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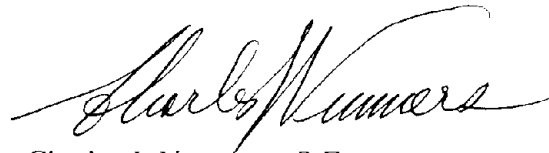
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Corrosion Control of Highway Structural Components by the Application of Powder Coatings

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FOREWORD

This report, *Corrosion Control of Highway Structural Components by the Application of Powder Coatings*, presents results of research and testing of organic powder coatings. It includes a discussion of powder coating materials and processes. Results of laboratory studies and field exposure of 20 alternative organic powder coating systems are presented. This report is intended for use by those responsible for specifying corrosion protective coating systems on highway structures who are unfamiliar with powder coating technology.




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Operations Research and Development

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16. Abstract <p>Recent regulations concerning volatile organic compounds (VOC's) and certain hazardous heavy metals have had an impact on the construction and maintenance practices of transportation authorities. Powder coatings are a 100-percent solids material that are heat cured, thus they have near-zero VOC emissions during application. This report presents the results of an evaluation of various powder coatings designed to protect atmospherically exposed steel and reinforcing steel from corrosion.</p> <p>Three categories of coatings were selected for the test program: a solvent-based control system, 13 proprietary single-coat powder systems, and 6 two-coat powder coating systems. The coatings were evaluated over three substrates: abrasive-blasted A36 steel, abrasive-blasted A588 steel, and cold-rolled A36 steel with a zinc phosphate pretreatment. Testing included a cyclic salt fog/natural marine exposure, a cyclic brine immersion/natural marine exposure, a natural marine exposure test, water penetration test, anodic disbondment test, and electrochemical impedance spectroscopy tests, and coated rebar exposure in concrete.</p> <p>Underfilm corrosion and subsequent coating disbondment was the significant failure mode of the powder coatings. Surface preparation, coating thickness, and coating holidays all contribute to powder coating performance. Using a zinc-containing primer or powder was the most effective means of controlling this phenomenon, though the data suggests that various zinc-containing materials are not necessarily equally effective at eliminating underfilm corrosion. Gloss- and color-retention characteristics were typical of the generic powder coating resin materials. Polyesters and acrylics had superior gloss retention, while epoxies and polyvinyl chloride (PVC) powders had significant chalking over the exposure periods.</p>					
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					LENGTH				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					AREA				
in ²	square inches	645.2	square millimeters	mm ²	mm ²	square millimeters	0.0016	square inches	in ²
ft ²	square feet	0.093	square meters	m ²	m ²	square meters	10.764	square feet	ft ²
yd ²	square yards	0.836	square meters	m ²	m ²	square meters	1.195	square yards	yd ²
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi ²	square miles	2.59	square kilometers	km ²	km ²	square kilometers	0.386	square miles	mi ²
VOLUME					VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft ³	cubic feet	0.028	cubic meters	m ³	m ³	cubic meters	35.71	cubic feet	ft ³
yd ³	cubic yards	0.765	cubic meters	m ³	m ³	cubic meters	1.307	cubic yards	yd ³
MASS					MASS				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)					TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION					ILLUMINATION				
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²	cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

NOTE: Volumes greater than 1000 l shall be shown in m³.

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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SUMMARY

Recent regulations concerning volatile organic compounds (VOC's) and hazardous heavy metals have had an impact on the construction and maintenance practices of transportation authorities. Low-VOC coatings have been implemented as a means of complying with recent regulations. Powder coatings are a 100-percent solids material that are heat cured, thus they have near-zero VOC emissions during application. "Corrosion Control of Highway Structural Components by the Application of Powder Coatings" was conducted to evaluate various powder coatings designed to protect atmospherically exposed steel and reinforcing steel from corrosion.

Three categories of coatings were selected for the test program: a solvent-based control system, 13 proprietary single-coat powder systems, and 6 two-coat powder coating systems. The 20 coatings were evaluated over 3 substrates: abrasive-blasted A36 steel, abrasive-blasted A588 steel, and cold-rolled A36 steel with a zinc phosphate pretreatment. These systems were tested in a cyclic salt fog/natural marine exposure, a cyclic brine immersion/natural marine exposure, and a natural marine exposure test. Water penetration, anodic disbondment, and electrochemical impedance spectroscopy tests were also performed on each system. The results of these various tests were used to quantify the performance of the various systems.

Throughout the laboratory tests, underfilm corrosion and subsequent coating disbondment was the significant failure mode of the powder coatings. A zinc-rich epoxy coating and systems that incorporated a zinc-containing material such as galvanizing or a zinc-loaded organic primer were the most effective means of controlling this phenomenon. Galvanizing, applying a zinc-loaded epoxy powder, and two solvent-based primers containing zinc were tested. Topcoat adhesion and underfilm corrosion varied for these systems. Further testing would be required to optimize the performance characteristics associated with different types of zinc-rich powder coating or duplex systems with zinc-containing primers.

In the exposure tests, gloss- and color-retention characteristics were dependent on the chemical structure of the resin. Polyesters and acrylics had superior gloss retention, while epoxies and polyvinyl chloride (PVC) powders exhibited significant chalking over the exposure periods.

Natural marine exposure test results suggested that polyester powders exhibited less underfilm corrosion than epoxy powders. Acrylic powder coatings were brittle and had a tendency to crack at the tested thicknesses [175 to 300 μm (7 to 12 mils)]. Substrate material and substrate pretreatment had little effect on the degree of underfilm corrosion of a particular system.

In addition to atmospheric exposure testing of the coatings, six systems were applied to steel reinforcing bars. Triplicate rebars for each coating were cast in beams fabricated with porous, chloride-contaminated concrete. The beams were statically loaded to induce cracking through the 41.3-mm (1.63-in) concrete cover. After an 18-month exposure in a marine environment with natural seawater spray, the beams were broken and the coatings evaluated. The evaluation showed that thicker (300 μm or 12 mils), holiday-free epoxy coatings provided better corrosion protection than similar materials at lower thicknesses. An epoxy-polyester hybrid deteriorated even at high (450 μm or 18 mils) thickness.

Observed failures on the reinforcing bars included pinhole corrosion, softening of the coating, and reduced coating adhesion. Epoxy coatings without holidays (related to coating thickness) performed better if the material was able to resist alkaline attack. Polyesters tend to be saponified during exposure in concrete. Zinc loading of epoxy powder or use of a zinc-containing primer was shown to improve coating performance over rebars in concrete.

From a practical standpoint for highway applications, powder coatings are useful for relatively small components that can be shop-coated. These include reinforcing bars, guardrail, reticular fences, signposts, and small subassemblies of larger structures (e.g., bridge bearings). Heat capacity of larger elements (thick structural members such as hanger plates) make powder coating application less attractive. Field application of organic powder coatings is still a developing technology. Its limitations include ability to locally heat the part. At least one source reports successful application of ethylene acrylic acid to lamp posts using flame-spray equipment.⁽¹⁾

The results of the field studies presented in this report suggest that the corrosion-control performance of a powder-applied barrier coating will not equal that of a solvent-based system with zinc-containing primer. Previous studies have shown that powder-applied epoxy coating does not provide significantly better corrosion protection than a solvent-borne epoxy over comparably prepared surfaces.⁽²⁾ There is no evidence that powder coating technology provides a film that inherently offers more corrosion protection than the same generic material applied using other means.

Powder coating technology does provide an application method that reduces VOC emissions and improves deposition efficiency when coating suitably sized materials. In its early years, powder coatings were typically high-build barrier films applied to pipelines and steel reinforcing bars to prevent corrosion. Powder coating technology is currently most attractive to finishers applying relatively thin films for aesthetic purposes to parts that can be easily handled (heated, etc.) in a conveyORIZED operation. With VOC regulations as a motive, applicators are now moving the technology into the application of corrosion-control coatings. The most common highway materials targeted for powder coating include concrete reinforcing bars, guardrail, reticular fences, and signposts. In these applications, the use of a zinc-containing primer will extend the lifetime of the coating by reducing the extent of underfilm corrosion and subsequent coating disbondment.

OBJECTIVES

The Federal Highway Administration authorized this study as a result of the recent interest in powder coating technologies for use on highway structural materials. The stated objectives of this program are:

1. Identify and evaluate commercially available powder coatings and systems for the corrosion protection of highway structural components that are exposed to a salt-rich atmosphere environment (including concrete reinforcing steel).
2. Evaluate alternative coating materials and the use of zinc-rich primers to increase the underfilm corrosion resistance of powder coating systems.
3. Determine the associated application and life-cycle costs of the superior powder coatings identified. Compare these costs with other available low-VOC corrosion-control alternatives.



CONCLUSIONS

1. The study did not identify any advantage in the use of powder coating to protect steel from corrosion in atmospheric exposure. Performance can be improved with the addition of zinc-rich primers and urethane topcoats, however, similar performance can be achieved with solvent-base, low-VOC systems.
2. The A775 epoxy rebar barrier coating performance declined as film holidays increased and thickness decreased. Significant underfilm corrosion failure occurred in 18 months for coatings applied at specified A775 rebar thickness [125 to 300 μm (5 to 12 mils)]. Corrosion began at coating holidays. The application of a zinc-rich primer before powder application or the addition of zinc dust to the epoxy powder reduced these failures.
3. The powder coating process and materials require adequate quality assurance testing to ensure expected field performance. Proper topcoat adhesion and film thickness are critical requirements to ensure successful performance.
4. The primary failure mode of powder coatings in this study was underfilm corrosion and coating delamination. Rust-through of the coatings and blistering of the coatings were not common failure mechanisms.
5. Polyester and acrylic powder coatings provided the best gloss retention after all exposures. Epoxy and polyvinyl chloride-based powder coatings had the worst gloss- and color-retention properties after exposure.
6. Polyester powder coatings allowed less underfilm corrosion than epoxy powders in the natural marine atmosphere exposure.
7. Acrylic-based powder coatings were brittle and cracked during the natural marine exposure, salt fog/marine exposure, and cyclic high-pressure/high-temperature seawater exposure tests. It should be noted that acrylics are typically applied at lower film builds [25 to 75 μm (1 to 3 mils)] as aesthetic coatings, rather than thick film [175 to 300 μm (7 to 12 mils)] barrier coatings.
8. The type of steel (A36 versus A588 weathering steel) used as the powder coating substrate had no effect on the amount of underfilm corrosion experienced by the generic powder coating system.
9. Using a zinc phosphate pretreatment over cold-rolled steel, instead of near-white metal blasted hot-rolled steel, had little effect on the amount of underfilm corrosion for any given powder coating system.

