemned to some degree of inaccuracy from the outset; a statistical approach is often used to balance discrepancies.

The original Brevoort and Roebuck paper (354) is a simplified guide intended to assist "nonexclusive" coating engineers in making reasonable decisions concerning coating systems selection based on cost, environment, and service. The paper provides much valuable average data on surface preparation, application, and material costs for four regions of the country together with service-life estimates in three environments of differing severity, and calculates cost per year. It also discusses such economic concepts as time value of money and discounted cash flow, and provides comparative examples of the cost of paint systems in the field and the shop as well as two field-applied systems. Much of this material is also used by Roebuck and Weismantel in the *Paint Handbook* (355). The second paper by Roebuck and Brevoort (331) expands on the first to some extent, enlarges tables to include more paint systems, and discusses the necessity for inspection. It updates the cost data from the original 1978 figures to 1981 figures. The 1981 figures are also used by Brevoort in the *SSPC Manual* (356). Appleman (346) has subsequently simplified the 1981 figures and further upgraded them by applying an inflation factor to 1984.

The Brevoort and Roebuck figures are based on industrial plant use and are not specific to bridges. Field figures represent costs "on the ground," although the authors do offer conversions for work in the air and for structures of more complexity. In the *SSPC Manual*, Brevoort comments on discrepancies that are apparent between the in-plant service of three-coat alkyd systems and service lives of similar systems on highway bridges in Washington and Massachusetts. Comparisons are also quoted between an 8- to 10-year plant service life of a three-coat vinyl system and similar systems on water tanks and dam gates that have lasted 20 years. Interviews with many highway departments across the country would also indicate that the Brevoort and Roebuck service-life estimates are extremely conservative when applied to bridge structures, and that some redefinition of the environmental descriptions is necessary in these different applications.

## Surface Preparation Costs

Table 11 gives ranges of estimates for cleaning bridge steel in both shop and field. Shop data presume the use of centrifugal

TABLE 11

RANGE ESTIMATES FOR COSTS OF SURFACE PREPARATION OF STEEL BRIDGES IN SHOP AND FIELD (1986)

Surface Preparation	Shop Cleaning (New Steel)	Field Cleaning (Low Rolled Beams in Place - Alkyd Coated - 15% rust) (\$/ft <sup>2</sup> )	Field Cleaning (High Complex Truss in Place - Alkyd Coated - 15% Rust) (\$/ft <sup>2</sup> )
SSPC-SP-1 (Cleaning of Old Finish)		0.15-0.30	0.20-0.35
SSPC-SP-2 (Hand-tool Cleaning)	0.25-0.30	0.45-0.55	0.55-0.65
SSPC-SP-3 (Power-tool Cleaning)	0.32-0.36	0.60-0.70	0.75-0.85
SSPC-SP-7 (Brush-blast Cleaning)		0.50-0.60	0.60-0.70
SSPC-SP-6 (Commercial Blast Cleaning)	0.28-0.32	0.85-1.00	1.00-1.25
SSPC-SP-10 (Near-white Blast Cleaning)	0.32-0.37	1.15-1.35	1.40-1.60
SSPC-SP-5 (White blast Cleaning)	0.45-0.55	1.60-1.75	1.90-2.10

blasting; otherwise shop preparation costs would approach those for low rolled beams in the field. The actual cost of centrifugal blasting will also be influenced by the size of the members and the job size itself. Small steel pieces may be more cost-effectively manually blasted even in the shop. Field cleaning data are divided into ranges for low steel of simple lines requiring a minimum of rigging (e.g., rolled-beam overpasses), and high steel with considerable intricacy (latticed arch trusses, for example). As noted elsewhere, specific aspects, such as the addition of containment, may multiply these costs by three to five times, depending on the extent of the containment. Older structures with heavier scale and highly pitted steel will also cost more to render to a given standard, and the cost per square foot of a spot-blast job will be higher than the same square footage cost on a full-blast job. Prices in the West are higher than the Gulf states and the East. Eastern state prices are generally lower than the Gulf state prices in the field but higher in the shop. Shop painting in the central states may be somewhat less expensive than in the East, although field costs are more comparable with the West.

#### Application Costs

Application costs (Table 12), like surface preparation costs, vary from one part of the country to another. Again the West Coast prices are higher than the East and Gulf Coast, and much the same as central states prices. Gulf states in the field may be slightly lower than the East Coast prices. Figures for brush and roller application of alkyd and oil systems were difficult to obtain and considerable disparity between costs from contractor to contractor was found. As in surface preparation costs, field

work costs more than does shop work, and application costs increase with the height and complexity of the structure.

Equally divergent were figures concerning comparable productivity rates from various application methodologies from which application costs might have been derived. Levinson and Spindel (357) estimate roller application to be one-third as fast as airless spray and three times as fast as brushing. Frondistou-Yannas (353) considers roller rate to be 1.5 that of brushing and half as fast as spray. Application prices listed are approximate only and ranges reflect not only variations in geographical location, but differences from one contractor to another, one bridge to another, and even one paint to another within a given coating classification.

#### Material Costs

Throughout the early 1970s and early 1980s raw material prices and, perhaps to a lesser extent, paint material prices fluctuated wildly in response to both general inflation and to the instability in price and availability of petroleum-based feed stocks. Current prices (1985) are less volatile, and because some systems, such as inorganic zinc-rich primers, are becoming commodities, this may add further stability. Future fluctuations must be anticipated, however, and these may produce considerable distortion of material costs relative to one another, and more importantly to other costs in the overall discipline.

The cost-per-gallon approach was conceived with paint material costs alone in mind, and took none of the direct costs of application and surface preparation into consideration. Cost per gallon made no attempt to incorporate ideas of coating system value in terms of realized protective service. Moreover, in failing to reduce coating costs to a normalized evaluation criterion

based on value per square foot of coverage, the method was misleading in evaluating even material costs except when comparing identical paint systems that by chance had equal volume of solids. Evaluations based on normalizing material costs by means of adjustments to cost per mil square foot using formulas based on volume solids gave a more realistic comparison, and, when film thickness multiples are incorporated and the costs of component costs added, a more viable comparison of material costs is provided.

Material costs represent no more than approximately 10 to 25 percent of the cost of the in-place coating system. As the type and degree of surface preparation and application is often variable from system to system, being dictated by the primer if nothing else, it is necessary to consider these costs at the same time as simple material costs in order to achieve viable comparative cost data for in-place systems.

Further refinements consider the expected service provided by the coating system (see Appendix B) and apply this to obtain a comparative annual cost of bridge protection. Finally, as will be seen later, this figure itself may be refined by the use of net-present-value-of-money techniques, and, if required, the cost of bridge maintenance over the long term, involving several repaintings, may be computed.

### Service Life

A meaningful assessment of the service life of a given coating system is one of the most elusive factors in the entire process of cost comparison. One of the most common questions that the coatings engineer faces from the bridge engineer who must select the coating system is that of expected service life. Answers are inevitably vague and couched in caveats. Service life is sig-

nificantly affected by bridge design, geographical location, and specific exposure, and by the extent of deicing, spring cleaning, and maintenance practices. Also critical to the life of the system are:

- the accuracy of the original system selection and specification design;
- the quality of surface preparation, application, and inspection practices; and,
- (in part at least) the condition of old paint systems that are to be repainted.

The sheer number of factors and the degree of variability in each is, of course, borne out by the wide differences in system performance that exist across the country and from bridge to bridge even in the same locality. As higher performance paint systems of greater complexity have been introduced, service life variability has (statistically at least) increased compared to those older, more tolerant systems of lower performance that were the norm 20 years ago.

Of those data sources on system service that do exist, many are deliberately or unintentionally biased, overly theoretical (based on panel studies, etc.), or are not necessarily applicable to bridge service. Where accurate figures are possible, what constitutes the end of viable service for one observer may be quite different for another. Even well-intentioned studies such as those of Roebuck and Brevoort (331) and Frondistou-Yannas (353) show gross differences with known or reported field service, and although attempts to rate service in more than one environment help, distortions still exist. As accurate as Frondistou-Yannas's rust curves may be, they would seem, at least, to some degree specific to those jobs on which they were based and require additional refinement for more accurate represen-

TABLE 12

RANGE ESTIMATES FOR COSTS OF COATING APPLICATION ON STEEL BRIDGES IN SHOP AND FIELD (1986)

Application Example	Shop Application (\$/ft <sup>2</sup> )	Field Application (Low Simple Rolled Beam Structure in Place) (\$/ft <sup>2</sup> )	Field Application (High Complex Truss Structure in Place) (\$/ft <sup>2</sup> )
Oil/alkyd by brush	0.13-0.15	0.17-0.19	0.21-0.24
Oil/alkyd by roller	0.10-0.12	0.13-0.15	0.16-0.18
Oil/alkyd by spray	0.09-0.10	0.11-0.13	0.13-0.15
Organic zinc rich by spray	0.19-0.21	0.24-0.26	0.29-0.32
Inorganic zinc by spray	0.21-0.23	0.25-0.31	0.31-0.37
High-build (two pack) epoxy by spray	0.17-0.19	0.20-0.25	0.24-0.30
High-build vinyl by spray	0.18-0.20	0.21-0.26	0.26-0.31
Aliphatic polyurethane finish by spray	0.16-0.18	0.18-0.23	0.22-0.28

tation on different structures in different states. It seems probable that, notwithstanding variables of specification design, inspection, and job execution, no one set of figures will satisfy a pattern seen in more than one area of a nation with so great a climatological divergence. (In this consideration, the necessity for the use of deicing salts is also included in the climatological profile.)

The service figures of Appendix B represent judgmental averages of paint system performance derived from the many other sources reviewed throughout this work, and from interviews with state DOT material officials, bridge engineers, paint manufacturers, and other experts across the country. They are not accurate for any specific bridge and they are intended for use as a guide only.

## DISCOUNTED CASH FLOW

The economic analysis of the comparative values of bridge painting via two or more coating systems must necessarily involve those same accounting procedures that are employed in making any large investment decision (358–360). Any discussion of coating system value must be based on the relative time value of money in maintaining the structure with one system rather than another, taking into account interest rates.

Discounted cash flow (DCF) analysis is important because the invested dollar ( $P$ ) accumulates interest ( $i$ ) and is worth  $P(1+i)^n$  if not spent now but invested for  $n$  years. Alternatively,  $P$  dollars spent  $n$  years in the future must be discounted by  $1/(1+i)^n$  to determine money equivalent today. The technique is discussed in more detail elsewhere (358–360), but it allows the determination of the value of money at a set epoch and compares the cost of all maintenance methodologies at the same epoch.

With these basic data and tools (with an appreciation of the probable effects of climate, design, accessibility, and environment for the particular structure in question, and, if available, some comparative history of costs and system service on this structure relative to others), it is possible to render some sort of realistic appreciation of comparative system value despite the many variables and unknowns.

Inevitably, so complex a problem lends itself to some form of computerization, and in 1979 a prototype computer model to deal with the problem was developed as part of a study on bridge corrosion costs (348, 353).

## BRIDGE CORROSION COST MODEL

The computer model on bridge corrosion costs (BCCM) was developed by Frondistou-Yannas as part of FHWA Contract DOT-FH-11-9528 (353). In its original form, the model is less than perfect; it nonetheless remains a beginning to the quantification and the formalization of that which was, for the most part, regarded as too chaotic, capricious, and quantitatively inextricable.

