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Developing High Quality Coatings

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Evaluation of Abrasion-Resistant Metallized Coatings for Civil Works Applications

by
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Vinyl coatings have been commonly used to protect U.S. Army Corps of Engineers hydraulic structures since the early 1950s. Under normal service conditions, vinyl coatings can protect the substrate for 30 years or longer. But vinyls exposed to very high abrasion fail completely in 12 to 24 months. The U.S. Army Construction Engineering Research Laboratory (USACERL) tested metallized coatings--much harder than conventional organic paints--in a highly abrasive environment to evaluate durability and corrosion resistance. Aluminum-bronze alloy, stainless steel, zinc, and zinc-aluminum alloy were applied by thermal spray to tainter gate No. 5 at Belleville Locks and Dam on the Ohio River. Results indicated excellent performance for the zinc and zinc-aluminum alloy coatings. However, aluminum-bronze and stainless steel coatings showed early signs of failure because of galvanic corrosion.

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FOREWORD

This study was conducted for the Electrical and Mechanical Branch, Engineering Division, Directorate of Civil Works, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Investigations and Studies (CWIS) Work Unit 31205, "Developing High Performance Coatings." Field application of coatings was also supported by U.S. Army Engineer District, Huntington. The Technical Monitor was Bob Pletka, CECW-EE.

This research was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. R. Quattrone is Chief of USACERL-EM.

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EVALUATION OF ABRASION RESISTANT METALLIZED COATINGS FOR CIVIL WORKS APPLICATIONS

1 INTRODUCTION

Background

Prior to World War II the U.S. Army Corps of Engineers (USACE) had established an extensive navigation system along the Ohio River. That system, which consisted of 53 lock and dam facilities, allowed navigation from Pittsburgh, PA, downriver to the confluence of the Ohio and Mississippi Rivers, near Cairo, IL. Beginning in the 1950s the original system of locks and dams was augmented by the construction of 18 modern locks and dams (Figure 1). Only two of the old facilities are still in operation. The newer dams, from Emsworth downriver to Smithland, together traverse a total river elevation of just over 400 ft*, averaging about 22 ft per dam. This is a much greater pool elevation change than occurred with the old dams, which averaged just 8 ft.

The new dams generated design constraints which have led to unforeseen maintenance problems. For example, water flowing under tainter gates of the new dams may attain velocities of over 35 ft per second.² To alleviate undertow and turbulence downstream of the high-lift dams, submerged baffles were located downstream of each tainter gate. The baffles create a hydraulic affect against the downstream tainter skinplates. This flow recirculates debris and suspended particles against the skinplates. Large debris such as logs several feet in a diameter and home appliances are common (Figure 2).

The high water velocities coupled with river debris and suspended particles such as river sand result in a highly abrasive environment, one in which standard USACE vinyl coatings formulated for river environments rapidly erode. Coating failure and substrate corrosion typically occur in 1 to 2 years (Figure 3).³

A further indication of the severity of abrasion on Ohio River lock and dam facilities is the longevity of USACE vinyl paint systems on Mississippi River lock and dam facilities. USACE vinyls were first applied along the Mississippi in 1950 the Red lead vinyl primer, with vinyl intermediate and topcoat system, was not repainted at Lock and Dam 23 at Hannibal, MO, until 1981. The interior of the gate, which experiences no abrasion, was inspected and returned to service at that time.⁴ Abrasion on the Mississippi River results mainly from iceflow during the winter months, but the abrasion at Greenup Locks and Dam on the Ohio River is estimated to be about 15 times as severe as that occurring at a typical Mississippi River Dam.⁵ This difference is due mainly to the different design features of Ohio and Mississippi River dams.

*Metric conversion table is on page 34.

²R. Weber, M. Brandt, T. Race, I. Calace, J. Rigsbee, and V. Hock, "An Evaluation of Metallic and Nonmetallic Coatings and Test Procedures for Erosion/Corrosion Conditions at Lock and Dam Structures," in E.L. Houch (Ed.), *Thermal Spray: Advances in Coating Technology: Proceedings of Thermal Spray Conference* (ASM International, 1988).

³A. Beitelman, *Test Coatings--Greenup Lock and Dam*, USACERL-EM Memorandum for Record (September 1981).

⁴R. Martell and A. Yee, "Vinyl Paints and Systems," *Journal of Protective Coatings and Linings*, Vol 5, No. 9 (September 1988).

⁵A. Beitelman (September 1981).