RECOMMENDATIONS

1. The study results indicate that powder coating performance can be improved if a zinc-rich primer is used. An epoxy powder containing zinc also enhances performance. Further research is needed to identify the best zinc system, thickness, and application parameters to be used.
2. Cost comparisons between powder coating and solvent-based coatings should be made on an individual basis. Part geometry, quantity, and coating specification will all affect the cost. Duplex powder systems and powders applied over a zinc primer will cost more than typical one-coat powders.



INTRODUCTION TO POWDER COATINGS

Throughout their history, organic powder coatings have experienced steady growth in the marketplace. Modern powder coating technology claims it can produce a quality finish that rivals that of a liquid coating while offering superior surface properties and economic and environmental benefits. For applications on highway structural and reinforcing steel, the corrosion control properties and application considerations of powder coatings are the most important criteria of choice. The many differences between powder coatings and traditional solvent-based coatings will be further discussed in this section.

Unlike conventional solvent-based organic coatings, powder coatings are dry in their unapplied state. The basic powder coating process requires the powder to be spread over the substrate and then heated to form a continuous film. Since powder coatings require only heat to flow and cure, they do not contain volatile carriers.

The methods currently used in industry to apply powder coatings are electrostatic spray, fluidized bed immersion, and thermal spray. Solvent-based coatings may be applied with spray equipment or by brushing and rolling. Solvent-based coatings may be applied to any substrate, regardless of size or geometry. It has taken significant technological advances in the application methods of powder coatings for them to be successfully applied to any size substrate. The obstacles to powder coating application include heat capacity of the coated part and so-called "Faraday effects." Heat capacity (the amount of energy required to raise a part's temperature) is related to a part's size and geometry. Parts with high heat capacity require large amounts of energy to cure the coating (if they can be cured at all). The Faraday effect refers to the electrostatic phenomenon that results in poor control of powder deposition (thickness) in complex shapes such as corners and recesses. The three powder coating application methods are each briefly described below.

The two most popular methods of applying powder coatings are electrostatic spray and fluidized bed immersion. The basic principle behind the electrostatic spray method requires that the part to be coated be electrically grounded. Charged powder particles are then sprayed onto the part. Powder will adhere to the part due to the electrical attraction between the particles and the part. The coated part is then oven cured to produce a finished film. The fluidized bed method employs the creation of a fluidized environment of powder and air within a chamber. The part is heated and dipped into the bed where the powder particles melt onto the heated surface to create the coating film. Both electrostatic spray and fluidized bed application methods require control of heating times to ensure proper curing of the powder resins. Because of the need for a curing oven or a fluidized bed, both of these methods have practical limitations to the size of the parts to be coated.

A third method of applying powder coatings is thermal spray. This method has recently been increasing in popularity as industry creates better-suited polymer blends for thermal spray application. These materials must be more resistant to large variations in heating temperatures than traditional materials. The method does not require oven curing and the application equipment is usually portable, so it is suitable for field applications of powder coatings. The basic process for thermal spraying of powder coatings is the same as for thermal spraying of metals, which is a well-developed technology. Fluidized powder is fed into a hand-held applicator gun and projected through a heat source (usually a flame). The powder melts while in the heat source. The melted polymer then impacts onto the preheated substrate to form a continuous film. Application can be successful in a wide range of environmental conditions provided that the substrate heat capacity is small enough that it can be preheated.

Improved long-term economic savings is one driving factor for the increase in popularity of powder coatings. After supplying the initial capital investment required to begin powder coating production (spray

booths and equipment, ovens, conveyor systems, thermal spray systems, etc.), maintenance and production costs are presently less than those of comparable solvent-based systems. Deposition efficiency (for the electrostatic spray and fluidized bed methods) is a major reason for cost savings. Powder that does not adhere to a part can be recycled. This can push deposition efficiencies up to 99 percent for these methods of applying powder coatings. Typical deposition efficiencies for solvent-based spray systems are in the 50- to 80-percent range. Environmental compliance with current regulations for volatile organic compounds (VOC) emissions is a substantial expense for a solvent-based coating production facility. Powder coatings are made up of 100-percent solids, and thus no VOC control is presently required during application of powder materials.

Other cost-oriented considerations of the powder coating process include heating requirements, surface preparation requirements, and physical constraints. For the electrostatic spray and fluidized bed immersion methods of applying powder coatings, heating times are required. Preheating, post-heating/curing, or a combination of the two may be necessary with temperatures up to 260° C (500°F). Solvent-based systems may require a drying oven, but typically do not require the amount of energy used during powder coating.

Most manufacturers of powder coatings recommend near-white metal abrasive blasting (SSPC SP-10) as surface preparation for a part because both a clean surface and a good surface profile is produced. The best performing solvent-based coating systems also require a near-white metal blast.

For the electrostatic spray and fluidized bed immersion methods of applying powder coatings, the physical size of the part to be coated is limited to the size of the application equipment and the ability to heat the part to the required temperatures. Solvent-based coatings can be applied to any size substrate of virtually any geometry, although application temperature and humidity requirements must be met. The thermal spray method of applying powder coatings has limitations on substrate size related only to the substrate's heat capacity. The success of thermal spray applications of powder coatings is very dependent upon application conditions, which may or may not be possible to achieve on all substrates.

A variety of powder coating materials are commercially available today. They can generally be divided into two categories: thermoset and thermoplastic. Thermosetting materials include epoxies, polyesters, and acrylics. They are generally based on low molecular weight solid resins. At elevated temperatures, thermosets flow and chemically crosslink to form a higher molecular weight film. The cured film is heat stable (i.e., will not resoften) with different physical properties than the original material.

Thermoplastic materials include polyethylene, polypropylene, nylon, polyvinyl chloride (PVC), and some polyesters. They are based on high molecular weight resins. At elevated temperatures, thermoplastics will melt and flow, but the cooled film will retain the chemical properties of the powder.

As with any coatings job, the powder coating materials must be subject to quality control inspection to ensure adequate performance. The physical properties of uncured powder coatings are important as they can affect the final coating film. Storage stability is of particular importance to the powder coating applicator. Most powders should remain stable and free of lumps or severe "caking" when stored in a cool dry place for up to 1 year. The ability of a powder coating to fluidize is very important as it is the only means of getting the powder to the substrate. Other properties that should be checked before a batch of powder coating is applied include the ability of the powder to hold electrical charge, gel time, and flowing properties.

Quality control (QC) of a finished powder coating will ensure a more uniform and reliable protective film. Tests that should definitely be conducted are the methyl ethyl ketone (MEK) rub test (for thermoset powders) and measurement of the cured film thickness. The rub test determines if the coating has

cured completely enough to produce a quality film. The thickness of the coating should be measured to see if it is within the specifications. An electrical holiday test should also be performed. Other simple inspections could include visual observations for pinholes or fisheyes from outgassing. The powder coater should also be required to provide QC checks on the prepared substrate before it is coated. Defects might include insufficient blast profile [50 to 75 μm (2 to 3 mils) is typical], inadequate surface pretreatment (if used), a surface that is not clean of visible oils and dirt (perhaps using a "white glove" test), and "bluing" of the substrate due to overheating prior to coating application.

From a practical standpoint for highway applications, powder coatings are useful for relatively small components that can be shop-coated. These include guardrail, reticular fences, signposts, and small subassemblies of larger structures (e.g., bridge bearings). There are applicators with sufficiently large facilities to coat larger elements (thick structural members such as hanger plates or I-beams), however, their large heat capacity makes powder coating application less attractive. Field application of organic powder coatings is still a developing technology. Its limitations include the ability to locally heat the part. At least one source reports successful application of ethylene acrylic acid to lamp posts using flame-spray equipment.⁽¹⁾

The results of the field studies presented in this report suggest that the corrosion-control performance of a powder-applied barrier coating will not equal that of a solvent-based system with an inhibitive primer. Previous studies have shown that powder-applied epoxy coating does not provide significantly better corrosion protection than a solvent-based epoxy applied over comparably prepared surfaces.⁽²⁾ There is no evidence that powder coating technology provides a film that inherently provides more corrosion protection than the same material applied using other means.

Powder coating technology does provide an application method that reduces VOC emissions and improves deposition efficiency when coating suitably sized materials. In its early years, powder coatings were typically high-build barrier films applied to pipelines and steel reinforcing bars to prevent corrosion. Powder coating technology is currently most attractive to finishers applying relatively thin films for aesthetic purposes to parts that can be easily handled (heated, etc.) in a conveyorized operation. With VOC regulations as a motive, applicators are now moving the technology into the application of corrosion-control coatings. The most common highway materials targeted for powder coating include guardrail, reticular fences, and signposts.



TECHNICAL APPROACH

GENERAL

The project was divided into distinct tasks. This provided an organized means of collecting data and drawing relevant conclusions from the findings. The primary portions of the program include:

Task A - Information Acquisition and Review. Conduct an information search to identify and collect pertinent data required for the selection of state-of-the-art powder coatings and powder coating-based systems.

Task B - Data Reduction and Analysis. Reduce and analyze the data collected in task A to characterize potential coatings for the corrosion protection of highway structures. Identify specific coating systems for tasks C and D.

Task C - Accelerated Weathering and Natural Exposure Testing. Conduct accelerated and natural exposure testing to evaluate candidate powder coating systems identified in task B.