The model was conceived as a tool to aid the bridge engineer in selecting the most efficient maintenance program for the protection of a given structure in terms of protection method (including within broad classifications preferred paint system and film thickness) and the optimized painting schedule. As part of its data base, the model considers information on performance and costs derived from studies of 2052 structures in California, Louisiana, Massachusetts, and Washington, as well as from the Steel Structures Painting Council (SSPC), American Society for Testing and Materials (ASTM), National Aeronautics and Space Administration (NASA), and industrial sources. Most performance data appear to be derived from test panels, although some originate from actual bridges.

Only four generalized paint systems appear to have been used in the initial model: (a) oleoresinous systems on hand-tool cleaned surfaces, (b) oleoresinous systems on blast-cleaned surfaces, (c) topcoated zinc-rich systems over near-white surfaces, and (d) vinyl, epoxy, and polyurethane barrier systems on near-white metal. ASTM A 36, galvanized, and weathering steel surfaces were selected as were new technologies such as metalizing. Environmental factors were generally classified as marine, industrial, rural, and desert. Bridge type was factored by classification of the structure in terms of the steel member categories (light, truss, and girder construction), which are then assigned square-foot-per-ton values. The classification is primarily based on determination that corrosion at edges occurs more rapidly than it does on flat plate areas, and rolled girders have a lower edge/plate ratio. There is no account taken of the propensity of other steel areas (such as lower flanges) to corrode earlier than webs, etc. Other factors considered are coating thickness and application procedure (shop vs. field and brush vs. spray). Size of the structure (as it affects rigging costs) is also included. Tests of the model performed by the FHWA applied to structures in Massachusetts, New York, and Virginia showed a correlation within 20 to 25 percent of the actual bid prices.

The model has been evaluated critically by Roberts and Davis (361) who conclude that “the bridge corrosion cost model cannot develop realistic cost data” on even the simplest structure, although it can be modified, and, with development, can be transformed into a viable tool for use by bridge authorities responsible for the maintenance of steel bridges. The critique of Roberts and Davis is balanced and contains many valuable ideas for refinements based on a sound understanding of the practical criteria that affect the bridge-painting contract.

The model is flexible, however, and is designed so that default values on performance, environmental severity, costs, etc. may be upgraded by any given bridge authority with more precise data available to that authority for use of a specific system in a specific area of the country. Users may upgrade the data base with updated information on the discount rate, with the film thickness averages more relative to their state’s own experience, with better rust curves developed from studies in their jurisdiction, and with up-to-date figures on the life expectancy of the specified system. Such refinements may lead to quite different adaptations of the model from one area of the country to another.

## CHAPTER TEN

## TRENDS, DIRECTIONS, AND RECENT AND ONGOING RESEARCH

### GENERAL

As a whole, it may be anticipated that system trends will continue to favor the high-performance zinc and barrier systems, and displace the older oil/alkyd systems. Transformation, however, will remain a gradual process and in the more rural areas of the country, where environmental pressures are less and where the older lead systems are giving satisfactory performance, change may not occur for many years. The development of viable cost-effective methods for removal of lead-based materials from existing structures should hasten this trend, although significant breakthroughs in this area are not anticipated in the near future. Spot repair of lead structures seems destined to be accomplished in most cases with lead systems, although the use of the aluminized epoxy mastics is expected to continue to expand as more and more manufacturers add this type of system to their product lines. Less encouragement can be seen for the growth of the aluminized, moisture-curing urethane, probably because of the restrictions on high builds from single coats, and reported delamination problems.

In general, a major trend throughout the industry will be to reduce the number of coats and single- or two-coat high-build systems will gradually succeed the current three- and four-coat methodology. In the moderate term this will undoubtedly prolong the current preference for the zinc/vinyl systems over the zinc/epoxy/urethanes. However, zinc/high-build epoxies and zinc/high-build urethanes used judiciously on a single structure with additional coats in highly vulnerable areas may subsequently encroach on the employment of the high-build vinyl system as the major high-performance coating system for new and radically blasted bridges. Uncertainties over the UV stability of vinyl systems may dissipate as a greater appreciation of the qualitative and quantitative parameters of vinyl formulations is realized by specification writers.

Growth in the inorganic zinc/epoxy/urethane systems should continue to accelerate as field histories prove the worth of these systems. Recently, PennDot announced construction plans for some 27 new bridges bearing shop-primed 3 to 5 mil DFT (dry film thickness) inorganic zinc primer that will be subsequently washed in the field before epoxy midcoating (4 to 6 mils dry film thickness) and finish coating with a 1½ to 2 dry mil aliphatic urethane coat. Two other structures are scheduled for similar epoxy/urethane systems built on a zinc-rich moisture-curing urethane primer.

A counter trend, away from the newer high-performance systems and other systems that are bound by excellent, if costly, surface preparation requirements, may, in some states, slow the aforementioned primary trend. Many factors contribute to this, not the least of which is the increasing divergence between the number of structures requiring attention and the number of dollars available to do the job. Notwithstanding the longer-term advantages afforded by the high-performance system, it becomes increasingly necessary to implement immediate redress of corrosion on many structures and to spread available funds as far as they will go as more bridges reach the point of critical maintenance.

Less widespread but potentially more influential is the increasing public awareness of the environmental impact (whether real or perceived) of blasting operations, and the more frequent use of containment methodologies (either local or general). This, together with the related expense of the disposal of spent grit (containing leachable levels of lead and hexavalent chromium salts above the EPA hazardous threshold) will also add to a reluctance of bridge authorities to undertake radical de-leading maintenance procedures.

Recent restrictions on the levels of arsenic, lead, cadmium, and beryllium, as well as free silica, gypsum, and carbonates, in unused mineral slag abrasives by the U.S. Navy (362, 363), have not yet spread to bridge work, but could well do so. Still other indirect environmental factors should not be overlooked. These include a growing reluctance of banks to provide mortgage money without land surveys for hazardous contamination. The proximity of such properties to bridge structures that had recently undergone extensive de-leading operations (especially those involving open blasting) could raise questions of liability, which may act as an incentive against the radical blasting maintenance procedures.

Although the industry has anticipated these trends and is currently evaluating numerous different surface preparation methodologies (from which it is hoped a less costly and environmentally compatible procedure will emerge), success in these endeavors has to date been minimal.

Supporting such counter trends are the more traditional objectives to higher performance systems. These include those state engineers who maintain, often with much justification, that conventional lead/oil/alkyd systems already provide adequate long-term performance. There will also remain those who, with only slightly less justification, cite the relatively higher risks of pre-

mature system deterioration with newer coating systems, and opt for the more user-friendly traditional systems having more certain, if more limited, success.

## SURFACE PREPARATION

For the most part, research is centered on the development of alternative procedures to dry blasting in order to mitigate those hazards inherent in the blast process (from toxic abrasives and atomized paint debris), and if possible to reduce the cost of the preparatory process through improved productivity. Wet blasting techniques are the principal practical developments from this approach, and although more sophisticated research directions are receiving attention, few at this point seem to either satisfy all criteria for successful surface preparation or provide cost-effective resolutions for the difficulties peculiar to large-scale employment on bridges (particularly in the field).

A pooled-funds study (364) (by SSPC) of the effectiveness of wet-blast cleaning methods concluded that although they are neither as effective nor as efficient as dry blasting, the wet-abrasive blasting proved quite practical in field applications providing production rates of 80 to 90 percent of the dry-blasting rates. Medium- to high-pressure (6,000–20,000 psi) water blasting with abrasive incorporated is described as being less effective (50 percent of dry-blasting production) and dangerous because of the very high thrusts and operator fatigue. Yet newer 35,000 psi water/abrasive techniques have also been introduced, with back pressures said to be very low.

Less effective, although less tiring to operators, are low-pressure wet-blasting variations, although paint and rust can be effectively removed. The report further concludes that all wet-blasting units reduce dust, and, when inhibitors are added, flash rusting can be controlled for several hours.

In another paper (365), high-pressure water jetting is described as slower than dry blasting in removing mill scale, but faster for the removal of energy-absorbent coatings. Surface quality is reported to improve as pressures increase, 20,000 psi being necessary for white-blast finishes that cannot be achieved by using longer dwell times at say 10,000 psi (which produces a lesser surface quality). Water jetting is also claimed to remove salt debris not stripped by blasting, which gives better blistering resistance and less underfilm rust creep of subsequently applied coatings. When inhibitors were used with water-jetting techniques, no coating failures could be related to chemical residues left on the surface.

Much attention is now being directed to a more complete understanding of the role of the abrasive media in coating system performance. Although ionic impurities such as chlorides and sulfates in the abrasive have for some time been considered detrimental to performance, in studies by Bleile et al. (366) the negative effects of abrasives containing copper and/or other less electrochemically active metals (with respect to the substrate) on the flash rusting of newly bared steel and on subsequent paint performance (hot water blistering) have been shown to be of even greater significance. Copper slag abrasives have been employed for years with success and some further study is advocated by other authorities (367). The Bleile study also indicates that low dusting abrasives are generally more productive than high dusting media, and that use rates (lb per ft<sup>2</sup>) for coal

slag and mineral grits are generally lower than the rates for smelter slag.

The aforementioned concerns of the U. S. Navy over arsenic and other heavy metal impurities in abrasive blasting media are receiving increased attention, and the subject has been recently discussed by several industry authorities (368–370). A related medical study linking certain types of slags to changes with lung tissue in animals is described by SSPC in ref. 371.

An increased awareness is also developing of the dangers of ionic impurities present on the steel or painted steel itself with respect to coating system performance.

A German study (290) of some 78 bridges has revealed the complexity of contamination on bridge structures by inorganic salts both in terms of the variety of contaminants and their distribution with regard to location, bridge design, and type of crossing. Contamination was found to be heaviest on horizontal members, and occurred not only on coating films, but between coating layers.

Research activities into some kind of quantification of the effects of ionogenic impurities (mainly sulfates and chlorides) on the quality of paint system service are now occupying the attention of several authorities, and the development of potential methodologies toward the detection and measurements of such contamination in the field is the subject of a newly commissioned study by the National Shipbuilding Research Program. The establishment of a quantitative or even qualitative (go/no go) surface cleanliness criteria for acceptable coatings service would be most advantageous, although it seems likely that such criteria would be dependent on the type of coating system employed and its film thickness (or its relative permeability to moisture).

A recent study by Weldon and Cain (372) effectively demonstrates the effects of sulfates and chlorides on the osmotic blistering failure of epoxy/polyamide and vinyl coating systems. Chloride levels of as little as 10 micrograms/ft<sup>2</sup> produced blistering within several weeks. Test strip ion titrators were employed for semi-quantitative chloride ion determination (373) and ferrous ion content (374). The difficulties in the establishment of threshold levels for ionic contaminants is demonstrated from the different threshold levels of ionic material necessary to produce blistering with the two coatings. Notably, when the ion seeded panels were rebasted before coating, no blistering occurred in subsequent testing. Baylis (375), in summarizing the progress of the International Standards Organization technical subcommittee (ISO/TC 35/SC12) in their development of international surface preparation standards, described similar semi-quantitative tests using dipyriddy papers to detect ferrous salts. Baylis also discusses a qualitative technique using flash rust spots on an applied white latex paint to reveal the presence of soluble salts on a pitted surface. In a recent SSPC paper, several corrosion indicator papers are also discussed (376).