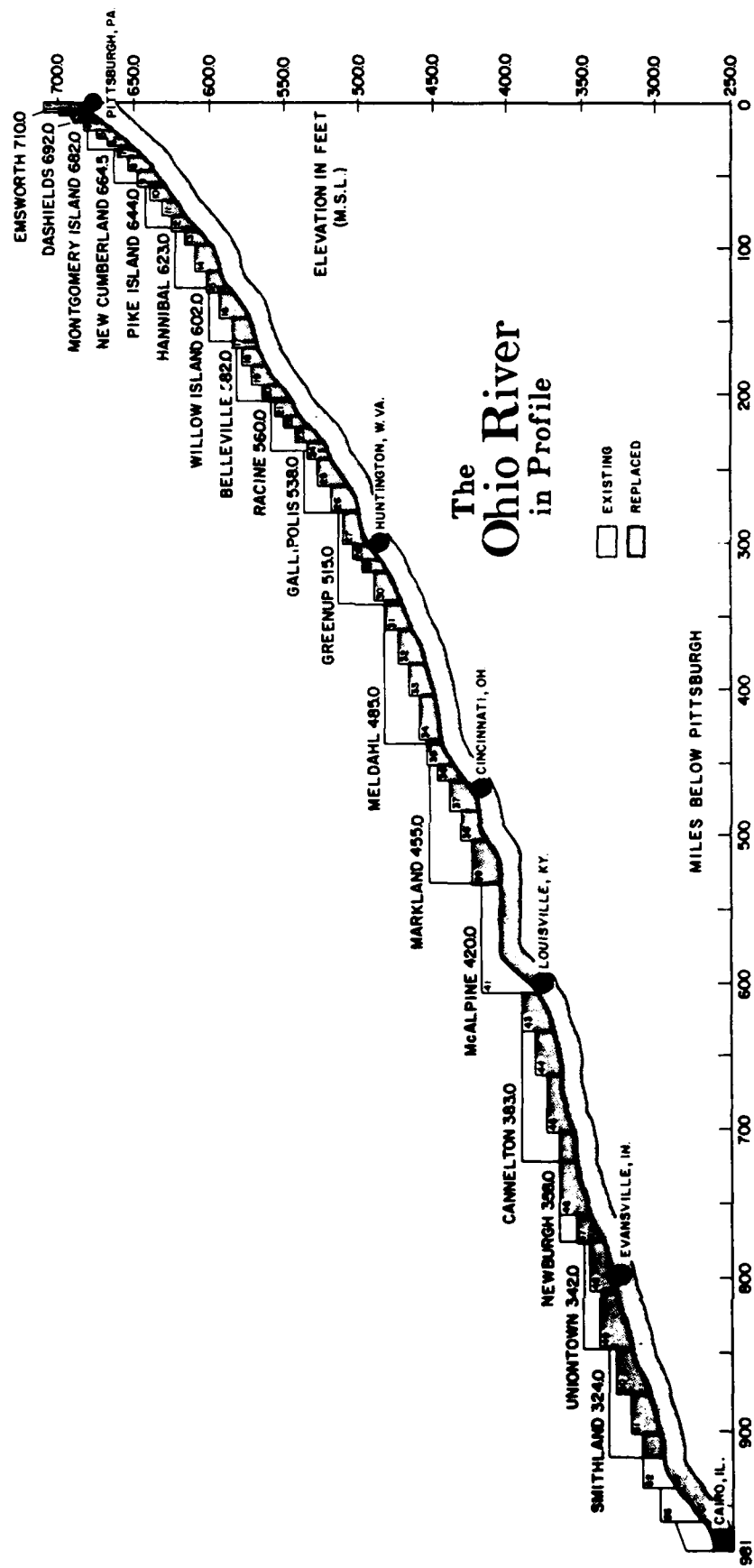


Figure 1. Ohio River Locks and Dams.

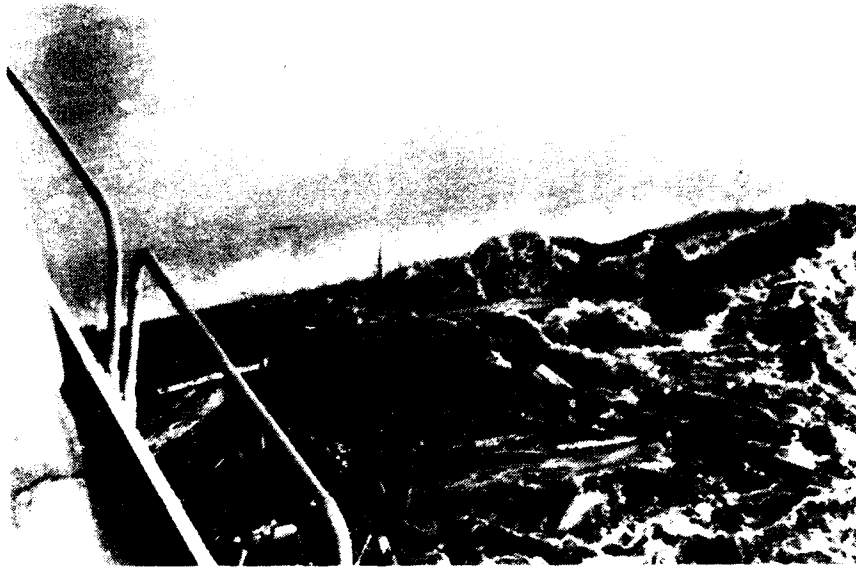


Figure 2. Large debris against downstream skinplates.



Figure 3. Coating failure and substrate corrosion.

Abrasion-resistant coating systems have previously been tested on Ohio River dams.⁶ Several coating systems were applied to a tainter gate at Greenup Locks and Dam in 1980. (These coating systems are summarized in Table 1.) The results were as follows:

1. The urethane laminate was applied using a squeegee and industrial heat gun. This material lost adhesion and was totally removed in less than 3 months, leaving only the vinyl primer.

2. The elastomeric urethane was applied by airless spray. Making repeated passes over the substrate achieved thick coating levels. Performance was dependent on coating thickness but not on type of primer. The 25 mil film was totally removed in less than 1 year. The 50 mil urethane coating was about 50 percent removed in 1 year. The 75 and 80 mil thickness showed deep cuts and small areas of exposed primer after 1 year.

3. The vinyl system employing a garnet abrasive material as a hardener was somewhat more successful than the control vinyl without garnet. Total failure occurred after approximately 2 years, while the control experienced severe corrosion after only 1 year.

In addition, stainless steel cladding has been used in areas of high abrasion.⁷ Pittsburgh District applied stainless steel cladding to the lower upstream portions of tainter gates at several locations. The stainless steel is very resistant to mechanical damage. But cladding sections typically have to be extended upward as galvanic corrosion occurs at paint film defects adjacent to the cladding. Also, severe pitting corrosion has been observed where cladding is used (Figure 4).

Because of the failures of vinyl coating systems and stainless steel cladding, the U.S. Army Construction Engineering Research Laboratory (USACERL) conducted a study to evaluate the durability and corrosion resistance of metallized coatings.

Objective

The objective of this study is to evaluate thermal spray metallized coating processes and materials for the abrasion and corrosion protection of ferrous metal substrates in freshwater immersion.

Approach

Materials selection criteria for metallizing and subsequent sealing were established. Metals and sealers were selected based on established criteria, a review of available literature, and USACE experience. Methods of application of metallized coatings were evaluated. Special attention was given to ease of application in the field and application rates at Belleville Locks and Dam. Metallized coatings were field applied and periodically evaluated for abrasion and corrosion resistance. Finally, a test method for comparison of relative corrosion/erosion resistance was developed.

⁶A. Beitelman (September 1981); A. Beitelman, *Application of Test Coatings - Greenup Locks and Dam*, USACERL-EM Memorandum for Record (July 1980).

⁷A. Beitelman, *Inspection of Coatings for Pittsburgh District*, USACERL-EM Memorandum for Record (June 1983).

Table 1
Abrasion-Resistant Coating Systems at Greenup

Primer	Topcoat	Dry Film Thickness (Mils)
Vinyl (V-766e)	Urethane laminate	23
Polyvinyl-polyurethane	Urethane elastomer	23, 45, and 80
Vinyl (V-766e)	Urethane elastomer	25, 50, and 75
Vinyl (V-766e)	Vinyl with garnet grit (V-106d)	8

Mode of Technology Transfer

Results of field experiments will continue to be monitored and if warranted the results of this effort will be incorporated into a Civil Works draft guide specification for the application of metallized coatings to hydraulic structures. This specification would address safety surface preparation, materials, application, quality control, and inspection for thermal spray metallic coatings.



Figure 4. Pitting corrosion on cladding section.

2 METALLIZED COATING SELECTION

Selection Criteria

Metallized coatings were first applied during FY86 and again in FY87. Selection criteria were modified slightly after inspection of coatings applied in FY86.