Task D - Electrochemical AC Impedance Testing. Conduct AC impedance tests to characterize the resistance to underfilm corrosion of candidate powder coating systems identified in task B.

Task E - Accelerated Testing of Coated Rebar. Perform accelerated tests simulating the harsh environment experienced by reinforced concrete bridges in marine environments. Test and evaluate various powder coatings for protection of the steel reinforcing bars.

Task F - Feasibility and Implementation. Assimilate the data generated in the program and identify those specific systems that appear appropriate for application to selected highway structural components.

TEST PANEL PREPARATION

Table 1 shows the task C coating/test panel conditions for the high-pressure/high-temperature seawater test, salt fog test, and natural marine atmosphere exposure test. The specific materials tested are discussed in the section, "Discussion of Powder Coating Materials." All 20 systems were evaluated over near-white metal blasted A36 steel at 300 μm (12 mils) thickness. Three alternative test panel conditions were tested with 12 of the 20 coatings. The alternative test panel conditions were the coatings applied over: (1) A36 steel at 175 μm (7 mils) thickness; (2) the zinc phosphate treated, cold-rolled steel at 300 μm (12 mils) thickness; and (3) preweathered and near-white metal blasted, A588 steel at 300 μm (12 mils) thickness.

For each of the alternative test panel conditions, 8 of the 20 systems were eliminated from the matrix. The following discusses the selection process for eliminating these eight systems.

Testing at 175 μm (7 mils) thickness was intended to demonstrate coating performance at thicknesses typical of rebar coatings. Eight systems inappropriate for rebar applications were not tested at 175 μm (7 mil) thickness. The remaining 12 systems provided a basis for comparing general coating performance at 175 μm and 300 μm (7 and 12 mils). The eight systems eliminated were:

- The three-coat, solvent-based system (system 1) was eliminated because it is not practically applicable to rebar.

- One of the triglycidyl isocyanurate (TGIC) polyester systems (system 5) was eliminated because another TGIC (system 6) was already being tested at this thickness.
- A flame-spray ethylene acrylic acid (EAA) system (system 8) was not designed to function at film builds less than 300 μm (12 mils).
- One acrylic powder (system 10) was not recommended for rebar applications.
- The epoxy-polyester hybrid (system 12) was not recommended by the manufacturer as a potential rebar coating.
- The zinc-rich powder/TGIC polyester system (system 15), the epoxy/TGIC polyester system (system 19), and the epoxy/polyolefin system (system 20) were not considered optimal rebar coatings. For optimal corrosion control, the epoxy base coat would be applied at 175 μm (7 mils) without the polyester topcoats. The topcoats are used to enhance atmospheric weathering.

The zinc phosphate pretreatment was intended to demonstrate the benefits of an alternative surface preparation technique (versus abrasive blasting). Zinc phosphate was applied to smooth, cold-rolled steel test panels prior to powder coating. Phosphating may be a cost-beneficial surface preparation for some types of highway structural components that cannot be blasted (e.g., guardrail). The following eight systems were not tested over zinc-phosphated test panels:

- The three systems (systems 1, 16, and 17) with solvent-based zinc-rich primers were eliminated because they are intended for application over near-white metal blasted steel only.
- The three rebar epoxies (systems 2, 3, and 4) were eliminated given existing data suggesting good corrosion performance of rebar epoxies over zinc phosphate, yet poor gloss retention of these materials.
- The flame-spray EAA (system 8) was not considered because this is a flame-spray process intended for near-white metal blasted surfaces.
- The non-topcoated zinc-rich epoxy powder (system 14) was not considered given its probable poor gloss retention.

The tests over A588 weathering steel were intended to evaluate possible powder coating to rehabilitate severely corroded weathering steel. The eight systems not tested for this application were:

- The solvent-based control (system 1) was not tested as data exists on this system over A588 weathering steel.
- The four boldly exposed epoxy-based powders (systems 2, 3, 4, and 14) were not tested due to their poor gloss retention.
- The topcoated galvanized steel system (system 18) was not evaluated because it does not appear practical to galvanize existing, corroded steel.
- The nylon system (system 11) and one of the polyester systems (system 5) were eliminated because remaining systems were given higher priority.

The anodic disbondment tests (task C) and electrochemical impedance tests (task D) were intended to demonstrate the performance of potential rebar coatings. The tests were performed on all 20 systems applied at 175 μm (7 mils) to A36 steel blasted to near-white metal with the following exceptions:

1. The organic zinc (system 17) and galvanized panels (system 18) were topcoated with an A775 epoxy instead of a TGIC-cured polyester. For rebar applications, the enhanced corrosion resistance of the epoxy is preferred versus the gloss retention of the polyester.
2. The flame-spray EAA (system 8) was applied at 300 μm (12 mils) because it is porous at lower film builds.

Table 1. Test coating/panel conditions for exposure testing.

<u>System No.</u>	<u>Generic Description</u>	<u>Commercial Description</u>	<u>Near-White Metal Blast A36 Steel 300 µm (12 mils) DFT¹</u>	<u>Near-White Metal Blast A36 Steel 175 µm (7 mils) DFT</u>	<u>Cold-Rolled Zn Phosphate A36 Steel 300 µm (12 mils) DFT</u>	<u>Near-White Metal Blast A588 Steel 300 µm (12 mils) DFT</u>
Solvent-Based Control System (1 System)						
1	IOZ/Epoxy/Urethane	Carbozinc D11 HS/Carboline 893 RCP/ Carboline D834	X			
Proprietary Single-Coat Powders (13 Coatings)						
2	A775 Epoxy	Lilly Greenbar Epoxy	X	X		
3	A775 Epoxy	Skotchkote 213	X	X		
4	A775 Epoxy	3M XC6159	X	X		
5	TGIC Polyester	Corvel 30000 Series	X		X	
6	TGIC Polyester	Lilly TGIC for Structural Components	X	X	X	X
7	Polyester	Lilly Proprietary Polyester for Structural Components	X	X	X	X
8	Flame-Spray Ethylene Acrylic Acid (EAA)	Envelon	X			X
9	Acrylic	EVTECH	X	X	X	X
10	Acrylic	Vitralon Acrylic Powder	X		X	X
11	Nylon	Morton Nylon	X	X	X	
12	Epoxy-Polyester Hybrid	Ferro VH Series Hybrid Powder	X		X	X
13	Polyvinyl Chloride (PVC)	Thermoclad DURAVIN	X	X	X	X
14	Zinc-Rich Epoxy Powder	Epoxiplate ZR1000	X	X		

Table 1. Test coating/panel conditions for exposure testing (continued).

<u>System No.</u>	<u>Generic Description</u>	<u>Commercial Description</u>	<u>Near-White Metal Blast A36 Steel 300 µm (12 mils) DFT</u>	<u>Near-White Metal Blast A36 Steel 175 µm (7 mils) DFT</u>	<u>Cold-Rolled Zn Phosphate A36 Steel 300 µm (12 mils) DFT</u>	<u>Near-White Metal Blast A 588 Steel 300 µm (12 mils) DFT</u>
Duplex System (6 Systems)						
15	Zinc-Rich Epoxy Powder/TGIC	Epoxiplate ZR1000/Lilly TGIC	X		X	X
16	Proprietary Solvent Zinc/Powder	JMK Enterprises System	X	X		X
17	Solvent Organic Zinc/TGIC	Unocal Primer/Lilly TGIC	X	X		X
18	Galvanized/TGIC	Galvanized/Lilly TGIC	X	X	X	
19	A775 Epoxy/TGIC	Lilly Rebar Epoxy/Lilly TGIC	X		X	X
20	Epoxy/Polyolefin	DuVal	X		X	X

¹DFT = Dry film thickness.

COATING APPLICATION

Table 1 identifies coating systems selected for testing. These 20 coatings were representative of the most commonly used powder coatings and promising new powder coating systems identified during the information search. This total included 1 solvent-based control system, 13 single-coat powder coatings, and 6 two-coat powder coating systems. Attempts were made to obtain diversity in the generic types of powder coatings tested (e.g., epoxies, polyesters, acrylics) as well as in the manufacturers of the tested systems.

With the exception of the solvent-based control, proprietary solvent zinc/powder, and flame-spray EAA, all systems were applied by a commercial powder coating applicator. Forms were provided to the commercial applicator and all application conditions were documented. These forms listed general identification data, coating application information, and cured coating information. General coating identification data included the coating system, substrate/surface preparation, number of duplicate panels, target dry film thickness (DFT), and any special notes. Application information included noting the primer system, preheat temperature and time duration, cure temperature and time duration, and any specific comments. The cured coating information included the date and time, MEK rub test (pass/fail), thickness measurements (three per panel side), holiday inspection, and comments on observed coating condition. Application information for the powder coating systems is included in appendix I.

The solvent-based control (system 1) is an inorganic zinc/epoxy/urethane system that has performed well in similar Federal Highway Administration programs. The generic coating system is considered one of the best possible coating systems available in terms of corrosion protection lifetime over steel. The initial costs of such systems are high, though life-cycle cost assessments suggest that these systems are the most cost-effective of the solvent-based systems. The inorganic zinc primer is notorious for its sensitivity to surface preparation. It requires a clean, white-metal blast surface. However, given that powder coatings are also sensitive to surface preparation and application conditions (see "Discussion of Powder Coating Materials"), this seemed to be a reasonable choice for a control system for comparison of powder coating performance. The solvent-based control was spray-applied by trained personnel using conventional equipment. Application and product information is included in appendix II.

Flame-spray EAA (system 8) was applied by a company specializing in flame-spray operations and recommended by DOW, the manufacturer of the flame-spray EAA coating.

The proprietary solvent zinc primer and powder topcoat for system 16 were applied by the system designer.

TASK C - ACCELERATED WEATHERING AND NATURAL MARINE EXPOSURE TESTING

Each of the coating systems described in table 1 was tested in this task. Four exposure tests were performed on each of the systems in the test matrix. These tests are described in detail below.