The growing awareness of the effects of atmospheric pollutants on the performance of coating systems and the kinetics of corrosion may spawn more practical changes in bridge maintenance. Although sand and winter debris are often swept from northern bridges each spring, less attention seems to be paid to an earnest effort to rid the structure of other contaminants. Excessive salting may leave structures in the snowbelt so heavily contaminated during the winter that even the color of a bridge is difficult to establish on the in-board rail and roadside box members. Increased adoption of yearly detergent or high-pres-

sure washing schedules, especially along rail areas or beneath the bridge where such accumulations occur, would do much to preserve the life of steel and paint system (particularly unprotected weathering steel in marine environments).

Of particular concern remains the effect of chlorides on the deterioration of weathering steel, where their removal by rain or other agents is precluded by bridge design. Studies of related deterioration phenomena and rectification via surface preparation and coating system protection continue to receive an enormous emphasis throughout the industry. Several highway planning and research (HP&R) studies relating to the corrosion of weathering steel are under way in Louisiana (377), West Virginia (378), and New Jersey (379), as well as continuing investigations in Michigan. In addition, SSPC has recently been awarded an FHWA contract to investigate the maintenance coating of weathering steel. Paint systems specifically designed to address the repair of weathered A 588 steel in the field are now appearing, and specification design methodologies that address the problems have been suggested.

Additional research focuses on the development and evaluation of alternative deicing media that would eliminate or at least reduce the deterioration inherent from the use of chlorides (379). To this end, studies in the United States are examining the practicality of calcium magnesium acetate (380, 381). In Europe and Canada urea has also been employed.

Anchor-pattern depth and its effect on coating performance has received increased attention lately (382–384). The work has recently been summarized in the *Journal of Protective Coatings and Linings* (385). The exact significance of anchor-pattern size is still open to considerable discussion among experts, and there are conflicting opinions even from the same authorities. In a paper by Keane on the development of surface preparation specifications by consensus (386), the effects of mil profile on performance are considered of less consequence than had been previously considered. This conclusion is also reflected in the SSPC Report on surface profile (328), which cautions that the presence of hackles and rogue peaks microscopically towering above the general profile height are much more critical. ASTM has recently issued a new standard for field measurements of anchor patterns (387).

In two studies by Sandor (388, 389) using salt-fog and immersion testing, the value of edge preparation of beveling on coating performance has been studied. When the radius of curvature of beveled edges approaches half the plate thickness, coating system performance at the edge is said to approximate that of the face plate. No advantages were noted when edges were striped before airless application.

Considerable work is under way to improve surface preparation specifications. In a recent SSPC survey (376), criticism was levied at the SSPC and Swedish Standards for inadequate representation of all groups of cleaning. Despite the introduction of rotary cleaning and descaling devices (390), which provide surfaces equivalent to white-blast, existing power-cleaning specifications reflect only the surfaces provided by the traditional tools and cite the removal of loose rust scale and paint only. New standards are being prepared, and standards applicable to water-blasted surfaces are also under development. New visual standards are also being studied that would expand the number of rust grades and remove differences among the current Swedish standards, actual practice, and the SSPC written definitions.

Finally, a new blast quality “industrial blast” is being introduced by SSPC. This blast quality will be designed to fit between the present brush-off and commercial grades.

## EMERGING DEVELOPMENTS IN COATINGS TECHNOLOGY

A definitive assessment of trends and directions in coatings technology as it relates to bridge maintenance is somewhat hampered by the proprietary nature of product development.

The fundamental trends in coatings formulations (toward 100 percent solids systems and toward water) are, for example, no less pertinent to bridge coatings than to paints for other markets. Trends away from the inhibitive oxidizing system to zinc and/or the barrier system have been noted in other segments of the industry for several decades. All these trends are encouraged not only by environmental pressures but by economic motives and a need to make more efficient use of chemical feed stocks. Moreover, toxicological concerns over solvents could be curtailed by eliminating solvents. Given the overall trends in bridge paint toward fewer coats and the reduced barrier properties of many water-borne systems currently in use, higher solids systems (toward 100 percent) would seem to be the most likely objective in the short term.

Overall trends would seem to favor the further development of high-build systems based on thermosetting coatings (such as epoxies and urethanes) instead of the high-molecular-weight thermoplastics. Despite the higher performance profile of the vinyls and chlorinated rubber systems, the inevitable depression of solids that the high-molecular-weight solution viscosities must bring will change the use strategies of these materials. Lower-viscosity polymeric, oligomeric, and even monomeric vinyl, acrylic, and other binders of this type may be expected to gradually displace their high-molecular-weight counterparts and use strategies will probably involve their combination with thermosetting systems as polyols, co-reactants, diluents, or modifiers, instead of using them as lacquers as the sole binder. Already these trends are becoming apparent as acrylics and vinyls are now used with some success as polyols for urethane systems and in hybridized epoxy systems. Vinyl/epoxies also show advantages in protracted pot lives and low-temperature drying properties. Still-lower-molecular-weight chlorinated rubber systems are doubtful because of the inherently poor stability against dehydrochlorination in this polymer. Spans coated with vinyl/urethanes and vinyl/epoxies are, however, already being tested in both Florida and Maine, and are doing well.

Thermosetting polymers, building molecular weight by condensation of low-molecular-weight reactive species after application rather than before, seem more easily adaptable to higher-solids technologies. High-solids urethane and particularly epoxies are receiving (and will continue to receive) much attention from manufacturers. Even with these thermosets, the trends are toward lower-molecular-weight liquid reactants at the expense of the more traditional binders, and a primary goal of many resin manufacturers is to provide systems where equivalencies favor the highest ratios of the lowest-viscosity reactants giving the lowest-viscosity resin/hardener combinations that may be applied with least difficulty without compromise to performance.

Although it seems unlikely that new coating systems based on radically new chemistries will appear in the next ten years or so, the application of molecular engineering in the synthesis of coatings resins is already providing many interesting and exciting new applications for coatings formulas, which may eventually show up in the bridge-painting market.

Although most users are quite familiar with terms such as polyester/urethanes, acrylic/urethanes, and coal-tar/epoxies, terms such as vinyl/urethanes, epoxy/urethanes, and epoxy/acrylics will become more common. Such expanded activity is not to be limited to actual reactive systems. Experiments with what are apparently diphasic systems, such as plasticized thermosets, are also under way. Typified traditionally by coal-tar/epoxies, some of the more promising epoxy mastics have utilized this type of technology.

The drive for higher solids will involve some compromise in pot life and application, in aesthetics, and almost certainly in performance. The response of tighter films of higher cross-link density (inevitable with short-chain lower-molecular-weight reactants) is a reason for concern on bridge structures where some degree of flexibility is indispensable. Judicious pigmentation and selected application methodologies (two-pack guns, etc.) can compensate for some of these inefficiencies, but it seems likely that some attributes will have to be sacrificed. It is possible, for example, that new coating systems designed for use in the snowbelt states may not be as acceptable in the different environments of Florida and the Gulf Coast areas, and that increased specificity in formulations may be necessary.

The FHWA/SSPC publication by Bruno and Keane (391) includes an excellent bibliography of recent work in this area.

Significant advances resulting from intense competition for the latex bridge-paint market are seen in the next decade or so. At this time, styrene acrylics (392) appear to have the inside edge, although urethane dispersions (393, 394), new vinyl technologies, and vinylidene chloride systems (employing a radical new paint formulation technology) (395, 396) bear some careful attention. Still newer high-nitrile polymers, when properly cured, have moisture and oxygen transmission properties that exceed those of today's solvent-based coatings.

Warness (397) describes Caltrans's formulating experience with latex bridge paints. Warness notes that not only are the latex polymers themselves critical to performance, but surfactants, defoamers, and wetting agent selection must be controlled. He reports that by the end of 1984 some 10,000,000 square feet of steel would be protected by the four-coat California latex system. Problem areas (poor blasting, nonuniform and/or inadequate film thickness, and interference materials) seem less related to the type of paint than to the normal deviations from good painting practice. Problems described as being related to the effects of application under cold, damp weather conditions are more definitely related to system type.

Chemically curing water-based systems are currently limited to epoxies. The reactivity of water with polyisocyanates precludes the use of urethanes. Great strides in such technologies are being made, however, and the effective water-based epoxy bridge systems (with properties that match those of their solvent-based cousins) seem closer to being realized than the latex systems. After a couple of false starts, the latest epoxy technologies utilize emulsifying species (398) that react with the curing agent and on curing are chemically bound within the polymeric matrix and are therefore less sensitive to moisture than is the case with

the latex systems. Kurnik (399) shows that the presence of water as a carrying solvent is in no manner substantially detractive to the performance of epoxy coatings when finally cured. Similar conclusions were originally reached by Masciale with earlier variants of the technology (400). Khambatta and Warner (401) describe water-borne epoxy systems as well as a cementitious latex system said to provide good performance over rusted surfaces.

Water-based alkyds, although widely used in OEM applications, have not shown as much acceptance on bridges.

In pigmentation, trends continue to reflect the efforts to eliminate lead and hexavalent chromium, and the swing from inhibitive primer to the zinc rich. One can expect some continued effort on the part of pigment manufacturers to develop viable lead and chromate replacements (402) and to more effectively utilize auxiliary pigment volume to make up for the reduced effectiveness of the nontoxic inhibitors. More careful selection of both prime (403) and extender pigmentation (30, 404) is to be expected as well as less flexibility in formulating practice.

With the continued success of zinc-rich primers will inevitably come attempts to extend zinc with aluminum, graphite, and other conductive extenders of various types. As with the inhibitive primers, it is to be expected that other attempts will be made to improve zinc-rich performance by means of even more subtle formulation refinements, having little to do with zinc content per se. They are typified by the effects of solvent selection noted by Orr (405) on the wetting properties of zinc primers.

New atomization methodologies for the production of zinc pigment, resulting in an elongated sphere, are described in a recent paper by Leclercq (406). It is claimed that formulations based on these new zinc pigments are cohesively stronger without compromise in the level of cathodic protection.

With the greater emphasis on the barrier principle, greater use of both non-leafing and leafing aluminum flake, as well as other lamellar pigments such as micaceous iron oxide and stainless steel, may be anticipated. This trend is already reflected in the aluminized epoxy mastics and the moisture-curing urethanes.

Where environmental problems or political pressures prohibit the use of lead, but where funding for radical rectification procedures allowing the full use of zinc systems is not available, the aluminized epoxy mastics will continue to score.

The potential market for a coating system that will provide viable protection for poorly prepared substrates will probably continue to engender considerable research and development on the part of paint manufacturers.

Higher-solids systems in zinc primers will probably follow the development of such techniques in other coatings (organic) and will be a consequence of any reduced zinc-binder ratios in solvent-based inorganics. Environmental pressures on such solvent-based inorganics as the alkyl silicates may eventually lead to more widespread use of water-based alkaline silicate zinc-rich primers.

The drive toward increased solids and lower viscosities will also foster more research into improved pigmentary/vehicle interfaces by the use of titanate, silane, and zirco aluminate surface treatments. Such treatments not only produce a marked elevation of the CPVC but have other profound effects on performance properties not apparently related to such CPVC shifts (407). It may be expected that in the 1990s the use of pigmentary surface treatments at both the raw material manufacturing stage



and, to a lesser extent, at the paint manufacturing stage will see considerable development.

## RESEARCH IN CORROSION CONTROL BY COATINGS

Current research trends in basic corrosion science (as it relates to corrosion protection) continue to concentrate on developing an improved understanding of such critical areas as transport phenomena (moisture, oxygen, and ionic materials), the corrosion process beneath the film and at and around holidays (cathodic disbondment, etc.), and the effects of polymeric and morphological heterogeneities, etc. Other studies are more specifically directed toward the prediction of corrosion either before it occurs or detection before it becomes obvious. Motivations for such research are not only to obviate corrosion via more specifically directed disruption or hindrance of the isolated processes, and thereby prolong the effectiveness of coatings, but to substantially reduce the long time spans necessary to evaluate corrosion control coatings tested by current popular testing procedures (salt fog, weatherometer, etc.).