The original metallized coating selection criteria were as follows: hardness, adhesion to steel, commercial availability, and corrosion resistance of applied material. After initial field tests in FY86, metallized coating materials were selected based on their anodic (sacrificial) properties when applied to mild steel immersed in freshwater.

Metallic Coatings Selected

Metallic coating systems were selected for application at Belleville Locks and Dam near Parkersburg, WV, U.S. Army Engineer District, Huntington.⁷ Of the original five coatings selected, only three were applied. Aluminum-bronze, 18-8 stainless steel, 17-12 stainless steel (not applied), Monel 400 (not applied), and zinc were the original materials selected. An 85-percent zinc/15-percent aluminum alloy was added as the selection criteria were revised. Monel 400 and 17-12 stainless steel were not applied because of lessons learned from the observed performance of aluminum-bronze and 18-8 stainless steel coatings. These coatings are cathodic to mild steel and premature coating failures were observed after less than a year of service.

Aluminum-Bronze

The aluminum-bronze alloy selected had a nominal composition of 10 percent aluminum, 89 percent copper, and 1 percent iron.⁸ Aluminum-bronzes containing 5 to 12 percent aluminum have excellent corrosion resistance and have been used in applications requiring abrasion resistance.⁹ Aluminum is added to copper to stabilize the corrosion product as a barrier film.¹⁰ The compositional requirements of this material are described in Military Specification Mil-W-6712C, Wire, Metallizing. This material is a readily available commercial product.

Stainless Steel

Stainless steels are well known for their corrosion resistance to freshwater, saltwater, and chemical solutions. Austenitic stainless steels such as 18-8 and 17-12 have demonstrated excellent resistance to impingement attack in a seawater jet.¹¹ Because of its excellent resistance to cavitation erosion, 18-8 stainless steel has been used on sonar domes.¹² Stainless steel wires (18-8 and 17-12) are described in Mil-W-6712C and are commercially available.

⁷Request for Proposal (RFP) No. DACW69-86-R-0043, "Specifications, Metallized Coating and Painting, Tainter Gate No. 5, Belleville Locks and Dam, Ohio River" (U.S. Army Corps of Engineers, Huntington District, April 1986).

⁸RFP No. DACW69-86-R-0043.

⁹*Metals Handbook (9th Ed.)*, Vol 2, *Properties and Selection: Nonferrous Alloys and Pure Metals* (American Society for Metals, 1979).

¹⁰K.N. Strafford, P.K. Datta, and C.G. Googan (Eds.), *Coatings and Surface Treatments for Corrosion and Wear Resistance* (Institution of Corrosion Science and Technology, 1984).

¹¹*Metals Handbook (9th Ed.)*, Vol 3, *Properties and Selection of Stainless Steels, Tool Materials and Special Purpose Metals* (American Society for Metals, 1979).

¹²*Metals Handbook (9th Ed.)*, Vol 3.

Monel 400

Monel 400, a copper-nickel alloy, is commercially available as metallizing wire. Its composition is described in Mil-W-6712C. The alloying of copper and nickel promotes the formation of a passive barrier layer which stabilizes the material.¹³ Typical uses of Monel 400 are propeller shafts and marine fasteners.¹⁴ Monel 400 has good resistance to both freshwater and saltwater.

Zinc

Zinc as a metallizing material has a long history. Zinc coatings were flame sprayed on bridges before 1920. USACE first evaluated zinc metallizing on Mississippi River Dam No. 15 in 1939.¹⁵ Zinc is sufficiently anodic to steel to be sacrificial, and it readily forms a protective passive barrier film composed primarily of zinc carbonate. However, compared to Monel 400 or stainless steels, zinc metallizing does not provide a particularly hard surface.

85-15 Zinc-Aluminum

Suggested as superior to either pure aluminum or zinc is 85-15 zinc-aluminum alloy.¹⁶ The aluminum raises the density of the applied material and assists in the formation of a protective barrier oxide or patina. Zinc-aluminum alloys are not as hard as copper-nickel alloys or stainless steels, but 85-15 zinc-aluminum will sacrificially protect mild steel, as well as acting as a protective barrier.

¹³K.N. Strafford et al.

¹⁴*Metals Handbook* (9th Ed.), Vol 2.

¹⁵*Treatise on Corrosion Resistance of Coatings for Lock and Dam Protection* (U.S. Engineer Office, Rock Island, IL, March 1939).

¹⁶H. Nagasaka et al., "Weathering Test on Zn, Al, Zn-Al Alloy Sprayed Coating for 5000 Days," *Metallize*, Vol 3, No. 1 (January 1987); T.W. Gardega, V. Lanza, and A.H. Roebuck, "Thermal Spray Coats," *Journal of Protective Coatings and Linings* (January 1986).

3 SEALER COATING SELECTION

Sealing Metallized Coatings

Organic sealers may be used with metallized coatings to form a synergistic system which can outperform the sum of the parts. This is especially true of anticorrosive metallizing systems for marine and industrial atmospheres.

The need for organic sealers arises because of the porosity of metallized coatings and the need to protect the coating and substrate from the environment. The density of sprayed metals is typically 85 to 95 percent of the density of the wire from which it was sprayed. The total oxide included in the sprayed film accounts for only 0.5 to 3.0 percent. By far the greatest lowering of the density is due to the characteristic porosity of sprayed metal coatings. Thicker metallized films typically in excess of 10 mils should be less prone to substrate corrosion due to moisture migration through pores. Metallized films of aluminum, zinc, and lead in the range of 5 to 9 mils are sufficient to prevent access to the substrate through continuous pores.¹⁷ However, certain metals, such as zinc, aluminum and zinc-aluminum alloys, may have reduced porosities due to the formation of protective oxides upon weathering.

Extensive experimental and field testing with sealers has been performed. Many sealers have been evaluated: epoxies, alkyds, urethanes, phenolics, and vinyls. In general, the sealer system selected should be appropriate for the intended exposure, independent of the metallizing. For example, marine coatings are appropriate for sealing metallized coatings in marine environments. In addition, copper, aluminum, zinc, and stainless steel substrates may require surface pretreatment to achieve adhesion of the sealer. Initial sealer coats should be applied at low viscosity and should flow readily to penetrate the porous metallized surface. Spray, brush, and roller are all suitable means of applying sealers; sealer topcoats may be applied at normal viscosities.

Sealer Selection Criteria

The selection criteria for sealers applied at Belleville Locks and Dam were basic. The most important criterion was that the coating sealer system be compatible with the intended exposure, namely, freshwater immersion. Selected sealers also exhibited a high degree of adhesion to the applied metal and were thinnable to the extent that they flowed readily and filled the pores of the metallized coating. It was also considered desirable that the sealer material be described by a USACE, industry, or other standard specification.