Natural Marine Exposure

Duplicate test panels for each coating were exposed at the Ocean City Research marine test site in Sea Isle City, New Jersey. The site is situated approximately 31 m (100 ft) from mean high sea level. The test panels were exposed facing south, 45° from horizontal. Each duplicate test panel contained four 6.35-mm (0.25-in) diameter circular holidays — two on each test panel side (except for systems 8 and 20, which had three holidays on one side only). Natural seawater spray was applied daily to increase the severity of

the test by introducing chlorides to the panel surface. The test duration was 18 months. Figure 1 shows the test panels exposed at Sea Isle City near the end of the test.



Figure 1. Panels exposed at Sea Isle City test site after approximately 18 months of exposure.

After 3 and 9 months of testing, the test panels were visually inspected according to ASTM D610 and ASTM D714. In addition, the estimated maximum cutback from each holiday (as evidenced by blistering or lifting of the coating) was recorded. After 18 months of exposure, the panels were similarly inspected, with the exception that the cutback from the holiday was destructively determined at the end of the exposure period. Also, after 3, 9, and 18 months, the 60° gloss was measured with a Gardner Glossgard Series portable glossmeter. A complete description of the ratings applied to test panels follows later in this section.

Salt Fog/Marine Exposure

Duplicate test panels were subjected to a cyclic accelerated test, including three cycles each consisting of 1.5 months of salt fog testing and 1.5 months of natural marine exposure. This test combines the corrosion acceleration of the salt fog environment with ultraviolet and wet/dry effects of the natural environment. The salt fog phase of testing was maintained in accordance with ASTM B117, "Standard Test Method for Salt Spray (Fog) Testing." The natural marine exposure was conducted at the Sea Isle City exposure site as described above, except without seawater spray. For each coating system, one of the duplicate test

panels contained four 6.35-mm (0.25-in) diameter circular holidays — two on each test panel side (except systems 8 and 20, which had three holidays on one panel side).

After 3 months of testing the test panels were visually inspected according to ASTM D610 and ASTM D714. In addition, the estimated maximum cutback from each holiday (as evidenced by blistering or lifting of the coating) was recorded. After 9 months of exposure, the panels were similarly inspected, with the exception that the cutback from the holiday was visually and destructively determined.

Cyclic High-Pressure/High-Temperature Seawater Exposure

Duplicate test panels for each coating were subjected to an accelerated test consisting of cyclic exposure to 172.35-kN/m² (25-lbf/in²), 65.5°C (150°F) seawater. This high-pressure, high-temperature test has provided rapid indications of coating failure. The cyclic nature of the test is intended to increase the severity of underfilm corrosion. Test panels were kept in a chamber that was flooded with high-pressure, high-temperature seawater during working hours (8 hours/day, 5 days/week) and empty (air at room temperature and pressure) during the remaining time in the week. For each coating system, one of the duplicate test panels contained four 6.35-mm (0.25-in) diameter circular holidays — two on each test panel side (except systems 8 and 20, which had three holidays on one panel side). The total test duration was 9 months.

After 3 months of testing, the test panels were visually inspected according to ASTM D610 and ASTM D714. In addition, the estimated maximum cutback from each holiday (as evidenced by blistering) was recorded. After 9 months of exposure, the panels were similarly inspected, with the exception that the cutback from the holiday was destructively determined.

Anodic Disbondment Test

The anodic disbondment test was conducted to simulate conditions postulated to exist at sites of localized corrosion on epoxy-coated rebar. Sagues and Powers conducted similar testing and found the corrosion morphology to be similar to that seen on corroding rebar (i.e., blisters filled with acidified liquid in an alkaline bulk environment).⁽³⁾

Duplicate test panels were prepared with two 50.8-mm (2-in) diameter acrylic cells, as shown schematically in figure 2. In the center of each cell, a 6.35-mm (0.25-in) diameter round holiday was made through to the steel substrate. Each test cell was fitted with a carbon counter electrode. The counter electrode was wired through a variable resistor to the test panel. The galvanic difference between carbon and steel generated an anodic current. The variable resistor was adjusted such that a nominal 0.1- μ A/mm² current flowed. The current flowing was periodically adjusted so that the current remained constant throughout the test period.

After the 134-day test period, the cells were destructively inspected. The pH of the electrolyte in each cell was measured. The acrylic test cell was then removed and the extent of disbondment from the intentional holiday was measured by removing the coating with a razor knife.

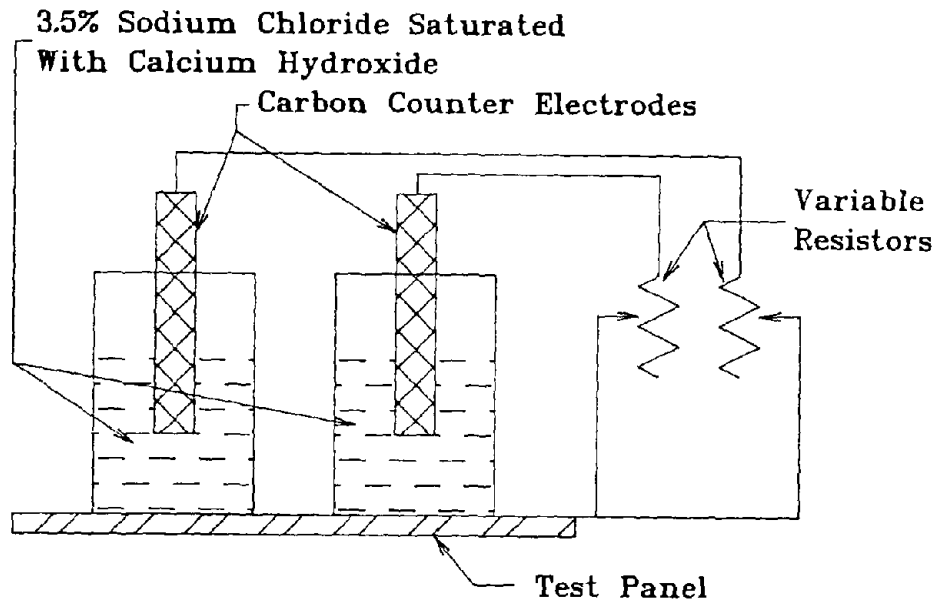


Figure 2. Anodic disbondment test setup.

Rating System

The panels subjected to the natural marine exposure test, the cyclic salt fog/marine exposure test, and the high-pressure/high-temperature seawater exposure test were rated on five different parameters: rusting of coated plane surfaces, blistering on coated plane surfaces, underfilm corrosion radius, coating disbondment radius, and U-channel rusting (where applicable). The anodic disbondment test panels were rated for underfilm corrosion and coating disbondment.

Rusting. The rust rating for each panel was determined by rating only the coated plane surfaces of each panel. Corrosion as a direct result of underfilm corrosion or damage to the edges of the panel was not rated in the rusting category. ASTM D610, "Method for Evaluating Degree of Rusting on Painted Steel Surfaces," was used to quantify the amount of rust visible on coated plane surfaces.

Blistering. The blistering rating for each panel was determined by rating only the coated plane surfaces of each panel. Any blisters resulting from physical damage to the coating (e.g., around the intentional scribe or at damaged edges) were not rated in the blistering category. ASTM D714, "Method for Evaluating Degree of Blistering for Paints," was used to quantify the amount of blistering visible on coated plane surfaces.

Underfilm Corrosion. The underfilm corrosion radius was a direct measurement (in millimeters) from the edge of the original circular scribe of the maximum distance corrosion had advanced. Both visual (as evidenced by lifting of the coating) and destructive (by physically removing coating with a knife) measurements were obtained for all tests.

Coating Disbondment. The coating disbondment radius was a direct measurement (in millimeters) of the distance that the coating was easily removed with a razor knife from the edge of the intentional scribe.

U-Channel Rusting. If rust stains were originating from any part of the complex-shaped U-channel, this yes/no rating was marked as yes.

Figure 3 is used to demonstrate the rating system. A rating for each of the five categories described above has been assigned to the figure. The ratings are as follows:

- Rusting* - 10; there is no rusting on coated surface (top half of panel).
- Blistering* - None; there are no blisters on coated surface.
- Underfilm Corrosion* - 0; the diameter of red rust is approximately the same as the original 6.35-mm (0.25-in) holiday.
- Coating Disbondment* - ∞ (infinite); the brown powder coat could easily be removed from the panel. This measurement is also typically referred to as "cutback."
- U-Channel Rusting* - No.



Figure 3. Example of tested panel inspection.

TASK D - ELECTROCHEMICAL AC IMPEDANCE TESTING

One test panel for each coating was prepared by applying $175 \pm 50 \mu\text{m}$ (7 ± 2 mils) of the coating to a steel panel with a 50- to $75\text{-}\mu\text{m}$ (2- to 3-mil) near-white metal blast profile. Those systems that could not be applied at the designated thicknesses were applied as thin as could be practically applied.

Each test panel was inspected for holidays using a Tinker and Razor holiday detector at a 1-kV setting. On test panels that showed isolated holidays, those holidays were avoided when considering cell placement. Test panels that showed evenly dispersed holidays using the 1-kV detector (i.e., zinc-loaded coating) were reinspected using a 67.5-V holiday detector. Holidays detected with the 67.5-V detector were avoided when considering cell placement.

Three 88.9-mm (3.5-in) diameter acrylic cells were affixed to each coated test panel using a silicone sealant. The coating under two of these cells contained a 6.35-mm (0.25-in) diameter intentional holiday made by using a flat-ended drill bit. The coating underneath the third cell was free of intentional defects. Each cell was filled with an electrolyte comprised of 3.5 percent sodium chloride saturated with calcium hydroxide. A carbon rod counter electrode affixed in the center of the cell facilitated electrochemical impedance measurements.

In addition to test panels prepared as outlined above, A775 epoxy-coated and bare steel panels were prepared with concrete cover.

Data taken on each test cell included single-frequency impedance measurements and electrochemical impedance spectroscopy (EIS).