More conventional testing methodologies will probably remain at least until some of the more scientific techniques can prove themselves. In view of the poor correlation of such tests as the salt-fog test and the Kestenich procedure with a long-term field performance, it is possible that customized modifications of these tests will increase. Cycling test methodologies using salt fog or Kestenich with QUV and hot and cold recycling are already being evaluated, and it is probable that techniques such as these will continue.

Although adhesion (408) and bond uniformity are possibly the most important factors in corrosion prevention by coating films, easy and accurate quantitative measurements of such film characteristics remain elusive. It should be emphasized that notwithstanding the moisture transmission rates of a coating film, if adhesion is maintained even in the presence of water, corrosion cannot occur. Current adhesion tests, however, generally measure adhesion under dry conditions, not the wet adhesion that is critical to the functioning corrosion-resistant coating. Efforts to better characterize this important aspect of coatings performance are being researched, however. Funke and Zatloukal (409) have examined wet adhesion by comparing the water absorption/time curve for both supported and nonsupported films. The point of intersection of such curves (where the water absorption of the supported films assumes the same value as the nonsupported film), called the "cross-over point" by Funke, may be considered to mark the initiation of water accumulation at the interface. By comparing the relative times of different coatings to achieve "cross-over," some comparative measure of wet adhesion seems possible. It would seem that increased emphasis on the characterization of wet adhesion may be expected in the coming years.

In a later paper, Funke (410) observes the dichotomy between the advantages of polar hydrophilic groups for adhesion to metal and the disadvantages of these molecular groups in their greater sensitivity to water. Although this tends to confound the attainment of good adhesion, Funke suggests several possible alternatives for improved wet adhesion even in the presence of such groups. These include the use of high-build systems, surface pretreatment, and increased immobility of the polymer backbone

in contact with the interface. Papers on adhesion and de-adhesion and their relationship to corrosion by Kumins (411) and Dickie (412) are also of interest.

The profound effects of stress and internal strain on the performance of coating films seem to have received little attention to date among those who design coating systems for corrosion protection. Internal stress is built up during solvent release or cross-linking as the volume change is restrained owing to the restriction of molecular segments via cross-linking. After application it is built up by absorption and desorption of moisture. Adhesion of the coating at the interface inevitably suffers. Even in single-coat systems, internal stress may be considerable. It may, for example, exceed the tensile strength of the film, when the film will inevitably crack or fail cohesively (413). If it should exceed the adhesive strength of the film, spontaneous delamination from the substrate may occur (414). The latter danger is of particular concern in thick thermosetting films (such as high-build epoxies) that are cast from fairly slow solvents.

Dynamic mechanical testing (DMT) of thermosetting polymers and coatings via the torsion pendulum and torsion braid analysis are also receiving increased interest. Automated test systems of this type are now available and are said to provide a viable approach to the accurate investigation of cure kinetics, effects of water up-take, plasticization, etc. (415).

A considerable body of research around the world has now been devoted to the investigation and the development of potential test methodologies for the evaluation of anticorrosive coatings using electrical and electrochemical techniques (416-419). As corrosion is generally electrochemically induced, and as the mechanism of transport through coating films involves either electrical phenomena or at least can be monitored by electrical property changes in the coating films, this is hardly surprising. The potential value of this type of testing lies in the fact that it should provide not only a comparative and (with luck) a quantifiable measure of the quality of protection, but that some measure of understanding of the actual mechanisms of deterioration, and, therefore, protection may be gleaned. Although the literature abounds with many studies of this type, results have been no better than mixed to date (408), and certainly the proliferation of viable techniques is at this time limited. Tooke and Hurst (420) evaluated apparatus and methods for the electrochemical techniques and concluded that, although studies of the dielectric properties of paint films provide rapid data on moisture permeability, and while electrical polarization techniques have value in characterizing the inhibitive properties of paint films, the techniques seem more limited to research and development or possibly diagnostic investigation of the paint film deteriorations than anything else.

Attempts to quantify the performance of coatings on metal by a measurement of impedance (by both DC and AC techniques) (421), capacitance (416), frequency response, electrical potential, and polarization effects are also receiving considerable attention from many researchers, and past results have been summarized by Leidheiser (422), Jullien (423), and Wolstenholme (424). Methods to date have involved the study of transport through barrier systems, the detection of water beneath the film, the corrosion growth at the interface, the detection of heterogeneities in the polymeric film (425), and the effects of pigments on the dielectric properties of coatings and on blister growth. Joly and Laout (419) note that polarization resistance measurements may be used in the testing of inhibitive pigments

and paints. Callow and Scantlebury (426–430) and Hepburn et al. (431) have done considerable evaluation on electrical impedance of coated metal electrodes.

The potentiostatic and galvanostatic degradation of zinc-rich protection with time have been examined (432, 433). Lindquist et al., using this type of technique, have successfully compared some eight commercial alkyl silicate and epoxy polyamide zinc-rich primers (434).

Apart from impedance studies, which generally show that (in barrier systems) as the coating resistance drops, the rate of corrosion increases, most of the electrical studies leave something to be desired, possibly because of the practical difficulty of obtaining truly perfect defect-free films of uniform thickness. The effects of pores and inhomogeneities on electrical properties of films and subsequent corrosion breakdown of the substrate have been evaluated by Mills and Mayne (68). Recent work of Callow and Scantlebury examining selectively dyed paint films under UV illumination indicates the possibility that such heterogeneities may be detectable via differences in film fluorescence after dyeing (435). Film integrity and the presence of pores in coatings have also been investigated using autoradiography (436). In these more practical experiments, Bayliss and Bray conclude that severe microvoids are entrained by certain application techniques (i.e., airless application) and that the drying times of many commercial systems may be too fast to allow air entrainment to dissipate before film setting. Large vacuoles (or voids produced by entrapped air) after airless application have also been described elsewhere in chlorinated rubber coatings (437).

Increased use of test methodologies involving cathodic disbondment techniques is now evident. This test (438) simulates and accelerates the effect of the natural cathodic polarization (and resultant alkaline condition) of the metal beneath paint films adjacent to defects and corrosion sites by artificially polarizing the substrate.

Other new nonelectrical techniques for the evaluation of corrosion and anticorrosive coatings that are receiving increasing attention include the use of ellipsometry (the measurement of the growth and/or dissolution of surface films beneath clear coatings by changes in the reflectance of elliptically polarized light) (439), and surface analysis using Auger, Sims, and Scanning Electron Microscope (SEM) energy dispersive X-ray analysis (440). Cunningham and Hansen (441) report the value of Electron Spectroscopy for Chemical Analysis (ESCA) and Fourier transform infra-red spectroscopy as tools in the early detection of weathering changes in exposed films as well as the promise of the same techniques in detecting and understanding the weathering process. Both Fourier transform infra-red spectroscopy and Fourier transform nuclear magnetic resonance spectroscopy are discussed by Mathias (442). Differential scanning calorimetry is being employed to measure the state of absorbed water in polymeric films (443) and radio chemical labeling techniques have been used to examine the diffusion phenomena through paint films (444).

Nondestructive tests to signal the onset of corrosion under the film before it becomes manifest are receiving attention from several researchers. Martin and McKnight (445–447) at the National Bureau of Standards (NBS) describe a technique using infra-red thermography that promises much, particularly when combined with reliability analysis. The latter technique is a philosophical departure from the approach to testing tradition-

ally employed in corrosion control by coatings and has evolved from its success in other fields. Traditional testing practice is based on comparative testing of one paint system against another and attempted correlation of the accelerated results with field performance. Problems of reproducibility and lack of quantification so limit this type of evaluation that correlation is often regarded as questionable. In reliability analysis, multiple panels of the same coating are evaluated at different controlled stress levels produced by temperature, humidity, UV, etc. The frequency of failure at a high stress level is then employed to predict the failure rate under field conditions. NBS is also involved in the evaluation of underfilm corrosion and blistering by a thermowave imaging technique (448), which, although not as adaptive to field investigations as infra-red thermography, appears to be a good laboratory tool.

Acoustic emission, used for years to detect mechanical failure in welds, for example, has recently been applied in the nondestructive evaluation of chemical structure of polymeric paint films, and its relationship to paint performance has been examined (449). Development of monitoring devices of this type for routine field use could eventually prove invaluable in providing early isolation and therefore less costly maintenance of coating systems in service.

## SPECIFICATION DESIGN

More widespread use of the single source responsibility contract in bridge painting can be expected on larger structures run by individual bridge authorities if costs do not become prohibitive. The telling factor in this development may well be the first serious failure of a structure painted under this type of contract and the performance of the contractor may persuade insurance companies of the value of formally underwriting the venture, which could further catalyze the adoption of this procedure.

Painting of smaller bridges will probably continue to be let by the present bidding process, although here more use of prequalification of contractors and applicators may be tried.

The criticality of coating system selection and an awareness of the nonuniversality of individual systems is receiving increasing attention. A new guide (450) to assist coating system design engineers in selecting the most suitable coating system for any bridge is currently being developed for the FHWA and is testament to the need for a better understanding of the relationship between the design, environment, and condition of in-service steel bridges and the types of paint systems best suited for their maintenance.

The Steel Structures Painting Council is also preparing a guide for maintenance painting (451) that will treat not only the process of establishing a maintenance program but also the repainting of steel structures. Although not specifically directed at bridge painting, this treatise should provide much valuable assistance in all aspects of the discipline.

Specifications must inevitably improve in type and in detail, and, because of the difficulties of batch control by performance alone as well as the obstacles in the correlation of accelerated testing with field performance, some wider utilization of QPL methodologies or development of compositional forms of inorganic zinc, high-build vinyl, epoxy midcoats and finish coats, and aliphatic urethanes must also eventually evolve. Perform-

ance control testing increasingly involves the testing of the total coating system instead of simple coatings alone. As more and more zinc-rich systems evolve, such full system performance criteria should be encouraged because of the incidence of system problems involving bubbling, zinc splitting failures, etc.

## JOB EXECUTION

Environmental restrictions will continue to grow, especially in large metropolitan areas, and restrictions once limited to isolated pockets of concern will gradually become more nationwide. Regulations are now being enforced by federal, state, and local government agencies as well as unions. Also, contractors are slowly being forced to deal with grit disposal, blood-lead monitoring, and the control of airborne particulates.

The advent of OSHA in the 1970s has brought about changes in rigging practices, and a new industry continues to grow where once all rigging was designed and implemented by individual contractors.

In application, developments will continue to reflect changes in materials technology. The response to higher-solids systems will inevitably continue the trends to higher airless pump ratios, air-assisted airless techniques, and the use of multi-component equipment with metered feeding. Hot-spray and electrostatic devices are also expected to increase as is the use of metallizing with its associated equipment.

Many contractors voice concern over the increase in litigation that has impact on their operation. For the most part this involves suits brought by the general public in response to property and personal damage from the contractor's operations, although suits relating to job performance are also increasing. The indirect effect of this is a dramatic increase in insurance premiums and a growing reluctance on the part of insurance companies to underwrite operations.