Selected Sealer Systems

Three basic sealer systems were selected for application to the stainless steels and aluminum-bronze. One very simple sealer system was selected for application to both 85-15 zinc-aluminum and pure zinc metallizing. Table 2 lists the sealer systems intended for each metallized coating.

¹⁷R.M. Burns and W.W. Bradley, Eds., *Protective Coatings for Metals (3rd Ed.)* (Reinehold, 1967).

Table 2
Sealer Systems

Metallized Coating Sealed	Paint Formulas Applied
Aluminum-bronze, stainless steels	Mil-P-24441 (epoxy polyamide)
Aluminum-bronze, stainless steels	V-766e (gray vinyl)
Aluminum-bronze, stainless steels	Steel Structure Painting Council (SSPC)
	Paint 27/SSPC Paint 9/V-766e
	(vinyl butyral wash primer/vinyl/vinyl)
85-15 zinc-aluminum, zinc	SSPC Paint 27 (vinyl butyral wash primer)

4 APPLICATION METHODS FOR METALLIZED COATINGS

Arc Spraying

In the arc spray process, metal wire is melted in an electric arc. The molten metal is atomized with a stream of compressed air and deposited on the substrate, where it cools and solidifies into a continuous coating. The power supply for arc spraying is similar to that used in an AC (alternating current) arc welder. High current at low voltage is supplied and may be adjusted to regulate application properties. Wire is fed to the arc spray gun using twin spools. As the wire ends approach contact, an electric arc is struck that melts the wire. Other application variables are atomization air pressure, gun-to-surface distance, and rate of travel of the spray gun.

Arc spray is capable of high temperatures which will deposit molten particles with high heat content and fluidity. Some diffusion of substrate and applied metal into each other can occur, and very high bond strengths can result. Arc-sprayed aluminum coatings may have more than three times the bond strength of flame-sprayed aluminum when applied to mild steel.¹⁸ Production rates for arc spray and flame spray application of stainless steel are the same,¹⁹ but energy costs for arc spray are substantially lower than for all other forms of thermal spray metallizing.

Arc spraying produces continuous high-level noise of approximately 105 dB. Guidelines adopted by the American Conference of Governmental and Industrial Hygienists (ACGIH) place a threshold limit value of 1/2 hour per day for 105 dB, so workers and observers must use appropriate hearing protection.

Flame Spraying

Flame spraying employs an oxyacetylene or oxypropane flame to melt the feed stock, which may be wire, powder, or rod. Compressed air disperses the molten metal into droplets and propels it to the substrate, where it cools and solidifies. Flame temperature and material feed rate are varied according to the material applied. Gun-to-surface distance and rate of gun travel will effect application properties.

Production rates for powder and wire stock are similar, and improvements for powder flame spray have been fielded in recent years. Powder flame spray, however, can produce less dense coatings having lower bond strengths. Relative to other thermal spray methods, flame spray produces coatings which are more porous and less dense and have lower bond strength. The relatively light weight and small size of flame spray guns are advantageous for field use. Flame spray produces continuous noise levels in the 95 to 105 dB range, requiring the use of hearing protection for operators and observers.

Other Thermal Spray Processes

The detonation gun process employs, in effect, a small, rapidly firing cannon, which produces coatings with very high densities and bond strengths. The detonation gun produces very high noise levels; it must be used in a sound-insulated room.

¹⁸C.A. Meyer, "Thermal Spray Coating--A Money Saving Technology," *Welding Design and Fabrication* (February 1982).

¹⁹C.A. Meyer.

Plasma spray uses an inert gas ionized in an electric arc to form the plasma. Generally, plasma spray coatings are superior to flame-sprayed coatings. Plasma spray equipment is quite expensive; it is used only where the quality of the coatings can justify the capital outlays. Typically it is not used in field applications.

5 FIELD APPLICATION OF METALLIZED COATINGS AND SEALERS

Surface Preparation

The entire area to be metallized was given an initial blast cleaning with Ottawa silica sand to remove any remaining vinyl coating. This initial blasting was outside the original scope of work but was conducted as a cost-saving measure by the contractor. In addition, all areas to be metallized were blasted, not more than 4 hours prior to metallization, with an aluminum oxide abrasive supplied by the Detroit Abrasive Company and designated as 46-F. A White Metal grade in accordance with Steel Structure Painting Council-Surface Preparation 5 (SSPC-SP5) was achieved. Surface profile was specified in the range of 2 to 4 mils. Surface profile was verified using a Press-O-Film Tester. A surface profile comparator could also have been used. The abrasive-blasted substrate was cleaned by blowdown with clean, dry compressed air prior to metallizing.

Extent of Metallizing

Tainter gate No. 5 of Belleville Locks and Dam was metallized in part during the summer and fall 1986. Subsequent metallized coatings were applied in summer 1987.

An approximately 700-sq-ft area was metallized with each of four coatings. Aluminum-bronze alloy and 18-8 stainless steel were applied and sealed in 1986, and zinc and 85-15 zinc-aluminum were applied and sealed in 1987. Metallizing extended across the length of the gate from just above the downstream waterline to the bottom of the gate and 3 ft up the upstream skinplate.

Three sealer systems were applied to approximately equal areas of the 18-8 stainless steel and aluminum-bronze metallizing, and the 85-15 zinc-aluminum and pure zinc surfaces received only one sealer system each.

Quality Control

The contractor was required to submit field samples of metallized coatings and sealers for laboratory evaluation. They were also intended to serve as on-the-job quality standards.

Working samples were applied to 12 by 12 by 0.5 in. mild steel panels cleaned to SSPC-SP5 with a surface profile of 2 to 4 mils. Metallic coatings were applied according to contract specifications and evaluated for thickness and qualitative adhesion. Sealer systems were then applied to the panels per contract specifications.

Coating thicknesses were monitored during application in accordance with SSPC-PA (Paint Application) 2, using a dry-film magnetic thickness gauge and a plastic shim. The plastic shim was used to help average the surface roughness and provide more accurate results. Magnetic thickness gauges could not be used on the 18-8 stainless steel because of its magnetic properties. In this case the working sample served as the sole reference and standard for coating application. Thickness of stainless steel coating could be verified by removing a section and measuring with a micrometer.

Adhesion was qualitatively evaluated by cutting through the coating using a knife or chisel. If, after doing so, the coating or any part of it 1/2 sq in. or larger could be lifted from the substrate without actually cutting the metal away, the adhesion would be deemed unsatisfactory.