Single-frequency impedance data was measured periodically on all cells. A GenRad Digibridge was used to acquire data immediately upon exposure and at approximately five logarithmically spaced times through the nominal 100-day exposure. The bridge measures the impedance response at each of two frequencies (120 Hz and 1 kHz) and processes this information to produce capacitance, resistance, and dissipation factor data assuming either a series or parallel RC circuit.

EIS was also performed periodically on one of the cells with a 6.35-mm (0.25-in) holiday and on the cell with no intentional defects. Data on the cell with the 6.35-mm (0.25-in) holiday were taken after approximately 0, 10, and 100 days of exposure. Data were taken after 1 day of exposure for several of these cells. Data on the cell with no intentional defects were taken after 0 and 100 days of exposure. Additional EIS data were taken as single-frequency data and visual observations warranted.

After a nominal 100-day exposure, final electrochemical data were taken. Following the final data recording, each cell was destructively inspected. Inspection data included blistering rating, underfilm corrosion observations, extent of disbonded coating, and electrolyte pH.

TASK E - ACCELERATED TESTING OF COATED REBAR

An exposure test was conducted to simulate coated rebar in low-quality concrete exposed to a harsh marine environment. Six powder coating were selected based on preliminary testing completed in Task C and Task D. Table 2 shows the coatings selected for testing.

Table 2. Coatings selected for accelerated testing of coated rebar.

System	Generic Name	Rationale for Testing
System 2	A775 Epoxy	ASTM A775 epoxy control.
System 3	A775 Epoxy	Additional ASTM A775 epoxy.
System 6	TGIC Polyester	Good performance in screening tests.
System 12	Epoxy-Polyester Hybrid	Good performance in screening tests.
System 14	Zinc-Rich Epoxy Powder	Good performance in screening tests.
System 17	Solvent Organic Zinc/TGIC	Good performance in exposure screening tests.

Three test rebars were coated with each coating. Two-meter (6-ft) lengths of #6 rebar [19-mm (0.75-in) diameter] were used for testing. Rebars were prepared and coated in general accordance with A775 requirements. Appendix I contains specific application information. To create intentional holidays, the center 51 mm (2 in) and end 150 mm (6 in) were masked after blasting, but prior to coating.

A single test rebar for each coating (six bars in total) was cast into a single concrete slab. Three concrete slabs were prepared to evaluate the triplicate specimens. The overall nominal slab dimensions were 1.5 m by 355 mm wide by 100 mm deep (5 ft by 14 in wide by 4 in deep). The rebar samples were located in the middle of the slab on 50-mm (2-in) centers. The specimens had a nominal cover thickness of 40 mm (1.5 in). The concrete used for casting the slab was composed of an ASTM Type I portland cement, clean sand, and a coarse aggregate mixture. The water-to-cement ratio was about 0.5. The concrete was mixed with a high water-to-cement ratio (0.50) and high chloride content 9-kg/m³ (15-lb/yd³) concrete. Chloride content was increased by adding an appropriate amount of sodium chloride. After casting, the concrete was allowed to cure for a 28-day period.

During the test period, beams were exposed to a constant load sufficient to initiate cracking (estimated to be in the 1- to 5-metric ton range). Cracks in the concrete were intended to accelerate the degradation of the coated rebars. The beams were ponded daily with seawater to further increase the severity of exposure.

At the conclusion of the 18-month test period, the rebars were physically removed from the beams by carefully breaking away the concrete. Underfilm corrosion was characterized at the intentional coating holidays. The quality and location of pinhole rusting in the coatings were also noted. Coating hardness and thickness were also measured before and after testing.

RESULTS OF TESTING

The following is a summary of the results of each test performed on the various candidate powder coating systems. Emphasis has been placed on the more meaningful types of data as interpreted by the results. These results are accompanied by appropriate discussion and comments. Many of the less meaningful results are omitted or presented with minimal discussion. A general discussion of the test results for specific coating types is included in the section, "Discussion of Powder Coating Materials."

TASK C - ACCELERATED WEATHERING AND NATURAL MARINE EXPOSURE TESTING

Of the five different rating parameters for exposure tests (rusting of coated plane surfaces, blistering on coated plane surfaces, underfilm corrosion radius, coating disbondment radius, and U-channel rusting), the underfilm corrosion and coating disbondment data were the most meaningful. Rusting or blistering on coated plane surfaces for the exposure tests was not common. Rusting of the U-channel was not a significant factor in the overall performance of the coating systems.

Natural Marine Exposure

After 18 months of marine atmosphere exposure, the only failure exhibited by the majority of the coating systems was underfilm corrosion at intentional holidays. With only one exception, underfilm corrosion radius around intentional holidays was closely related to the radius of coating disbondment.¹ None of the systems exhibited blistering on the coated plane surfaces. Rusting of coated plane surfaces was observed on the A775 epoxy (system 4) and on the proprietary polyester (system 7). The acrylic coatings, being brittle, cracked around the holidays. The system 9 acrylic had significantly more cracking than the system 10 acrylic. Figures 4 and 5 show representative panels from the acrylic coating systems.

Figure 6 shows the average radius of coating disbondment for each system measured destructively after the 18-month exposure period. The figure shows that on the basis of coating disbondment, the zinc-rich epoxy powder and galvanized/TGIC systems performed similarly to the solvent-based control. All other systems had more severe coating disbondment than the solvent-based control. Systems incorporating zinc in the coating had less severe coating disbondment than systems without zinc.

The proprietary solvent zinc primer/powder topcoat system had poor adhesion (total disbondment) of the powder topcoat to the solvent-borne inorganic zinc primer, while the inorganic zinc primer did not experience any degradation. Figure 7 shows the poor intercoat adhesion of the proprietary system.

¹ System 16 panels experienced total topcoat disbondment; the proprietary solvent zinc primer prevented steel substrate corrosion. Thus, the disbondment was not attributed to underfilm corrosion from the intentional holidays.

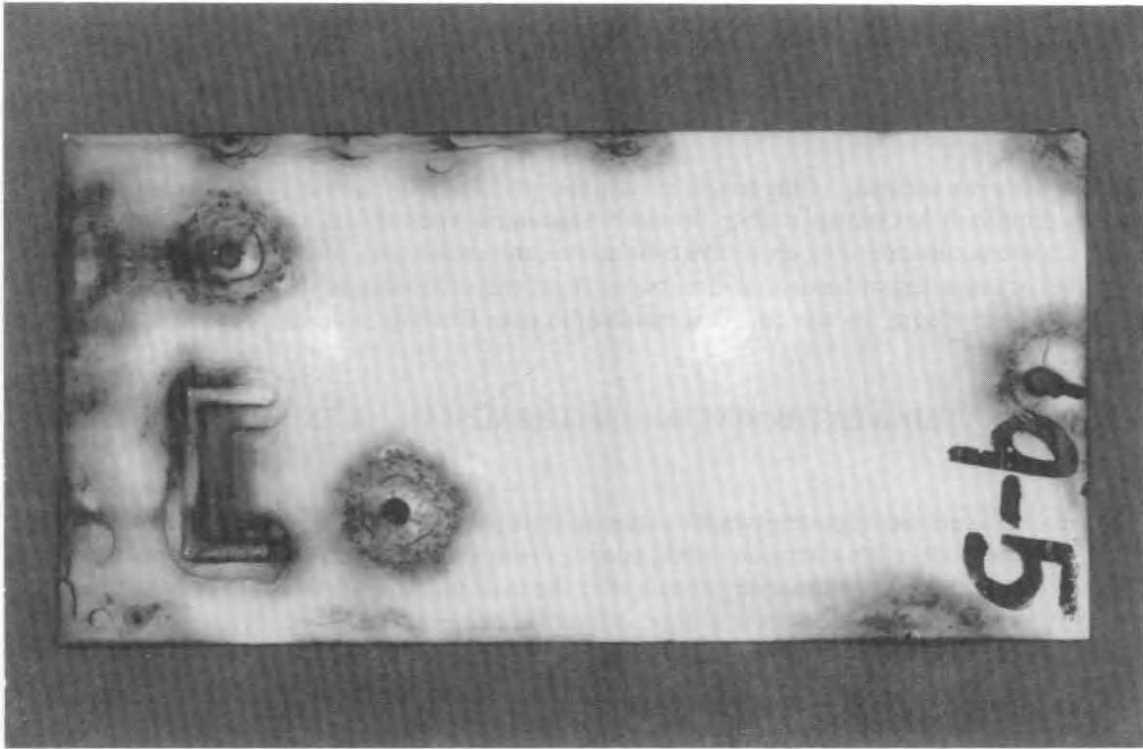


Figure 4. Acrylic (system 9) after marine exposure.

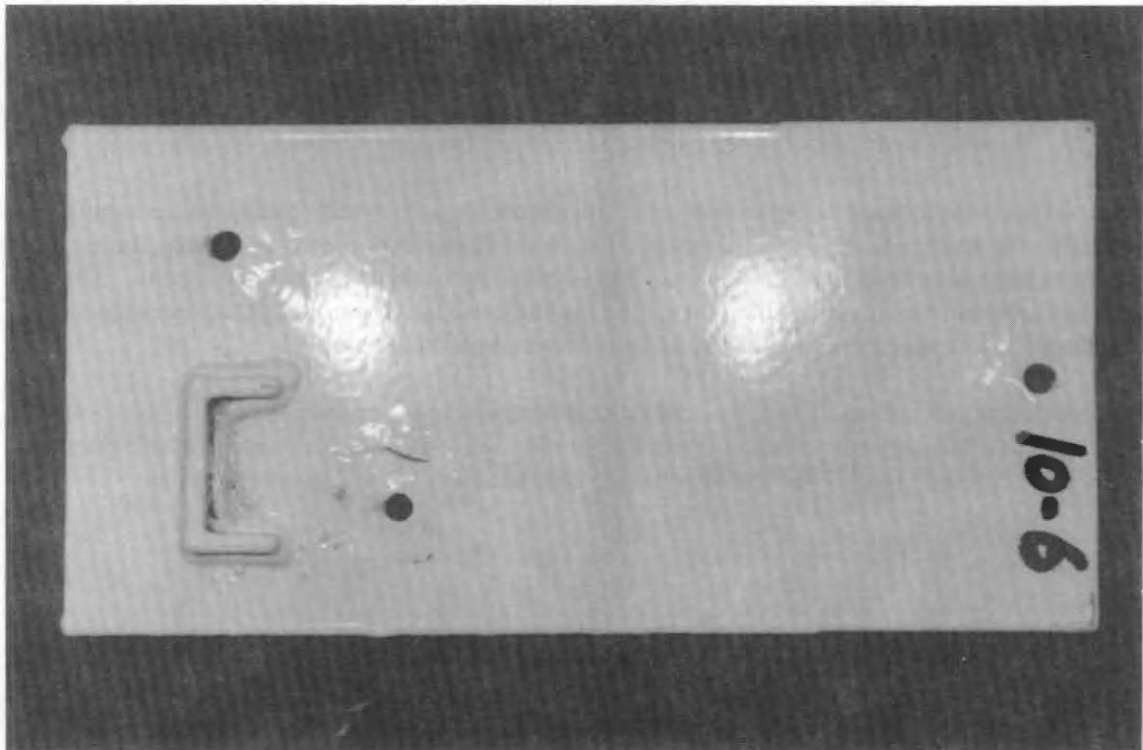


Figure 5. Acrylic (system 10) after marine exposure.