With the higher cost of bridge painting, most contractors foresee that state and local engineers with job responsibilities will become increasingly aware of the technologies of the process and the materials used. Some contractors note that these authorities are increasingly employing the service of outside engineers, consultants, paint specialists, and more inspection forces to ensure that the value of the money spent is better preserved. The effect of such specialists on job execution seems variable and dependent on the level of their individual expertise. The best will assist contract operations, while preserving the bridge authority's interest.

## INSPECTION

Considerable effort is now under way to redress the deficiencies in inspection through the education process. The bridge-paint inspection course recently rewritten for the FHWA is proving valuable, and the practicality of having experienced inspection personnel present this material is undoubtedly judicious. New general paint inspection manuals are soon to be offered by the American Institute of Steel Construction (AISC) and ASTM, as well as the Corps of Engineers, while inspector accreditation programs are being offered by NACE.

The advent of improved teaching tools and visual aids such as VCR equipment should also assist in the training of inspec-

tors, bringing the practicality of shop and field preparation and application into the classroom as well as generally improving the presentation and comprehensibility of the courses. Such VCR training courses are already being offered by the Institute of Applied Technology and are distributed through SSPC. Much wider use of these techniques may be expected in the future.

It is to be expected, and in fact is already in evidence, that VCR equipment will also be used to support still photography in the actual inspection process. The versatility of the VCR cameras, particularly the newer, less cumbersome models for low-light situations and close-up work, is matched only by the indisputable value to the job record such recordings provide.

Some improvements in inspection instrumentation may also be expected with digital electronic film thickness gauges, psychrometers, and other equipment. Eventually (as techniques are proven and instrumentation is commercialized) it is hoped that nondestructive inspection tools such as infra-red thermography may be introduced.

The contracting of inspection services to the private sector appears to be increasing, and, as more use is made of more complex, high-performance systems, this trend may also be expected to continue, especially if the single-source responsibility contract becomes more common in bridge painting.

## IN-SERVICE MONITORING

The corollary of what seems a certain continued escalation of both the costs and the complexity of the bridge-painting process is naturally enough a need for improved cost-effectiveness and, in consequence, a more ordered appreciation of the relative service of different coating systems in different environments and on different types of structures. Much of the current guesswork must be removed from the projections of system service. In large part, this must inevitably depend on the better and more uniform execution and control of the job process. Without a precise documentation of the nature and patterns of deterioration, however, accurate assessment of the life of the given system on a given bridge (and eventually a more generalized profile of the system's service on different structures in different environments) cannot be achieved.

The formal establishment of deterioration curves is an important key to the quantification of both service and cost, as well as an aid in specification refinement. It is also reasonable to assume that once statistically reliable deterioration curves of system service are established for a given structure, not only can better maintenance programs be planned at the outset, but actual deterioration can be compared against that anticipated and early preventive maintenance may be employed to counteract specific or local deficiencies before the deviation between reality and projection become too great. Similarly, the effects of unanticipated environmental changes (the proximity of new manufacturing plants or the relocation of chemical storage sites, for example) may be more accurately assessed for changes in rates of deterioration before such effects become too devastating to the paint system.

Further evolution of the bridge corrosion cost model and the need for reliable data for the refinement of this tool, and for its adaptation to specific states or areas of the country, will also encourage more formalized in-service monitoring programs. The establishment of a central data bank for receipt and dissemi-

nation of the collected understandings of disciplines would, because of requirements for more accurate data, generate more programs of formal coating system service documentation.

Several papers considering coating system service and costs were presented at Corrosion '86. Kline and Keyman (452) give valuable data on the service lives of zinc-rich and galvanizing systems, although the data are nonspecific to bridges. The paper also compares several U.S. and European scales of grading paint system deterioration and discusses maintenance scheduling. A further updating of the work of Roebuck and Brevoort (453) was also presented at the same conference. Although the performance figures noted in the tables of the new paper still appear inappropriate to practical applications for bridge service, the paper now considers the use of computers in the development of comparative maintenance costs. Smith (454) also demonstrates the use of computers in the manipulation and retrieval of data required for the management of maintenance painting programs. Like the Roebuck and Brevoort paper, this paper seems more directed at plant maintenance than bridges. Additional service and cost comparisons are also found in papers by Masciale (455), Hergenrother (456), and Mudd and Boyer (457). The Masciale paper is particularly interesting in that it specifically considers the refurbishment of old coating systems with the epoxy mastics.

## COSTS

Improved accuracy and more formal quantification of the costs of coating systems, along with the various individual cost

elements of the job process, will be important considerations if the potential value of the bridge corrosion cost model as a tool in the decision-making process of bridge maintenance programs is to be realized.

Indeed, as service life is itself an important element in the establishment of cost-effectiveness, it is likely that the organization of both cost and service will progress to some extent simultaneously.

What are needed are data; from contractors, from coatings manufacturers, from equipment suppliers, and from those who analyze bid packages. Because of the subjectivity and variability of the bid development process, the more data the better.

Armed with increasingly more accurate data, statistically condensed from this input, repeated applications of the bridge corrosion cost model to more and more structures will inevitably shape the model into a far more practical tool. Deficiencies in the present model will be isolated and, as these are corrected, the model's efficiency will improve.

The analysis and organization of cost data can also do much to further a more precise understanding of other aspects of the job process among participating engineers and, via subsequent publication, other interested parties. Critical but poorly disseminated data on aspects of job execution that have direct bearing on painting costs—production rates for blasting and the effects of steel condition or abrasive and nozzle size or air pressure, the relative application rates with different types of coatings and techniques, grit use, material volumes, and equipment capabilities—all may be thus quantified and better appreciated.

## CHAPTER ELEVEN

## CONCLUSIONS AND RECOMMENDATIONS

This synthesis has attempted to review the state of practice in the selection and use of coating systems on steel bridges from all vantage points, consideration being given not only to the design and performance characteristics of the coating systems but also to their specification, application, and control, all of which will affect the success and cost-effectiveness of any job. The following conclusions and recommendations have been condensed from the whole study as being most significant.

### OVERALL TRENDS

In all areas of the discipline the practice seems to be in a state of flux as the industry struggles to keep pace with the technological changes that have been taking place in coatings technology during the past 25 years. The predominant motivations for such changes have been the drive for longer, more cost-effective service from coating systems. Other factors that have become increasingly important include environmental concerns over lead, hexavalent-chromium-based pigments, photochemical reactive solvents, and the economic inducements of the reduction and elimination of expensive solvents that the high-solids systems and water make possible. By reducing a typical paint system from 3 to 7 coats to 2 to 3 coats, the industry has attempted to reduce the costs of paint jobs, which would have increased as a result of labor and materials cost increases, and the costs of increased surface preparation procedures, inspection, and design.

### SURFACE PREPARATION

Surface preparation by abrasive blasting is rapidly becoming the norm throughout the industry, particularly in new construction where centrifugal blasting affords cost-effective excellence in substrate preparation. In field work, abrasive blasting to a minimum of a commercial blast is being adopted in many states in the total rehabilitation of those older bridges having severely deteriorated existing paint systems and in the spot-blasting maintenance of less deteriorated structures.

Blasting has been fostered not only by the generally increased awareness of the value of the uniform, clean, and profiled substrate, and its contribution to the long-term durability of all paint systems, but by the inappropriateness of the older preparatory methodologies to newer paint systems based on barrier and/or zinc-rich protection. Perhaps the only situations where blast cleaning is not cost-effective are on those bridges where lead-based paint systems utilizing the old TT-P-86A Type I red-

lead and oil primers are still used in dry or non-salt water environments. The extremely long-term protection offered by these systems and by other lead-based systems in many rural parts of the country makes their upgrading via blast cleaning difficult to justify even from an engineering standpoint.

A newer development, particularly suited to field work, is the utilization of wet-blasting techniques. Increased employment of this type of surface preparation may be expected with the development of an increased awareness of the impact of chloride and sulfate nests on the overall performance of coating systems. The limitations of the dry-blast process in the total removal of such contamination from corroding steel, and a sharpened awareness of the hazards of silicosis, certainly foster the adoption of the wet-blasting approach. Wet abrasive blasting and water blasting are also further encouraged by concerns over the hazards (real or perceived) that are incurred in the removal of lead paints from older structures. The total or partial de-leading of bridges across the country will undoubtedly increase; wet abrasive blasting techniques for such de-leading operations may be less costly when the total cost of containment, removal, and disposal of cleaning debris is compared to other techniques.

### COATING SYSTEMS

The most obvious trend in coating systems used on bridge steel over the last two decades has been the gradual abandonment of the inhibitive alkyd and oil-based systems in favor of coating systems based on zinc and high-performance barrier vehicles. Non-lead/non-chromate inhibitors have not provided the same performance profile as did lead systems, although they are being employed with success on bridges in California and Massachusetts.

The use of the zinc-based systems is increasing, particularly in coastal and industrial areas of the country and where the use of deicing salts is heavy. Many states now employ two different coating systems; one, usually lead based, for spot maintenance in non-salt environments, and a second high-performance system, usually zinc based, for salt water or chemical environments. Some are experimenting with non-lead inhibitive alkyds and latex systems, aluminized urethanes, and high-build aluminized epoxy mastics in lieu of lead-based systems in spot maintenance and on old complex riveted structures with latticed features and back-to-back angles. Application of zinc systems on such older structures is more difficult because of cleaning difficulties and control of film thickness.

Of the many new systems that have been evaluated over the past 20 years, however, the alkyl-silicate-based zinc-rich primer

with a vinyl topcoat has emerged as a successor to the BLSC system as the primary coating system for steel bridges today, although newer zinc systems with aliphatic urethane topcoats with and without high-build epoxy intermediate coats are now being seriously examined by several states and bridge authorities.

Less satisfactory have been developments in new paint systems for spot-cleaned substrates; applications for which traditional lead-based paint systems were singularly suited. Unfortunately, as concerns over hazardous waste disposal and air pollution produced during blasting operations grow, it seems likely that, in the face of the inadequacies of other suitable preparatory techniques, a consequent reluctance to blast will generate (at least temporarily) some increase in the use of spot power-cleaning methodologies. Increased market opportunities for nontoxic coating systems for use over marginally cleaned substrates are already spawning many new coatings directed at this specific application.

The abandonment of lead in favor of high-performance systems has not been accomplished without problems, and reports of paint failures have induced caution in those who would utilize the newer system. Such failures as have occurred, however, rarely translate to deficiencies in the actual product. More often than not the problems relate to insufficiencies in specification design, surface preparation, application, and film thickness, and serve to illustrate the gap that exists between the development of the coatings technology and the technical preparedness of the industry to adapt to the practical utilization of such products.

Although many paint systems now available are adequate for the job, new developments can be expected. Higher-solids systems (particularly urethanes and epoxies) leading to simpler, less costly, and more environmentally acceptable one- and two-coat systems may be expected, as may the development of systems with improved performance over wet or poor surfaces and with greater tolerance for application variables. Continued research effort in the area of lead and chromate pigment replacement may be expected for the field maintenance of older structures. Lower-solids monomeric and oligomeric hybrids, low-temperature curing epoxies, and higher-solids vinyls are possible, and it seems likely that developments in the water-borne technologies (most immediately, water-borne epoxies) will be significant. As chemically curing thermosets approach 100 percent solids, severe pot-life/dry-time reversals may increase the use of two-component spray equipment, whereas higher-solids thermoplastics will further increase pump sizes and the use of hot-spray delivery. Some relief in the material costs of systems such as aliphatic urethanes may be expected as the small manufacturers compete in what is certain to become an expanding market.