Application of Aluminum-Bronze

The aluminum-bronze coating was field applied using a two-wire arc spray gun manufactured by TAFA, Inc., of Concord, NH. Material was applied by blocking out a 4-sq-ft area on the substrate making parallel spray passes with a 25 to 50 percent overlap per pass. Successive coats needed to achieve the specified 10-to 15-mil thickness were applied at 90 degrees to the previous coat. Surface-to-gun distance was maintained at approximately 6 in. and gun speed at 3 to 6 in. per second. Production rates with no down time were estimated at 60 to 80 sq ft per hour. Three spray passes were needed to achieve the desired coating thickness. A 0.0625- to 0.125-in. spark gap was maintained between the two wires. Voltage was kept at 28 to 32 v.

Figure 5 shows the application of aluminum-bronze by two-wire arc at Belleville. The two-wire arc method produced a bright green light, necessitating the use of dark filters such as a welder would use. The process also produced a high level of noise. Observers and workers wore ear protection at all times while the two-wire arc gun was in use. The arc process also produced a significant quantity of smoke and metal fumes. The smoke caused considerable staining of areas adjacent to the metallizing gun, including the aluminum-bronze itself.

Coating thicknesses were measured with an assortment of gauges. An Elcometer "Inspector" gauge and a Positector 2000 yielded similar results. In addition to the magnetic thickness gauges, a micrometer was used to measure the thickness of coating applied to a 1- by 3-in. coupon taped to the skinplate. The thickness of the coupon was subtracted from the micrometer reading to obtain the coating thickness. This method consistently gave measurements 1 to 2 mils higher than the magnetic gauges. Actual measurements on the applied coating produced readings of 7 to 22 mils, with an average of 10 to 15 mils.

Wire feed problems were a major drawback in the application of the aluminum-bronze, and down time exceeded work time. The contractor suggested that the wire had been coiled improperly, causing twisting in the feeder tubes, but this claim was not substantiated. Noise levels were high enough to cause discomfort even with the use of ear plugs. One observer stationed in the work area reported symptoms of metal frame fever or temporary flu-like symptoms.



Figure 5. Two-wire arc coating application.

Application of 18-8 Stainless Steel

Initial wire feed problems with the arc gun were cleared up, and application proceeded rapidly. However, inclement weather caused considerable down time, and other metallizing sections were not completed until 1987.

Thickness measurements were determined employing the taped 1- by 3-in. coupons previously described. Magnetic thickness gauges cannot be used on stainless steels or other ferromagnetic metals. Coating thickness averaged 10 to 15 mils. General observations on sight and sound were similar to those made for application of aluminum-bronze.

Sealing Aluminum-Bronze and 18-8 Stainless Steel

Aluminum-bronze and 18-8 stainless steel coatings were each sealed and coated with three different systems (Table 2). All sealers and topcoats were applied using conventional air spray. Initial coats were applied at low viscosities to ensure good penetration. Topcoats were applied at normal viscosities. No special problems were encountered in the application of sealer and topcoat materials.

Application of 85-15 Zinc-Aluminum

Zinc-aluminum was applied using a Metco 12E wire flame spray gun (Figure 6), manufactured by Metco, Inc., Westbury, NY. The spray speed using acetylene gas with 0.125-in. wire was 25 lb per hour. Higher deposit rates may be achieved with 12E gun modifications. Relative gas flows were 45 oxygen at 30 psi, 42 acetylene at 15 psi, and 53 air at 70 psi. Flow rates were measured with a Metco 2GF flowmeter.

Wire flame spray with 85-15 zinc-aluminum is much less noisy than the two-wire arc process. The light produced by the process can be observed directly without discomfort. Much less smoking and metal fumes are created by this process than by electric arc spray. No occurrences of metal frame fever were noted during application of 85-15.

The large amounts of wire consumed during application necessitated a regular maintenance schedule for the 12E gun. The contractor dismantled, cleaned, lubricated, and replaced worn parts as needed every other day. Wire-feed problems were encountered when 0.1875-in. wire was used, and subsequently 0.125-in. wire was substituted with no problems.

Coating thickness was specified to be 10 to 15 mils. Measured values ranged from 12 to 25 mils. The average measured thickness was about 16 mils. Production rates averaged around 50 to 60 sq ft per hour.

Application of Zinc

Zinc was also applied using a Metco 12E wire flame spray gun. The spray speed using an oxyacetylene flame was 32 lb per hour. Relative gas flows were similar to those used for 85-15 zinc-aluminum, and 0.125-in. wire was used. Noise, smoke, fumes, and flame brightness were the same as for zinc-aluminum flame spray. Coating thickness was specified to be 10 to 15 mils. Measured values ranged from 12 to 24 mils, with an average thickness of about 17 mils. Production rates were about 50 to 60 sq ft per hour.

Sealing 85-15 Zinc-Aluminum and Zinc

Zinc and zinc-aluminum both were sealed using a two-component vinyl butyral pretreatment or wash primer conforming to SSPC Paint 27. This material consists of a vinyl butyral vehicle pigmented with zinc chromate as a base component. To this is added a solution of phosphoric acid. The acid serves as an etchant, the vinyl as a binder, and the zinc chromate as a corrosion inhibitor. The material was applied in a thin coat with brushes and rollers. The applied material had a patchy appearance and an olive green color when dried.



Figure 6. Wire flame spray gun coating application.

6 FIELD EVALUATION OF METALLIZED COATINGS AND SEALERS

Aluminum-Bronze

The sealed aluminum-bronze section has been inspected twice since being applied. Figure 7 shows a portion of the aluminum-bronze after 9 months of exposure on the downstream side of the tainter gate. The three sealer systems are clearly delineated in the photograph. Dark areas indicate the presence of corrosion products on the surface. (Aluminum-bronze and stainless steel coatings are cathodic to, and will corrode, mild steel substrate immersed in freshwater. It was hoped that the sealers selected would prevent water from reaching the substrate-metallized coating interface. That this was not the case is evident from the galvanic corrosion present.) One noteworthy defect is the long, horizontal corroded area in the three-coat V-766e-sealed section. Presumably this failure was caused by large debris, such as a tree, which cut through the sealer and some or all of the aluminum-bronze coating. There is pinpoint rusting in each of the sealed areas. Most of the corrosion is along the nose section or radius on the downstream skinplate, where the abrasion is the most severe. In one small area (about 9 sq in.) along the nose section, the aluminum-bronze delaminated, exposing the substrate. Delamination may have resulted from poor bond strength caused by surface contamination from moisture, flash rusting, or oil. Insufficient preheating of the substrate can also cause poor mechanical bonding of the coatings. In addition, poor blasting with a deficient surface profile can result in poor adhesion--high surface profile helps dissipate high shear stresses which form as sprayed coatings cool. Substrate corrosion may also have played a role in the coating delamination. This can occur as corrosion products expand to the greater volume they require.