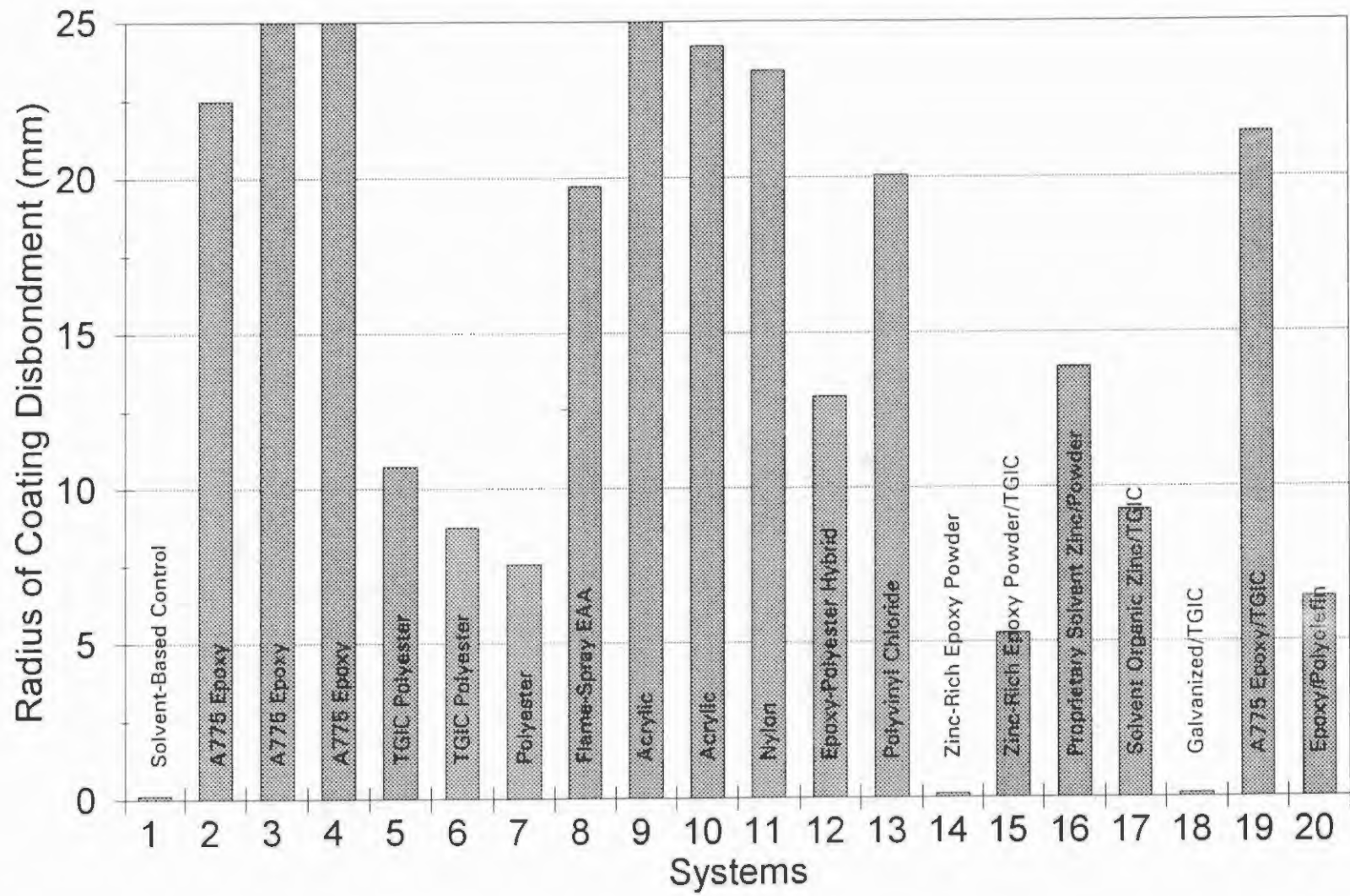


Figure 6. Radius of coating disbondment after 18-month marine atmosphere exposure.

The zinc-rich epoxy powder showed minimal underfilm corrosion. The same coating with a TGIC topcoat had noticeable underfilm corrosion. This may be due to the increased coating thickness of the non-topcoated zinc material [250 to 500 μm (10 to 20 mils) for system 14 versus 112 to 150 μm (4.5 to 6.0 mils) of zinc-rich epoxy powder for system 15].

Of the non-zinc systems, the polyesters and the two-coat systems showed the least underfilm corrosion.

Figure 8 shows blistering around the intentional scribe on the front side of a PVC-coated panel. It is interesting to note that the PVC coating disbonded entirely on the exposed side of the panel, while less disbondment [approximately 25.4 mm (1 in)] was observed on the back of the panel. This may be because the coating on the front of the panel has increased time-of-wetness and increased UV exposure.

Figure 9 shows the relationship between visual observations of underfilm corrosion and destructive measurements. A 2-to-1 relationship between destructive and visual data exists for the powder coatings tested. Observation of a consistent relationship supports the theory that a "front" of coating with poor adhesion appears ahead of active underfilm corrosion. This may be due to moisture penetration or mechanical weakening of the coating to substrate bond. In any case, it clearly shows that the failure is progressing from the defect instead of from phenomcnal action on the film surface (e.g., water vapor transmission).

Figure 10 shows the gloss data before and after exposure. Clearly, the polyesters and acrylics had the best gloss retention. Most colored panels faded in the natural marine environment. Figure 11 shows the front (facing sunlight) and back (shadowed by the panel) of PVC-coated panels (system 13) after 18 months of exposure. The flame-spray EAA panels (system 8) also faded significantly during the exposure test. Figure 12 shows chalking of a zinc-rich epoxy powder-coated panel (system 14).

Table 3 summarizes the results of the natural marine atmosphere exposure.

Salt Fog/Marine Exposure

Figure 13 shows average radius of coating disbondment for each system measured destructively after the complete 9-month exposure period. None of the powders outperformed the solvent-based control.

The only coatings that showed significant rust-through were one of the polyesters (system 7) and one of the acrylics (system 9). Both of the coatings on these systems were brittle and cracked during exposure. Figures 14 and 15 show representative panels after exposure. All other systems had an ASTM D610 rust rating for plane surfaces of "9" or better.

Zinc loading of the epoxy powder improved the coatings' performance. Notice the relative difference in the performance of the systems incorporating zinc into the system (systems 14 through 17).

Table 4 summarizes relative coating performance.

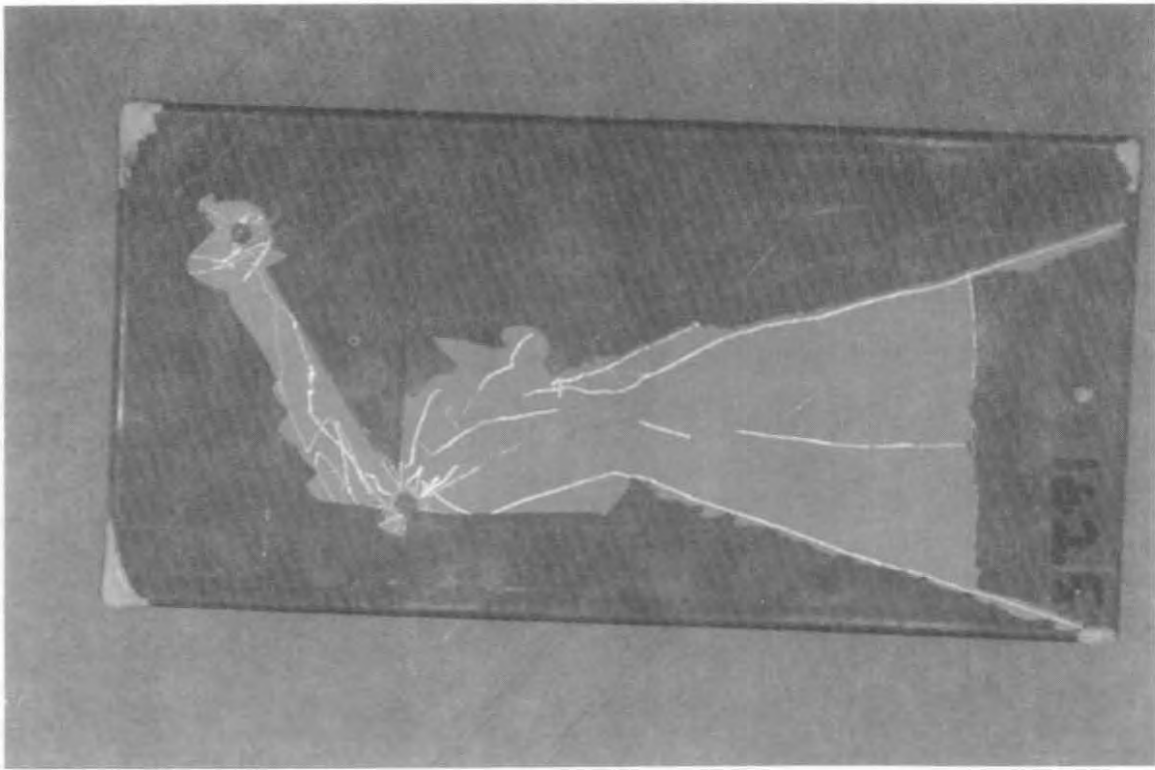


Figure 7. Poor intercoat adhesion of proprietary solvent zinc/powder (system 16) after marine exposure.