## SPECIFICATION DESIGN

On most smaller structures the same specification is continually duplicated from bridge to bridge, leading in some cases to several system failures of the same type. The monitoring of paint system service on completed bridges remains an inexact process, and communications between the field and the specification writers are often poor. This leads to a specification refinement process that is slower than it should be and unnecessarily wasteful because of the repetition of mistakes. Regular and more frequent communication between specification writers,

including materials engineers, and bridge engineers, residents, and inspection crews could do much to accelerate and improve the specification refinement process. The specification writer's contribution is part of the overall job process cycle (see Fig. 12). It is not a finite task divorced from the rest of the job or one that once completed is never again to be reviewed.

Current bridge-paint specifications still seem more concerned with individual coatings than with the paint system taken as a whole. Improved specifications will be required in which not only individual coatings but the total system is considered in detail, and specific attention is directed to areas of proved criticality (cure verification; recoat time frames; the effects of climatic conditions on cure, adhesion, and performance; and film thickness ranges for each coat and the complete coating system).

Response to deficiencies in specification writing would seem to lie in education and training. Possibly the type of course recently revised and now being offered by the FHWA for inspectors, with a somewhat different emphasis, would serve well. In addition to the standard review of corrosion, basic corrosion control by coatings, surface preparation, application, etc., greater emphasis on the coating system design, composition, and the relevant elements of paint technology would better prepare the specification writer. The FHWA manual on the selection of coating systems for bridge painting is a start, but the specification writer requires more expertise in the actual preparation of the technical document itself. This can only come from a detailed understanding of the strengths and vulnerabilities of the coating system in light of the peculiarities of job execution, bridge design, and environment. Objectives of such courses should be not only to encourage the development and refinement of modern bridge specifications by instruction and example, but to provide a greater understanding of the meaning and ramifications of the many terms, constants, and clauses in terms of the product's composition and its behavior as part of a complete paint system on a given structure.

## CONTRACTOR PREQUALIFICATION

One method to improve the quality of bridge painting could be through prequalification of painting contractors and their operatives. Although other trades such as welders, electricians, and plumbers have long required certification by means of documented experience as apprentices and journeymen (as well as proctored examinations on theory and practice), the skills of the painter have been judged too basic to warrant such controls. With today's many and diversified chemical compositions, equipment, and processes, adequate training and qualification of painters (with some specific emphasis in bridge work) is essential.

## INSPECTION

It is important for the bridge authority to maintain proper control of the painting process. Unfortunately, control (and particularly field inspection) is the one facet of bridge painting that is frequently not properly performed. Many bridge-paint inspectors are not well trained and often perform paint inspection as a secondary task to other inspection duties. In many states there are no bridge-paint inspectors as such at all. In

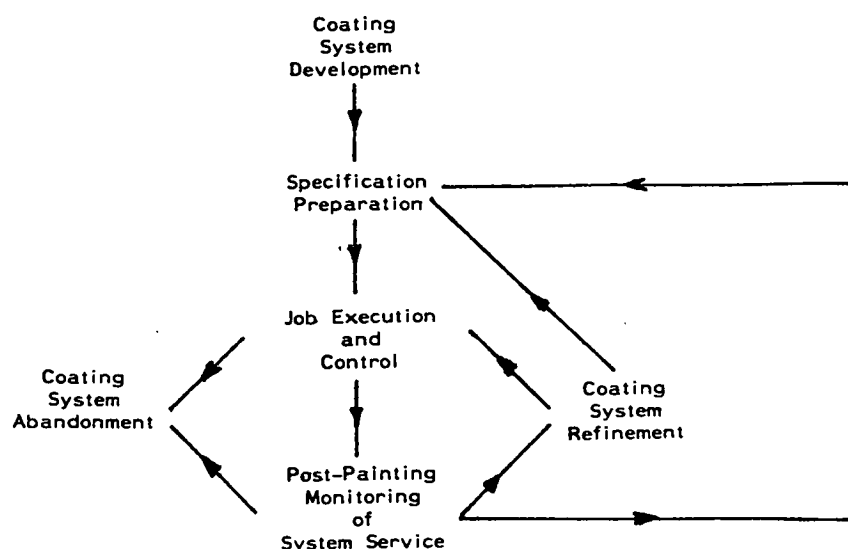


FIGURE 12 Bridge painting job process cycle.

others there is an understanding of the problem, and there may be short classroom courses and workshop sessions. The FHWA is currently implementing a formalized bridge-paint inspection course.

#### MATERIALS CONTROL AND TESTING

State materials laboratories are generally well equipped, and staff have an adequate expertise with the required analytical and test procedures, although they may not have a background in paint technology and the formulation process.

Badly needed are more reliable accelerated testing methods. The salt-spray test is still widely employed, but most users remain uncomfortable with its value as anything but a screening tool in the early formulation development of new coatings. Weatherometer studies satisfactorily reproduce one element (UV) of the normal environment, but do little to simulate the aggressively corrosive environment that is common on many bridges. No formal test procedures effectively simulate the conditions of most northern structures in the winter months where cycles of freezing and thawing and salt contamination can wreak havoc with a deteriorating coating system. Little attention has been given to the effects on complex steel/multi-coat paint composites of cycling stresses, either mechanical (such as vibrations) or climatological. The effects of these stresses, particularly in combination with corrosives, oxygen, moisture, and UV, need careful evaluation. Few existing test procedures seem well designed to both simulate and intensify (without distortion) all of the destructive agencies that affect painted steel bridges.

In view of the lack of correlation with actual field service that is afforded by test procedures such as salt spray, new approaches to short-term testing (typified by reliability analysis and cluster analysis) should be given every opportunity to prove themselves. These concepts, together with pre-failure detection of coating system distress or the initiation of underfilm corrosion (using infra-red thermography, electrochemical, or acoustic

emission techniques), are welcomed and refreshing departures from conventional evaluation techniques.

#### ASSOCIATED FACTORS

There is a greater concern and awareness by bridge design engineers for ease of painting, ease of future maintenance, and the suitability of structural design for the use of the high-performance coating system. The adoption of simple and continuous beams with large, flat, uninterrupted areas serves for easier maintenance than riveted trusses with a profusion of latticed members and intricate designs. Designs to facilitate inspection and ready rigging in future maintenance, catwalks, access ports, and permanent movable painting platforms, if possible, will inevitably reduce the cost of painting.

Continued research into alternative deicing materials, such as calcium magnesium acetate and urea, is also important. Although initially more costly, the longer-term cost-effectiveness of these materials compared to chlorides should be measured in terms of the accelerated deterioration of both structural and reinforcing steel that is caused by the more corrosive deicers.

#### IN-SERVICE MONITORING

Bridge deterioration is rarely uniform. The cost of maintenance might also be reduced by more careful analysis of the deterioration patterns of a given structure or a group of similar structures as the paint system ages. The correlation of such patterns with exposure, design, traffic flow, and other factors as well as with the properties of the coating system, serve well as feedback for new specification design. Through this and concepts such as "specific utility" (the consideration of the bridge not as a simple structure but as a combination of substructures each with specific requirements of coating type, film thickness, number of coats, etc.), a more uniform deterioration of the structure as a whole might be achieved, which will both lengthen

the interpainting service life and render each painting more efficient.

The accurate documentation of system service and the necessary correlation of areas of distress with bridge design, system type, environment, and job execution factors is still imprecise and often nonexistent even on test structures. Field trials will always remain a vital step in the proving of any viable coating system, and in view of the unpredictability of the job process, further documentation of that process including surfaces, conditions, and peculiarities existing before and after painting is essential if any meaningful interpretation of service success and/or failure is to be gained. All too often field tests are valueless for want of these records, and where data are available, their interpretation and the distribution of realized conclusions may also be imperfect.

On many structures, records of what went where and when do not seem to be readily available. In consequence the assessment of service lives and cost per year of service are not known with any accuracy.

## SERVICE AND COSTS

The formalization and quantification of cost and service data on coating systems is also a prerequisite to the generation of long-term bridge maintenance programs and to the gradual refinement of potentially valuable tools such as the bridge corrosion cost model. The simple recording (with or without photographs) of rust percentages on selected structures on a regular basis will do much to provide the required accurate assessment of paint system service. Although accuracy in this is necessary, accuracy is not the immediate problem that organizing such a program seems to be.

Although performance of any particular paint system on one structure will necessarily differ from performance on another (depending on the quality of job execution, on environment, location, traffic density, etc.), given enough data (centrally correlated), mean value service profiles for each coating system

over a broad range of service environments might be established for use in the development of formal maintenance programs.

## IMPROVED COMMUNICATION

There is a continual need for improved communication and data dissemination at all levels of the practice. Misinterpretation of data, misunderstandings and confusion over terminology, inaccuracies in description, premature assumptions, and incomplete or erroneous conclusions are not unfamiliar problems in the reporting of data, and transmittals of reports and opinions are often plagued by distortions of emphasis and meaning.

Even in the published literature, misstatements concerning coatings and coating systems are not unknown, and a plethora of claims and counterclaims (some with appropriate test data) about individual coatings, processes, and equipment abound. Unfortunately, it is not difficult to design, select, and present test data in formats most flattering to a specific product, and it can be difficult for an engineer or specification writer not totally familiar with the technology to discern truth from distortion.

On the other hand, there is a large quantity of excellent reliable data in the form of published and unpublished records, studies, reports, journals, papers, articles, books, theses, and opinions from many sources relating not only to bridge painting but to associated technologies. These would provide a valuable reservoir of data from which all those having any kind of responsibility to the discipline might glean much assistance if they could readily access them. A feasibility study for such a data bank has already been completed, although the idea has not materialized (apparently for want of commitment). Some renewed evaluations of such a data bank would seem, from this vantage, a most forward-thinking step.

This synthesis can be no more than a partial compendium of such data. Within its scope it can do little justice to the depth and diversity of all the information that is available on the subject to the many who might benefit from its improved accessibility.



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## APPENDIX A

### INSPECTION REQUIREMENTS

#### INSPECTION REQUIREMENTS:- GENERAL

##### 1.) Enforce Specification and Maintain Control of Job

a.) The inspector protects the bridge authority's interests as the field representative of the engineer. He ensures that all requirements of the specification are continuously maintained. The inspector controls the job with firmness but fairness, and accurately reports all activities in a timely fashion to the engineer.

b.) The inspector reads, understands, and fully appreciates all articles of the technical specification, as well as associated documents of pertinence such as blast standards, pictorial representations, and the coating manufacturer's product Data Sheets. Where possible before the job starts the inspector will fully familiarize himself with the equipment being used as well as with the individual coatings, their properties and application characteristics.

c.) The inspector is fully cognizant of the intent of the specification, of areas of criticality in job execution (e.g. blast requirements, acceptable film thickness ranges, cure requirements, recoating schedules, etc.), and realizes the consequences of specification deviations. He examines the structures to be painted prior to job start-up, and anticipates areas of criticality that may be related to design features, location, and/or exposure.

d.) The inspector provides counsel to the engineer on any design feature whereon the specification may be compromised or inappropriate because of access, steel condition, etc..

e.) The inspector knows and understands all inspection procedures required by the specification, is familiar with the use of the instrumentation involved, and is a climber, comfortable with working on steel irrespective of height and type of rigging.

f.) The inspector is fully acquainted with the safe practices of rigging, equipment handling and materials safety, and will render counsel to the engineer concerning the same where necessary without delay.