The bay areas, formed by stiffeners at the bottom of the gate, showed very little corrosion. The small area metallized with aluminum-bronze on the upstream skinplate was in good condition, with only slight pinpoint rusting and no scratches.



Figure 7. Aluminum-bronze coated tainter gate section after 9 months.

Figures 8 and 9 depict approximately the same area as Figure 7 after 20 months of service. A general worsening of the overall condition is evident. Figure 10 shows the growth of the delaminated area, described above, after 20 months. After 20 months the bays and upstream skinplate continued to be in better overall condition than the radius and upper metallized portions.

Large areas of sealer were worn off in some areas, particularly along the nose section. The wash primer with vinyl topcoats exhibits areas of white and gray, evidence that the gray topcoat has eroded to expose the white intermediate coat. Portions of the metallized surface exhibit greater pinpoint rusting than do adjacent metallized areas. Thickness measurements indicated that these areas often correspond to areas of relatively thin metallizing.



Figure 8. Aluminum-bronze coated tainter gate section after 20 months.



Figure 9. Aluminum-bronze coated tainter gate section after 20 months--close up.



Figure 10. Growth of delaminated area after 20 months.

18-8 Stainless Steel

The stainless steel section was also inspected after 9 and 20 months of service. Figures 11, 12, and 13 show the three sealer systems applied to the 18-8 after 9 months of exposure. There are no deep cuts in the 18-8, nor is there any delamination of the coating, as was observed with the aluminum-bronze coating. There is, however, considerable pinpoint corrosion for each sealer system in the areas shown in the photographs. The bays at the bottom of the gate are in better condition than the upper portions of the downstream skinplate; they exhibit only slight pinpoint rusting. The upstream skinplate portion of the stainless metallizing has not been seriously scarred or eroded. However, each of the sealer systems and adjacent vinyl-coated surfaces have formed blisters. (A similar effect has been noted in vinyl-coated areas adjacent to cable trays and protective cladding where stainless steel is used.) The upstream skinplate had been blasted and metallized with zinc and therefore was not inspected after 20 months of exposure.

Figure 14 depicts the 18-8 stainless steel coated section after 20 months of exposure. About the same amount of surface rust is visible as was at 9 months. Considerable algal growth and a black stain are also visible. The bays at the bottom of the gate remain in fair condition, with only moderate pinpoint corrosion.

The paint sealers have largely eroded from the nose section. Each sealer system has a fairly uniform appearance, but slightly less corrosion is visible on the section sealed with two coats of Mil-P-24441.



Figure 11. Stainless steel sealed with SSPC27/SSPC9/V-766e after 9 months.



Figure 12. Stainless steel sealed with V-766e after 9 months.

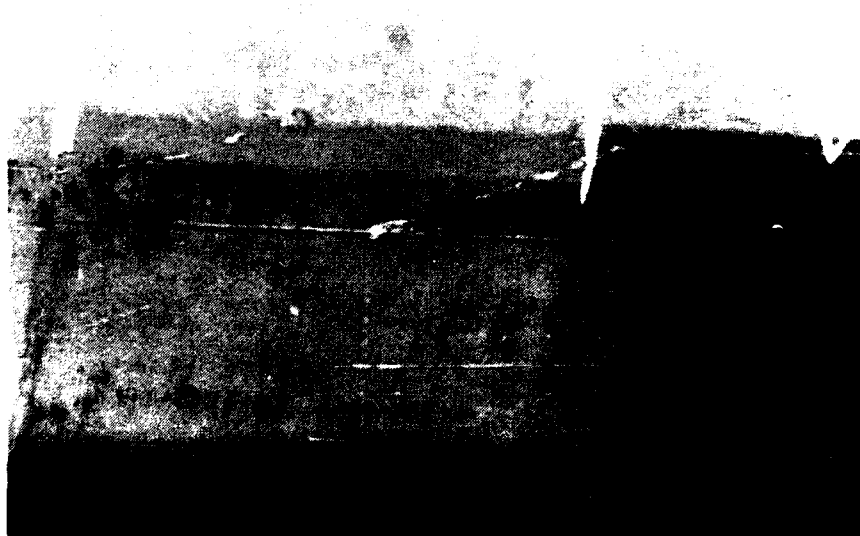


Figure 13. Stainless steel sealed with Mil-P-24441 after 9 months.

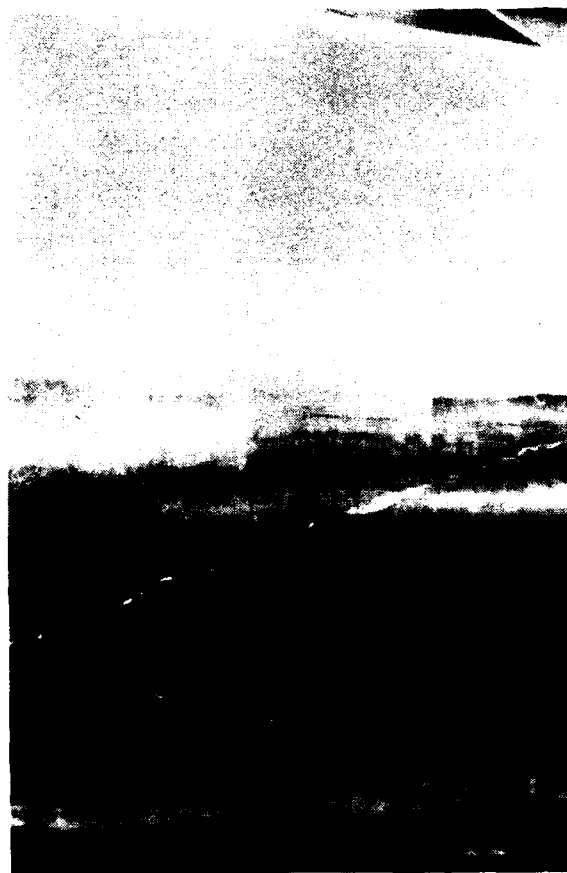


Figure 14. Stainless steel section after 20 months.

Sealers for Aluminum-Bronze and 18-8 Stainless Steel

The primary reason for using sealers with aluminum-bronze and stainless steel metallizing was to prevent galvanic corrosion of the substrate due to water migration through the porous metallic coatings.