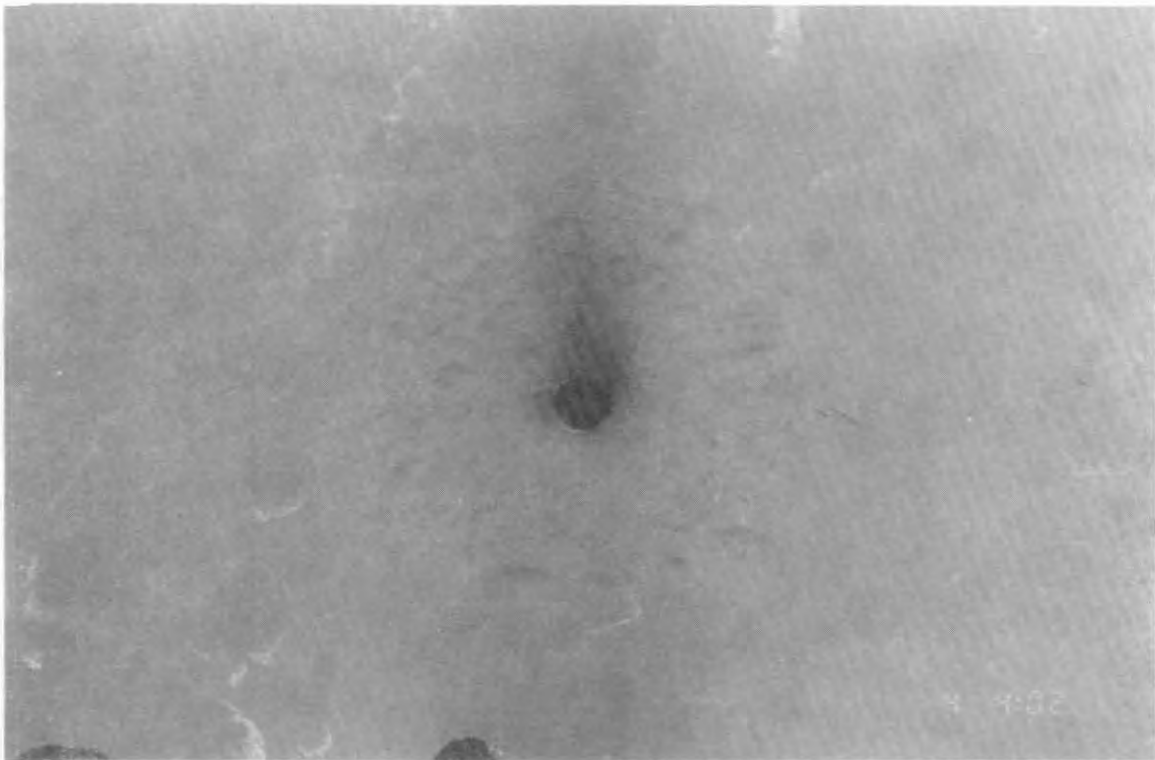


Figure 8. Blistering around holiday on PVC (system 13) panel after marine exposure.

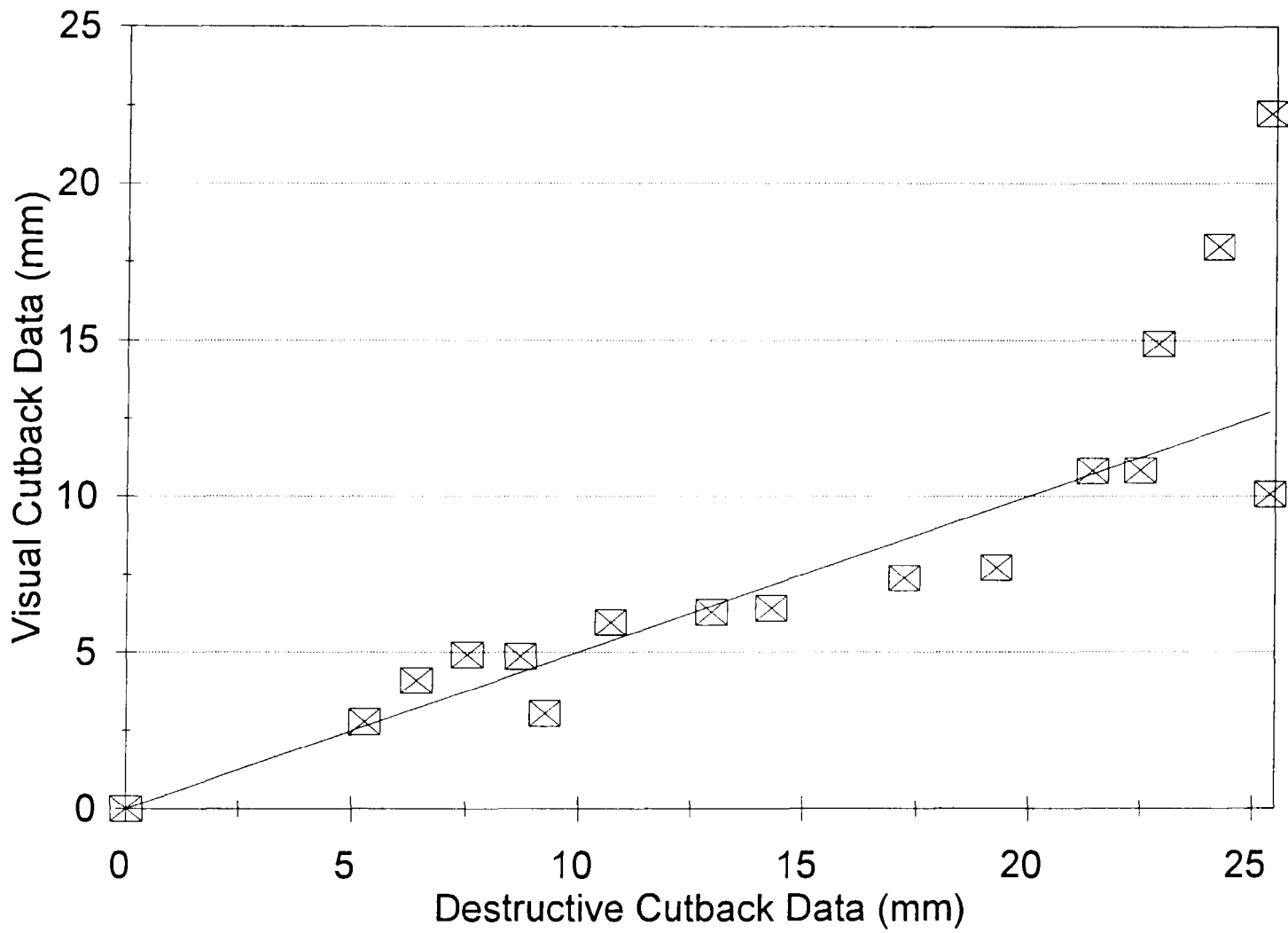


Figure 9. Correlation between coating disbondment observed visually and destructively.