##### 2.) Monitor and Regulate Job Process

a.) The inspector's principal duties involve the control of cleaning, surface preparation and application of all coatings. These requirements are consequently dealt with in Tables XVII through XXI

##### 3.) Interface with Engineer and Contractor's Representative

a.) The inspector is capable of clearly communicating with both contractor, superintendent, foreman and bridge engineer concerning all aspects of the job process.

b.) The inspector maintains a daily log of all operations detailing crew size and make-up, hours worked and activities, as well as climatic conditions, and measurements taken (film thicknesses, application schedules, adhesion data, etc.). He records the daily productivity rates, the job process from bent to bent, the records, dates and make-up (including batch #'s) material delivery, storage conditions and amounts of paint and abrasive used daily. All activities are illustrated with a photographic record, especially areas where problems, disputes, or anomalous conditions occur.

##### 4.) Response to Extraordinary Conditions

a.) The inspector is sufficiently familiar with operations to recognize unusual and possibly untoward phenomena at the outset, reporting the same to the engineer before the problem is compounded by recoating, etc.

#### 5.) Other Functions

a.) Depending on a particular job, the inspection requirements may also involve control of containment and traffic control. He may also be required to certify the job for payment.

#### INSPECTION REQUIREMENTS:- PREBLAST WASHING

- 1.) Verification of washing schedule with reference to general cleaning and yearly bridge maintenance.
- 2.) Establishment and supervision of geometrical order of washing procedure (Upper truss, upper deck, lower deck, legs, etc.).
- 3.) Verification of acceptability of washing procedure and washing solution make-up.
- 4.) Verification of rinsing operation.
- 5.) Verification of suitability of washed surfaces to receive new coating.

## INSPECTION REQUIREMENTS:-SURFACE PREPARATION

### 1.) Before Operation

- a.) Verification of surface quality standards with engineer and contractor.
- b.) Verification and control sampling of contractor's abrasive (type and size) as suitable to achieve required anchor pattern and profile depth. Estimate mix ratios of grit/ shot in shop work.
- c.) Preparation of practical standards (photographs or plastic sealed panels) that represent the required quality of cleanliness as called for by the specification and interpreted by the engineer.

### 2.) During Operation

- a.) Verification and recording of climatic conditions as suitable for the cleaning process. (temperature - steel and ambient, relative humidity and dew point, wind speed and direction).
- b.) Examination of abrasive composition and mix (shop work), and comparison to control.
- c.) Examination of traps, separators and air to ensure no contamination by oils or water.
- d.) Examine blast quality and profile at intervals convenient to the contractor (lunch breaks, etc.) and mark non-cleaned areas and areas of insufficiency for reblasting. On hand and power cleaned jobs examine cleaned areas and peripheries for loose rust and film removal and for feathering of edges.
- e.) Examination of day's blast before blowdown.
- f.) Establishment of areas requiring reblast.
- g.) Verification of blow down and steel condition prior to priming.
- h.) Use of potassium ferricyanide indicator papers, or other means (white latex paint) to verify removal of soluble iron salts.
- i.) Record data and time of start and finish of blasting operations and blow down.
- j.) Photograph typical areas, bad spots after rejection and after reblast, special conditions, disputed areas and untoward practices.
- k.) Record number of blast nozzles being employed and daily production rates. In shop work record sq. footage prepared by centrifugal blasting.
- l.) Mark and photograph for structural examination and repair any areas of excessive metal loss, perforation, rivet loss, tears, etc. uncovered by blasting process.
- m.) Document all extraordinary conditions, excessive or recurring contamination, deeply pitted steel, etc. clearly recording their location and extent.
- n.) Monitor and record time, materials, manpower and equipment used (especially when addressing rectification of any extraordinary conditions that may fall outside the scope of the specification).

In jobs where blasting process is contained with enclosures, it may also be necessary for the inspector to monitor enclosure efficiency, clean-up and spent grit storage. Actual sampling of fixed and movable air quality monitors is more likely to be performed by other specialists.



## INSPECTION REQUIREMENTS:-PRIMING AND PRE-TREATMENT COATS

### 1.) Before Operation

- a.) Verification and recording of existing climatic conditions as suitable for priming as per specification.
- b.) Review of weather forecast and determination of reasonable probability that primer may safely cure without weather change induced compromise.
- c.) Record batch numbers and check for batch approval.
- d.) Examination of thinner (solvent) for suitability, sample if necessary.
- e.) Inspection of boxing and mixing procedure, sample if necessary.
- f.) Verification of addition of thinners and thinning ratios. Recalculation of theoretical wet film thickness required to achieve specific dry film build after thinning.
- g.) Check contractor's tips for wear, check lines and equipment.

### 2.) During Operation

- a.) Monitor climatic conditions.
- b.) Verify in-pot agitators are in place and working during use.
- c.) Verification of application process, adequate rigging, correct technique, number of passes, etc., freedom from dry spray, bubbling, sagging, etc.
- d.) Monitor wet film thickness and counsel contractor on expected dry film thickness with reference to the specification.
- e.) Sample if necessary.
- f.) Record date and times of start and finish of priming operation.
- g.) Ensure that correct induction times are observed and that no paint is applied beyond an allowable pot life (may be particularly important where pot life termination does not result in high viscosity increase and gelation, i.e. wash primer, etc.).

### 3.) After Operations

- a.) Check film cure, quality and thickness.
- b.) Mark up holidays, skips, and thin spots for touch-up or application of make-up coat.
- c.) Mark up runs, sags, wrinkled and/or mudcracked areas, and other areas of deficiencies for rectification.
- d.) Mark up areas of excessive film thickness for engineer's judgement on acceptability.
- e.) Mark up areas of excessive film contamination including zinc salting for cleaning prior to application of mid or finish.
- f.) Ensure proper procedures (including surface preparation and coating type) are known and fulfilled by applicator in application of make-up coat or touch-up.
- g.) Monitor and record time, material, manpower and equipment used (especially when addressing rectification of any extraordinary condition that may fall outside scope of specification).

## INSPECTION REQUIREMENTS:- INTERMEDIATE, MID OR TIE COATING

### 1.) Before Operation

- a.) Verify that all required touch-up of primer has been successfully completed.
- b.) Verification that condition of primed surface in general and in touch-up areas is suitable for recoating (adequately cured, adhesive, free of contamination, etc.).
- c.) Verification and recording of existing climatic conditions as suitable for coating application.
- d.) Review of weather forecasts and determination of reasonable probability that new coat will safely cure without weather change induced compromise.
- e.) Record batch numbers and check for batch approval.
- f.) Examination of thinning solvent for suitability, sample if necessary.
- g.) Inspection of boxing and mixing procedure, sample if necessary.
- h.) Verification of addition of thinner and thinning ratios (recalculate theoretical wet film thickness range requirements to achieve dry film build as per specification).
- i.) Check tips for wear, check lines and equipment.
- j.) Verify that contractor's recoat schedules are in compliance with specification (N.B. Ensure that touch-up areas as well as general sections have been given adequate time to cure).

### 2.) During Operation

- a.) Monitor climatic conditions.
- b.) Verify in-pot agitators (if applicable) are in place and working during application.
- c.) Verification of application process, adequate rigging, correct application techniques, number of passes, freedom from dry spray, sagging, etc..
- d.) Ensure that any zot coat or mist coating operation is performed according to manufacturer's requirements regarding the amount and type of dilution, the film thickness, and the interval between the zot or mist coat and full coat application, etc..
- e.) Check wet film thickness and counsel contractor on expected dry film thickness with reference to the specification.
- f.) Sample coatings if necessary.
- g.) Record data and time of start and finish of midcoat operations.
- h.) Ensure the correct induction times are observed and that no paint is applied beyond the allowable pot life (may be particularly significant where pot life termination does not result in high viscosity increase and gelation- i.e. wash primer).

### 3.) After Operation

- a.) Check film for cure, quality and film thickness (use Tooke gauge for repeated checks of magnetic type on multi-coat systems).
- b.) Mark up holidays, skips, thin spots for touch-up or application of a make-up coat.
- c.) Mark up runs, sags, wrinkled, bubbled, pinholed and other areas of deficiency for rectification.
- d.) Mark up areas of excessive film thickness for engineer's judgement on acceptability.
- e.) Mark up areas of excessive contamination for cleaning prior to finish coating.
- f.) Ensure that proper procedures (including surface preparation and coating type) are known and followed by applicator in application of make-up or touch-up coat.
- g.) Monitor and record time, materials, manpower and equipment used (especially when addressing rectification of any extraordinary condition that may fall outside the scope of the specification).

## INSPECTION REQUIREMENTS:-FINISH COATS

### 1.) Before Operation

- a.) Verify that all required touch up of previous coats has been successfully completed.
- b.) Verification that condition of coated surface in general and in touch-up areas is suitable for recoating (adequately cured, adhesive, free of contamination, etc.).
- c.) Verification and recording of existing climatic conditions as suitable for coating application.
- d.) Review of weather forecasts and determination of reasonable probability that new coat will safely cure without weather change induced compromise.
- e.) Record batch numbers and check for batch approval.
- f.) Examination of thinning solvent for suitability, sample if necessary.
- g.) Inspection of boxing and mixing procedure, sample if necessary.
- h.) Verification of addition of thinner and thinning ratios (recalculate theoretical wet film thickness range requirements to achieve dry film build as per specification).
- i.) Check tips for wear, check lines and equipment.
- j.) Verify that contractor's recoat schedules are in compliance with specification (N.B. Ensure that touch-up areas as well as general sections have been given adequate time to cure).

### 2.) During Operation

- a.) Monitor climatic conditions.
- b.) Verify in pot agitators (if applicable) are in place and working during application.
- c.) Verification of application process (adequate rigging, correct application techniques, number of passes, freedom from dry spray, bubbling, frothing, sagging, flooding and floatation of color, etc.).
- d.) Check wet film thickness and counsel contractor on expected dry film thickness range with reference to specification.
- e.) Sample coating if necessary.
- f.) Record date and time of start and finish of topcoat application.
- g.) Ensure that correct induction times are observed and that no paint is applied beyond allowable pot life.

### 3.) After Operations

- a.) Check film for cure, quality, film thickness (use Tooke gauge for repeated checks of magnetic film thickness gauge on multi-coat systems).
- b.) Check total system for adhesive and cohesive integrity.
- c.) Verify uniformity of color and gloss. Mark up deficient areas for recoating.
- d.) Mark up holidays, skips, and thin spots for touch-up or application of a make-up coat.
- e.) Mark up runs, sags, wrinkles, frothed, bubbled, pinholed and other areas of deficiency for rectification.
- f.) Mark up areas of excessive film build for engineer's judgement on acceptability.
- g.) Ensure that proper procedures (including surface preparation) are known and followed by the applicator in the application of touch-up and make-up coats.
- h.) Verify that total film thickness of coating system is in compliance with the specification.
- i.) Monitor and record time, materials, manpower and equipment used (especially when addressing rectification of any extraordinary condition that may fall outside the scope of the specification).