Pinpoint rusting was noted for each sealer system used with aluminum-bronze and 18-8 stainless steel coatings. Clearly, the sealers did not perform as intended. The pinpoint corrosion is the obvious result of moisture penetration and galvanic corrosion. Pinholes and holidays in the applied sealers may have allowed water migration, causing corrosion. All organic coatings will eventually be penetrated by moisture when immersed. A wicking action at continuous pores may have provided enough moisture for corrosion to begin. Finally, erosion of the metallic coatings themselves could have exposed continuous porosity, allowing corrosion to occur.

One sealer system was marginally superior on aluminum-bronze, and another was better on stainless steel. On aluminum-bronze the wash primer system with vinyl intermediate and topcoats outperformed the epoxy system and V-766e vinyl system. This was probably due to the improved adhesion of coatings applied over wash primers on certain substrates. Also, the wash primer can be expected to penetrate the porous metallizing to a greater extent because of its low vehicle solids, pigment content, and very low viscosity. Surface tension can also effect penetration to a degree.

The epoxy sealer system was slightly superior to the other two sealer systems applied to 18-8 stainless steel coating. The mode of failure for the stainless steel coating was primarily pinpoint rusting, so the epoxy system evidently prevented the migration of moisture by virtue either of being more resistant to erosion or of having a lower water permeability.

85-15 Zinc-Aluminum

Zinc and 85-15 zinc-aluminum metallic coatings were selected for application at Belleville after an initial inspection of the aluminum-bronze and 18-8 stainless steel coatings indicated premature failure. The comparative hardness of metals such as stainless steel was sacrificed in favor of metals which would galvanically protect the mild steel substrate.

After 10 months of exposure zinc and zinc-aluminum coatings showed no signs of deterioration. The formation of zinc and aluminum oxides and hydrates on the surface and in the coating pores should reduce the coating porosity.

Zinc alloys containing 15 to 17 percent aluminum have improved corrosion resistance.²¹ Research results indicate that the advantageous properties of both metals are obtained. Thermally sprayed zinc-aluminum alloys yield a two-phase coating. The zinc-rich phase affords galvanic protection of the steel substrate; an aluminum-rich phase passivates and has good barrier properties. These results, however, may not be valid under all exposure conditions. Multiphase alloys may form tiny corrosion cells because of potential differences between the alloy phases.²² This condition may worsen as the aluminum-rich phase passivates, which could further shift its potential relative to the zinc-rich phase. How the Ohio River environment will affect the 85-15 zinc-aluminum alloy in the long run is not known. However, 85-15 zinc aluminum has a higher bond strength and is harder than either aluminum or zinc sprayed alone.²³

Figure 15 is a full-length view of tainter gate No. 5 at Belleville Locks and Dam, taken in June 1988. Both the zinc and zinc-aluminum coatings had been in test for 10 months, and the aluminum-bronze and stainless steel had been in test for 20 months. The zinc-aluminum coating supported more algal growth than the other metallized coatings; the entire nose section was bright green from the growth. Lower portions of the zinc-aluminum coating are brown, which may be dead algae.

No red rust was visible on the zinc-aluminum coated section, and there was no measurable loss of coating thickness. The coating surface was somewhat polished along the curved nose-section, indicating that some wear was occurring.

Zinc

The zinc metallized coating was also in excellent condition. The pure zinc coating does not appear to support as much algal growth as the zinc-aluminum coating. The lower portions of the gate were brown, probably from river scum adhering to the rough metallized surface. No red rust or cuts in the zinc coating were visible. There was no measurable loss of coating thickness, although there was some polishing of the zinc along the nose section.

²¹"Ohio DOT Undertakes Spray Metallurgy Tests," *Roads and Bridges Magazine* (August 1986).

²²K.N. Strafford et al.

²³"Ohio DOT Undertakes Spray Metallurgy Tests."

Sealers for 85-15 Zinc-Aluminum and Zinc

Vinyl butyral wash primer was used to seal the zinc and zinc-aluminum coatings. An extension of the service life of the zinc and 85-15 coatings of probably 2 to 3 years could be expected from a fully developed sealer system with topcoats. However, the vinyl butyral wash primer was intended only to seal the porosity but not to protect the coatings from environmental degradation and erosion.

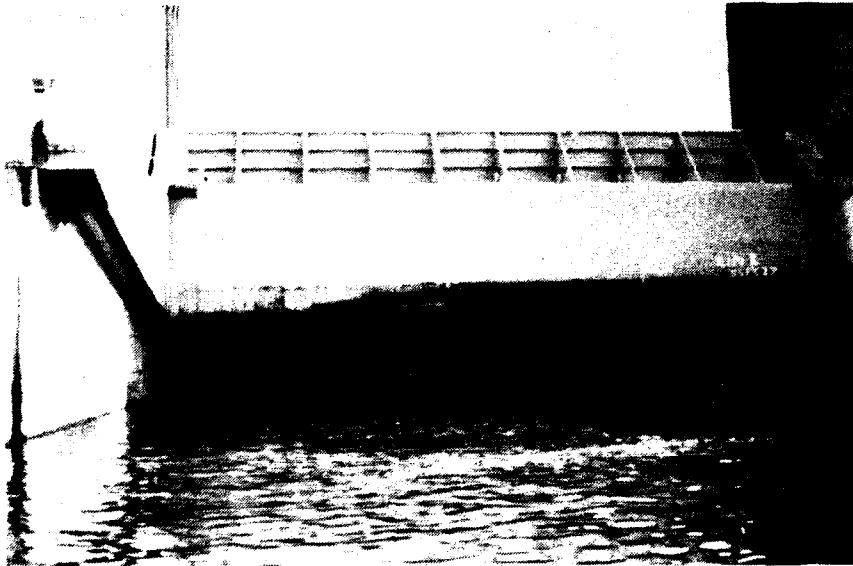


Figure 15. Tainter gate No. 5 at Belleville locks and dam.

7 ACCELERATED EROSION-CORROSION TESTING

The primary mechanism of coating failure at Belleville Locks and Dam and similar facilities is erosion-corrosion. During the Belleville metallized coatings evaluation, an accelerated erosion-corrosion test was jointly developed by USACERL and the University of Illinois, Department of Materials Science.²³ This test was used to predict the relative erosion-corrosion resistance of zinc, 85-15 zinc-aluminum, and vinyl paint (V-766e) in a sand-water slurry.

The density of the materials tested is known, and coating thickness as a function of coating weight was calculated. Thus, coating weight loss data was converted to thickness of coating lost per week of accelerated test. Interestingly, the vinyl paint eroded at the lowest rate, followed by zinc and zinc-aluminum. In practice, however, metallized coatings are applied at a much higher thickness than the vinyl paint, and when this factor is taken into account the test predicts that vinyl paint should last slightly longer than 85-15 zinc-aluminum. The pure zinc is predicted to last about two-and-a-half times longer than the vinyl.

Accelerated tests may yield misleading information and should not be relied on to predict actual service life. They may, however, be useful for forecasting how different materials will perform. The correlation between actual service exposure and accelerated test results will continue to be monitored.

²³R. Weber et al.

8 RELATIVE COSTS OF METALLIZING AND PAINTING

To be recognized as a valid alternative, metallic coatings must have a demonstrated cost effectiveness. Economic effects can be measured by calculating current cost levels, net future value (NFV), net current value (NCV), and average equivalent annual cost (AEAC). Comparing the AEAC of two different coating systems will indicate which is cheaper to use over the life of a structure.²⁵

Vinyl Paint Systems at Current Cost Levels

The cost of an applied vinyl paint system is easily calculated from data available in literature sources. Vinyl paint systems require (1) a near white metal blast, which costs \$0.90/sq ft; (2) vinyl zinc-rich primer and vinyl intermediate and topcoats, which cost \$0.40/sq ft; and (3) paint application costs of \$0.62/sq ft. Thus, the current cost level for a vinyl system like that used on locks and dams is \$1.92/sq ft.

Zinc Metallized Coatings at Current Cost Levels

Metallized coatings require a slightly more expensive white metal blast costing \$1.10/sq ft. The typical average cost of applying a 15-mil zinc coating is around \$2.20/sq ft for materials and labor. The total current cost level of zinc metallizing, then, is \$3.30/sq ft. The cost of sealing this system with a two-coat vinyl system would add \$0.58/sq ft, bringing the total cost of the sealed metallized system to \$3.88/sq ft.

Net Future Value of Vinyl Paint Systems

The net future value (NFV) is the sum of the scheduled maintenance recoatings over the life of the structure, adjusted for inflation. Several assumptions must be made to calculate the net future value of the coating systems of interest. First, a constant rate of inflation must be assumed; second, the recoating interval must be estimated; and, third, the life of the structure must be estimated.

The remaining structural life for Ohio River dams is assumed to be 30 years, inflation is calculated at 4 percent, and the recoat interval is 2 years. Thus, the following equation is used to calculate NFV:

$$\text{NFV} = \text{current cost} \times (1 + i)^n. \quad [\text{Eq 1}]$$

Inflation is i and the number of years is n . The total NFV is calculated for $n = 2, 4, 6 \dots 28$ and is found to be \$50.87/sq ft.

²⁵G.H. Brevoort, "1988 Protective Coating Cost, Selection and Justification," *The Economics of Protective Coatings, Proceedings of the Steel Structure Painting Council Seventh Annual Symposium* (November 1988).

Net Future Value of Zinc Metallizing

The net future value of zinc metallizing is calculated for two service intervals. If the coating is reapplied every 5 years ($n = 5, 10, 15, 20, 25$), then NFV for a 15-mil zinc coating sealed with vinyl is \$36.30/sq ft. For a 10-year recoat interval ($n = 10, 20$) NFV is \$14.25/sq ft.

Net Present Value of Vinyl Paint Systems

The net present value (NPV) of maintenance recoating is the worth of net future value invested at current interest rates. The prevailing interest rate is taken as 8 percent and where n is the structure's life.

$$NPV = NFV \frac{1}{(1 + i)^n} \quad [\text{Eq 2}]$$

Net present value of the vinyl paint system is calculated to be \$15.98/sq ft.

Net Present Value of Zinc Metallizing

Assuming a 5-year recoat interval for the 15-mil zinc metallized coating sealed with vinyl, the NPV is found to be \$11.41/sq ft. For a 10-year service interval NPV is \$4.48/sq ft.

Average Equivalent Annual Cost of Vinyl Versus Zinc Metallizing

The average equivalent annual cost (AEAC) is the sum of the current cost and net future value of maintenance recoating converted to net present value and distributed over the life of the structure. The AEAC is calculated from

$$AEAC = NPV \times \frac{i(1 + i)^n}{(1 + i)^n - 1} \quad [\text{Eq 3}]$$

where i is the interest rate and n is the structure's life. The AEAC of the vinyl system is \$1.42/sq ft/yr. The AEAC of the zinc coating assuming a 5-year service interval is \$1.01/sq ft/yr, and for a 10-year service interval, \$0.40/sq ft/yr. Table 3 shows current cost, net future value, net present value, and average equivalent annual cost for each coating system.

Table 3

Cost Comparison of Zinc Metallizing Versus Vinyl Paint

Coating System	Maintenance Interval	Current Cost(\$)*	NFV(\$)*	NPV(\$)*	AEAC(\$)**
Three-coat vinyl	2 yr	1.92	50.87	15.98	1.42
15-mil zinc with vinyl sealer	5 yr	3.88	36.30	11.41	1.01
15-mil zinc with vinyl sealer	10 yr	3.88	14.25	4.48	0.40

*\$/sq ft

**\$/sq ft/yr

9 CONCLUSIONS

Coatings cathodic to mild steel, such as stainless steels, Monel, and aluminum-bronze alloys, should not be used in freshwater immersion where exclusion of water from the substrate cannot be guaranteed. The presence of water at the interface of the mild steel substrate and the metallized coating will cause galvanic corrosion of the steel substrate. Sealing coats did not adequately prevent the penetration of water through the porous coating to the substrate interface at Belleville.

Coatings anodic to mild steel, such as 85-15 zinc-aluminum and pure zinc, appear to offer an attractive alternative to conventional paint coatings for use in abrasion-corrosion environments such as those found at Belleville and other Ohio River dam facilities.

Among the many thermal spray application processes available, wire flame spray and arc spray are probably most suitable for field application of zinc and zinc-aluminum. Each method offers its own unique advantages.

It is necessary to continue the performance evaluation of the coatings applied at Belleville annually to establish the service life of zinc and 85-15 zinc-aluminum coatings. It is estimated that zinc and 85-15 zinc aluminum coatings will provide 5 to 10 years of corrosion protection at locations such as Belleville.

A cost comparison of vinyl coatings and zinc metallizing indicates that substantial savings would be realized by using the zinc coating. A 5-year maintenance interval for zinc metallizing would indicate a cost savings of \$0.41 per sq ft per year, and \$1.02 per sq ft per year would result from a 10-year service life over the life of a structure. Cost savings for the zinc-aluminum coating would be similar. For Belleville Locks and Dam a maximum total annual savings of \$31,000 over the 30-year estimated structure life could produce total savings of \$930,000.

METRIC CONVERSION TABLE

1 in.	= 25.44 mm
1 ft	= 0.305 m
1 sq ft	= 0.0929 m ²
1 lb	= 0.4536 kg
1 psi	= 6.89 kPa
1 mil	= 25 μ

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