## APPENDIX B

## COATING SYSTEMS FOR STEEL BRIDGES—SERVICE COMPARISON

## COATING SYSTEMS FOR STEEL BRIDGES - SERVICE COMPARISON

## (INHIBITIVE COATING SYSTEMS)

SYSTEM GROUP	SYSTEM DESCRIPTION (Primer / Intermediate / Finish)	SURFACE PREPARATION SSPC-SP	FILM THICKNESS Dry Mills	RESISTANCE TO WATER	RESISTANCE TO U.V.	RESISTANCE TO ALKALIES	RESISTANCE TO ACIDIC POLLUTANTS	RESISTANCE TO ABRASION AND IMPACT	SERVICE IN ENVIRONMENT 1B DRY EXTERIOR Years	SERVICE IN ENVIRONMENT 2A FRESH WATER WET Years	SERVICE IN ENVIRONMENT 2B SALT WATER WET Years
I	Pr. Red Lead / Linseed Oil Int. Red Lead-Iron Oxide / Oil-Alkyd Fin. Alum. / Alkyd or Phenolic Fin. (Alt.) BLSC / Oil-Alkyd	2	2.0 1.5 1.0 1.0	Good	Good	Poor	Good	Fair	30	15	10
II	Pr. Zinc Chromate / Alkyd Int. Zinc Chromate / Alkyd Fin. Alum. / Alkyd or Phenolic Fin. (Alt.) BLSC / Oil-Alkyd	3 or 7	2.0 1.5 1.0 1.0	Good	Good	Fair	Fair	Good	25	13	8
III	Pr. BLSC / Linseed Oil-Alkyd Int. BLSC / Linseed Oil-Alkyd Fin. BLSC / Linseed Oil-Alkyd	3 or 7	2.0 1.5 1.5	Good	Good	Fair	Fair	Good	30	15	10
IV	Pr. Non-Toxic Inhib. / Oil-Alkyd Int. Non-Toxic Inhib. / Oil-Alkyd Fin. Non-Toxic Inhib. / Oil-Alkyd Fin. (Alt.) Alum. / Alkyd or Phenolic	6	2.5 2.5 2.0 2.0	Good	Good	Fair	Poor	Good	20 P 22 P	10 P 12 P	6 P 8 P
V	Pr. Inhibitive Latex Int. Inhibitive Latex Fin. Non-Inhibitive Latex (2 Coats) Fin. (Alt.) Non-Inhibitive Latex Aluminum / Latex.	6	2.0 2.0 3.5 1.5	Fair	Very Good	Fair	Poor	Fair	20 P	10 P	6 P
									P Projected Service Life		

**COATING SYSTEMS FOR STEEL BRIDGES - SERVICE COMPARISON**

**(ZINC BASED SYSTEMS)**

SYSTEM GROUP	SYSTEM DESCRIPTION (Primer / Intermediate / Finish)	SURFACE PREPARATION SSPC-SP	FILM THICKNESS Dry Mills	RESISTANCE TO WATER	RESISTANCE TO U.V.	RESISTANCE TO ALKALIES	RESISTANCE TO ACIDIC POLLUTANTS	RESISTANCE TO ABRASION AND IMPACT	SERVICE IN ENVIRONMENT 1B DRY EXTERIOR Years	SERVICE IN ENVIRONMENT 2A FRESH WATER WET Years	SERVICE IN ENVIRONMENT 2B SALT WATER WET Years
VIA	Pr. Alkyl Silicate Zinc Fin. High Build Vinyl	10	3 5	Excellent	V. Good	Excellent	Excellent	V. Good	40 p	25 p	15
VIB	Pr. Alkyl Silicate Zinc Int. WP-1 Vinyl Wash Primer Fin. High Build Vinyl.	10	3 0.3 5	Excellent	V. Good	Excellent	Excellent	V. Good	40 P	25 P	15
VIC	Pr. Alkyl Silicate Zinc Int. Epoxy/Polyamide (High Build) Fin. Aliphatic Urethane	10	3 4 2	Excellent	Excellent	Excellent	Excellent	Excellent	40 P	25 P	17 P
VID	Pr. Alkyl Silicate Zinc Int. Epoxy/Polyamide (High Build)	10	3 5	Excellent	Fair-Good	Excellent	V. Good	Excellent	40 P	25 P	16 P
VIE	Pr. Alkyl Silicate Zinc Int. High Build Aliphatic Urethane	10	3 4	Excellent	Excellent	Excellent	Excellent	Excellent	40 P	25 P	15 p
VIIA	Pr. Alkaline Silicate Zinc Int. WP-1 Vinyl Wash Primer Fin. Vinyl	10	3 0.3 2	Excellent	V. Good	Excellent	Excellent	V. Good	40 P	25 P	15
VIIIB	Pr. Alkaline Silicate Zinc Int. Vinyl Fin. Vinyl	10	3 1 1.5	Excellent	V. Good	Excellent	Excellent	V. Good	40 P	25	15
VIIIA	Pr. Phenoxzy Zinc Int. WP-1 Vinyl Wash Primer Fin. Vinyl	6	3 0.3 5	Excellent	V. Good	Excellent	Excellent	V. Good	35 p	13	10
VIIIB	Pr. Phenoxzy Zinc. Int. Epoxy/Polyamide (High Build) Fin. Aliphatic Urethane.	6	3 4 1.5	Excellent	Excellent	Excellent	Excellent	Excellent	35 P	13 P	10 P
IX	Pr. Chlor. Rubber Zinc. Int. Chlor. Rubber High Build Fin. Chlor. Rubber Finish	6	3 3.5 2	Excellent	V. Good	Excellent	Excellent	V. Good	35 p	15 p	10 p

P Projected Service Life

**COATING SYSTEMS FOR STEEL BRIDGES - SERVICE COMPARISON**  
**(ZINC BASED SYSTEMS)**

SYSTEM GROUP	SYSTEM DESCRIPTION (Primer / Intermediate / Finish)	SURFACE PREPARATION SSPC-SP	FILM THICKNESS Dry Mills	RESISTANCE TO WATER	RESISTANCE TO U.V.	RESISTANCE TO ALKALIES	RESISTANCE TO ACIDIC POLLUTANTS	RESISTANCE TO ABRASION AND IMPACT	SERVICE IN ENVIRONMENT 1B DRY EXTERIOR Years	SERVICE IN ENVIRONMENT 2A FRESH WATER WET Years	SERVICE IN ENVIRONMENT 2B SALT WATER WET Years
X	Pr. Vinyl Zinc Rich Int. Vinyl Fin. Vinyl	10	2.0 3.0 3.0	Excellent	V. Good	Excellent	Excellent	V. Good	35 P	20 P	12 P
XIA	Pr. Epoxy/Polyamide Zinc Rich Int. Epoxy/Polyamide Midcoat Fin. Epoxy/Polyamide Finish	10	3.0 4.0 2.0	Excellent	Fair-Good	Excellent	V. Good	Excellent	35 P	20 P	12 P
XIB	Pr. Epoxy/Polyamide Zinc Rich Int. Epoxy Polyamide Zinc Rich Fin. Vinyl Aluminum	10	3.0 1.5 3.0	Excellent	Excellent	Fair	Fair	V. Good	35 P	20 P	12
XIC	Pr. Epoxy/Polyamide Zinc Rich Int. Epoxy/Polyamide Red Lead (Marine Envir. Only) Fin. Vinyl Toluene/Acrylic Finish	10	3.5 1.5 1.5	Excellent	V. Good	Excellent	V. Good	V. Good	35 P	20 P	12
XIIA	Pr. Unalkyd Zinc Rich (2 Coats) Fin. Vinyl Toluene/Acrylic	10	3.5 1.5	Excellent	V. Good	Excellent	V. Good	V. Good	30 P	15 P	10
XIIB	Pr. Moist. Cure. Urethane Zinc Int. Epoxy/Polyamide Midcoat Fin. Aliphatic Urethane Finish	6	2.0 2.0 2.0	Excellent	V. Good	Fair	Fair	Excellent	35 P	25 P	12 P
XIII	Pr. Galvanizing	8		Excellent	Excellent	Good (pH 9.5)	Fair-Poor	Excellent	35	25	10
XIIIA	Pr. Galvanizing Int. WP-1 Vinyl Wash Primer Fin. Vinyl	8	0.3 5.0	Excellent	V. Good	Excellent	Excellent	V. Good	40 P	30 P	18 P
XIIIB	Pr. Zinc Metallizing Fin. Vinyl (Carboxylated)	5	8.0 2.0	Excellent	V. Good	Excellent	Excellent	V. Good	40 P	25 P	15 P
XIIIC	Pr. Zinc Metallizing Int. WP-1 Vinyl Wash Primer Fin. Vinyl (Hydroxylated)	5	8.0 0.3 2.0	Excellent	V. Good	Excellent	Excellent	V. Good	40 P	25 P	15 P

P Projected Service Life

**COATING SYSTEMS FOR STEEL BRIDGES - SERVICE COMPARISON**

**(BARRIER SYSTEMS)**

SYSTEM GROUP	SYSTEM DESCRIPTION (Primer / Intermediate / Finish)	SURFACE PREPARATION SSPC-SP	FILM THICKNESS Dry Mills	RESISTANCE TO WATER	RESISTANCE TO U.V.	RESISTANCE TO ALKALIES	RESISTANCE TO ACIDIC POLLUTANTS	RESISTANCE TO ABRASION AND IMPACT	SERVICE IN ENVIRONMENT 1B DRY EXTERIOR Years	SERVICE IN ENVIRONMENT 2A FRESH WATER WET Years	SERVICE IN ENVIRONMENT 2B SALT WATER WET Years
XIVA	Pr. Vinyl (Carboxylated) Int. Vinyl (2 - 5 Coats) Fin. Vinyl	10	1.5 1.5 (x3) 1.5	Excellent	V. Good	Excellent	Excellent	V. Good	40 p	25	15
XIVB	Pr. WP 1 Vinyl Wash Primer Int. Vinyl (Hydroxylated) plus (2 - 4 additional Ints.) Fin. Vinyl	10	0.3 1.5 (x3) 1.5	Excellent	V. Good	Excellent	Excellent	V. Good	40 p	25	15
XV	Pr. Chlor. Rubber Primer Int. Chlor. Rubber Mid. Fin. Chlor. Rubber Fin.	6	1.5 3.0 1.5	Excellent	V. Good	Excellent	Excellent	V. Good	35 P	20 P	12
XVIA	Pr. Epoxy/Polyamide Int. Epoxy/Polyamide Fin. Epoxy/Polyamide	6	2.5 2.5 2.0	Excellent	Fair-Good	Excellent	V. Good	Excellent	35 P	25 P	12
XVIIA	Pr. Aluminized Epoxy Mastic	7	5.0	Excellent	V. Good	Excellent	V. Good	Excellent	10 P	7	4
XVII B	Pr. Aluminized Epoxy Mastic Fin. Aluminized Epoxy Mastic	7	5.0 5.0	Excellent	V. Good	Excellent	V. Good	Excellent	25 P	15	10
XVII C	Pr. Aluminized Epoxy Mastic Fin. Epoxy/Polyamide Color Coat	7	5.0 5.0	Excellent	Good	Excellent	V. Good	Excellent	25 p	13 P	8 P
XVIIIA	Pr. Moist. Cure Urethane Alum Int. Moist. Cure Urethane Alum. Fin. Moist. Cure Urethane Alum.	6	2.5 2.5 2.5	Excellent	V. Good	V. Good	V. Good	Excellent	10 p	7	4
XVIIIB	Pr. Moist. Cure Urethane Alum Int. Moist. Cure Urethane Alum Fin. Aliphatic Urethane Color Coat	6	2.5 2.5 2.0	Excellent	Excellent	Excellent	Excellent	Excellent	15 p	10 P	8 P
XIX	Pr. Coat-Tac Epoxy Fin. Coat-Tac Epoxy	10	8.0 8.0	Excellent	Poor	Excellent	Excellent	Excellent	40 p	30 P	15.

P = Projected Service Life

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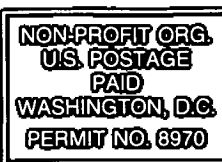
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