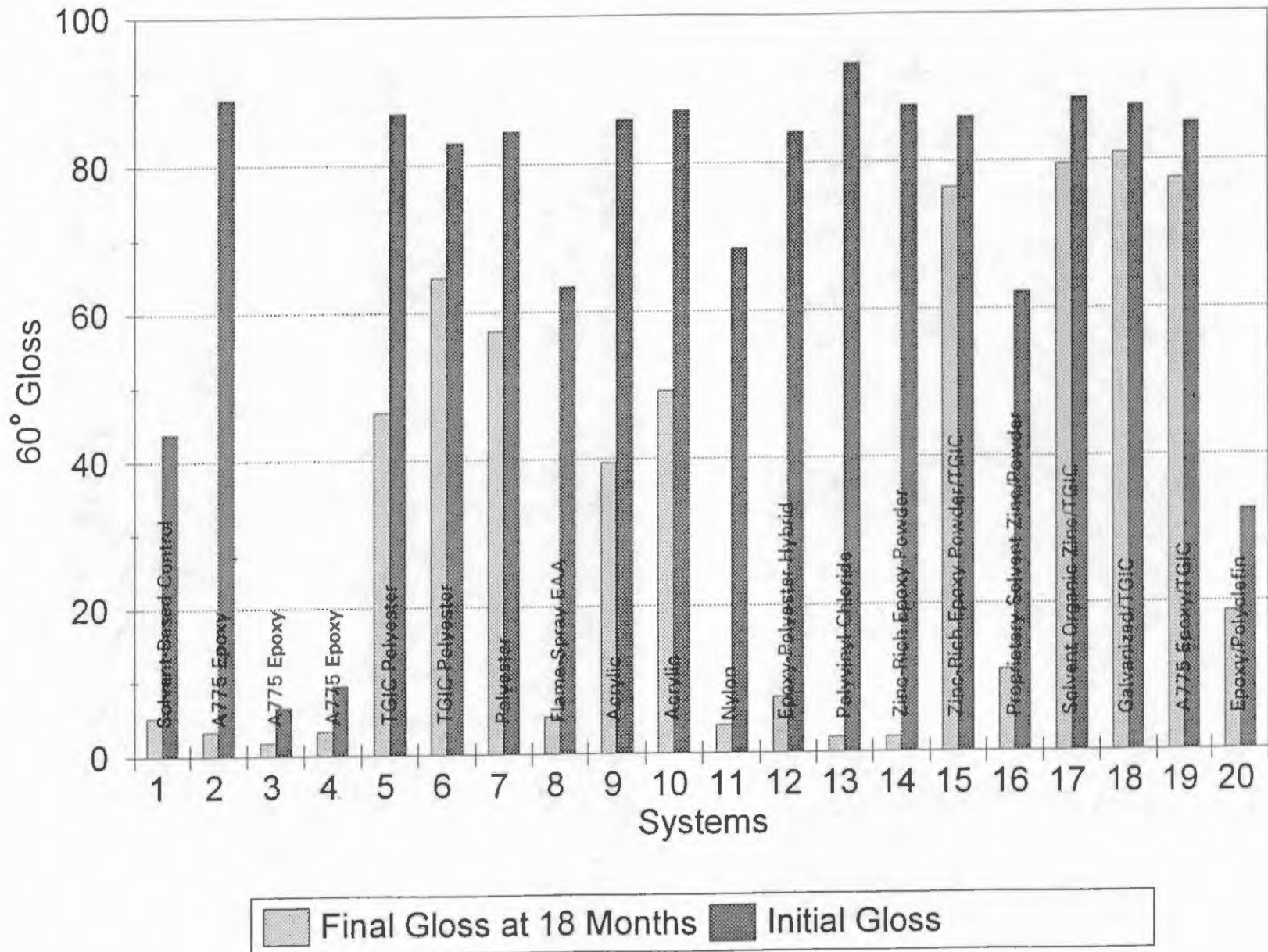


Figure 10. Coating gloss after 18-month marine atmosphere exposure and prior to exposure.

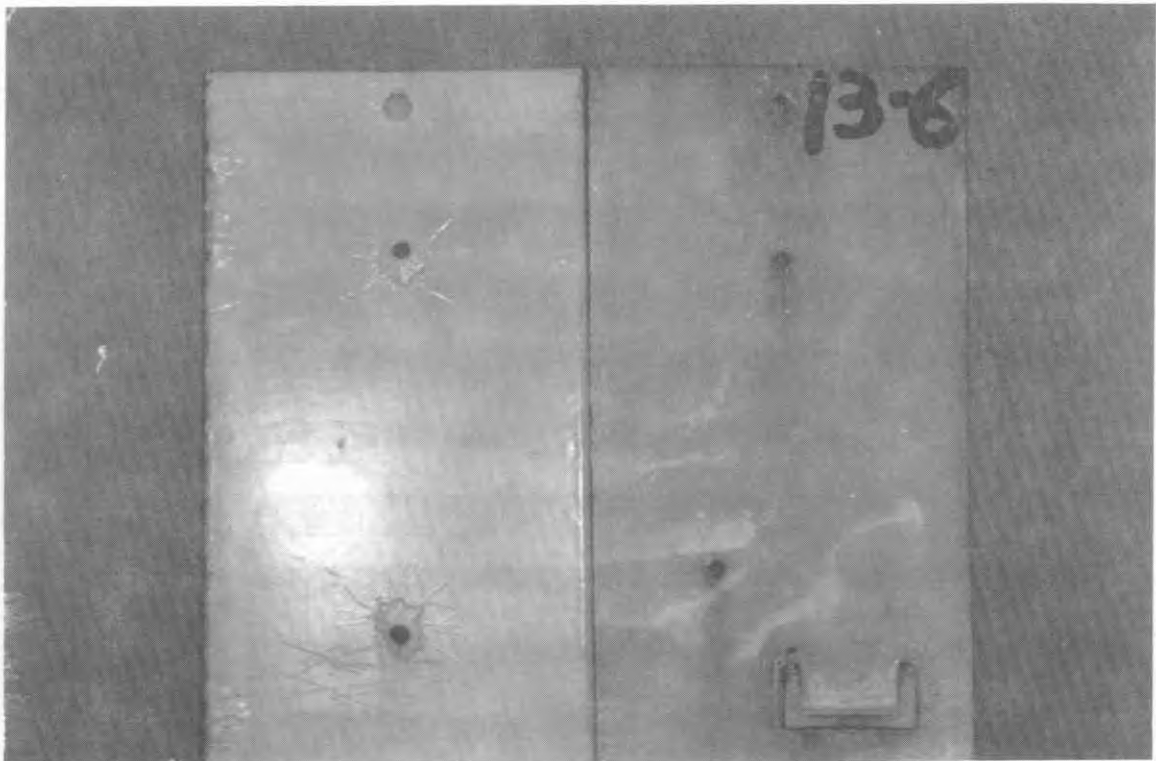


Figure 11. PVC (system 13) panel back (left) and front (right).

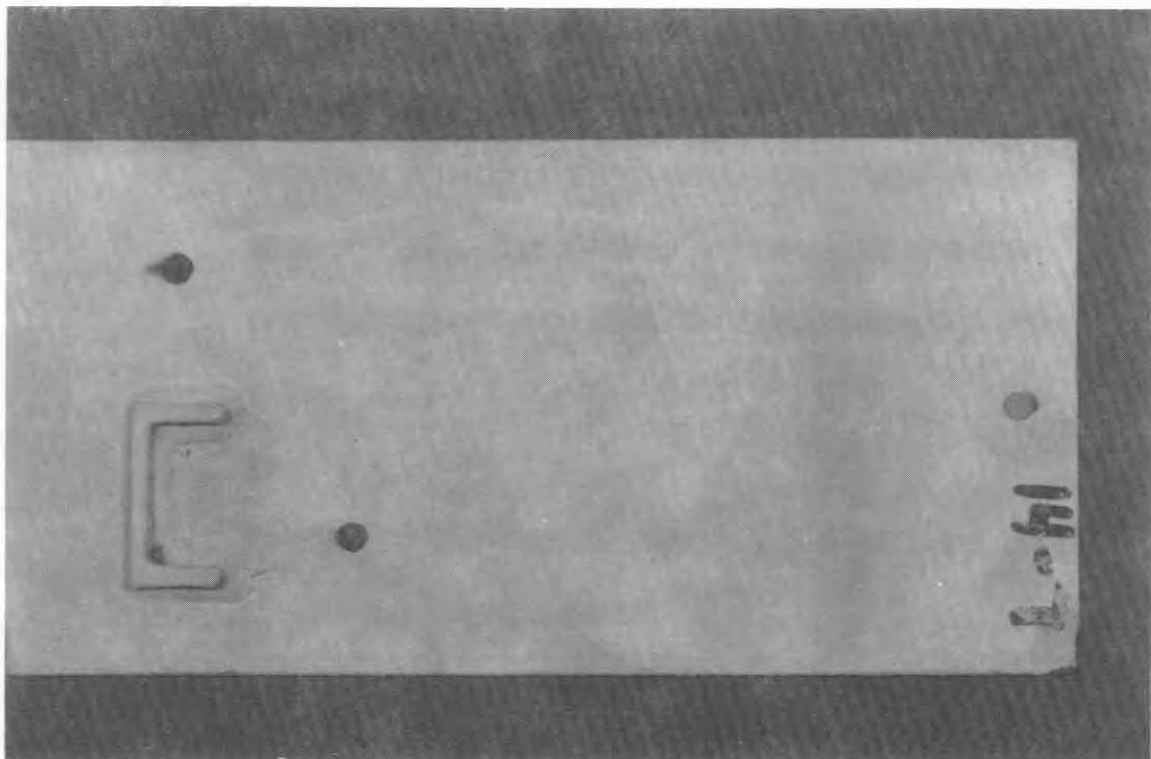


Figure 12. Chalking on zinc-rich epoxy powder (system 14).

Table 3. Natural marine exposure test summary.

Phenomena	<6.35-mm average for all holidays	6.35- to 19-mm average for all holidays	>19-mm average for all holidays
Underfilm Corrosion Around Holidays	(1) Solvent-Based Control (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/TGIC (16) Proprietary Solvent Zinc/Powder (18) Galvanized/TGIC (20) Epoxy/Polyolefin	(5) TGIC Polyester (6) TGIC Polyester (7) Polyester (8) Flame-Spray EAA (12) Epoxy-Polyester Hybrid (17) Solvent Organic Zinc/TGIC (19) A775 Epoxy/TGIC	(2),(3),(4) A775 Epoxies (9) Acrylic (10) Acrylic (11) Nylon (13) Polyvinyl Chloride
Gloss Retention	Less than 25% loss of gloss	Between 25% and 75% loss of gloss	Greater than 75% loss of gloss
	(6) TGIC Polyester (15) Zinc-Rich Epoxy Powder/TGIC (17) Solvent Organic Zinc/TGIC (18) Galvanized/TGIC (19) A775 Epoxy/TGIC	(3),(4) A775 Epoxies (5) TGIC Polyester (9) Acrylic (10) Acrylic (20) Epoxy/Polyolefin	(1) Solvent-Based Control (2) A775 Epoxy (8) Flame-Spray EAA (11) Nylon (12) Epoxy-Polyester Hybrid (13) Polyvinyl Chloride (14) Zinc-Rich Epoxy Powder (16) Proprietary Solvent Zinc/Powder
Rusting	ASTM D610 "10" on all panels and no channel rust	ASTM D610 "10" on all panels and rust on at least one channel	ASTM D610 "9" on at least one panel
	(1) Solvent-Based Control (2),(3) A775 Epoxies (10) Acrylic (11) Nylon (16) Proprietary Solvent Zinc/Powder (18) Galvanized/TGIC (19) A775 Epoxy/TGIC (20) Epoxy/Polyolefin	(5) TGIC Polyester (6) TGIC Polyester (8) Flame-Spray EAA (9) Acrylic (12) Epoxy-Polyester Hybrid (13) Polyvinyl Chloride (14) Zinc-Rich Epoxy Powder (17) Solvent Organic Zinc/TGIC	(4) A775 Epoxy (7) Polyester

System number appears in parentheses followed by the generic type.

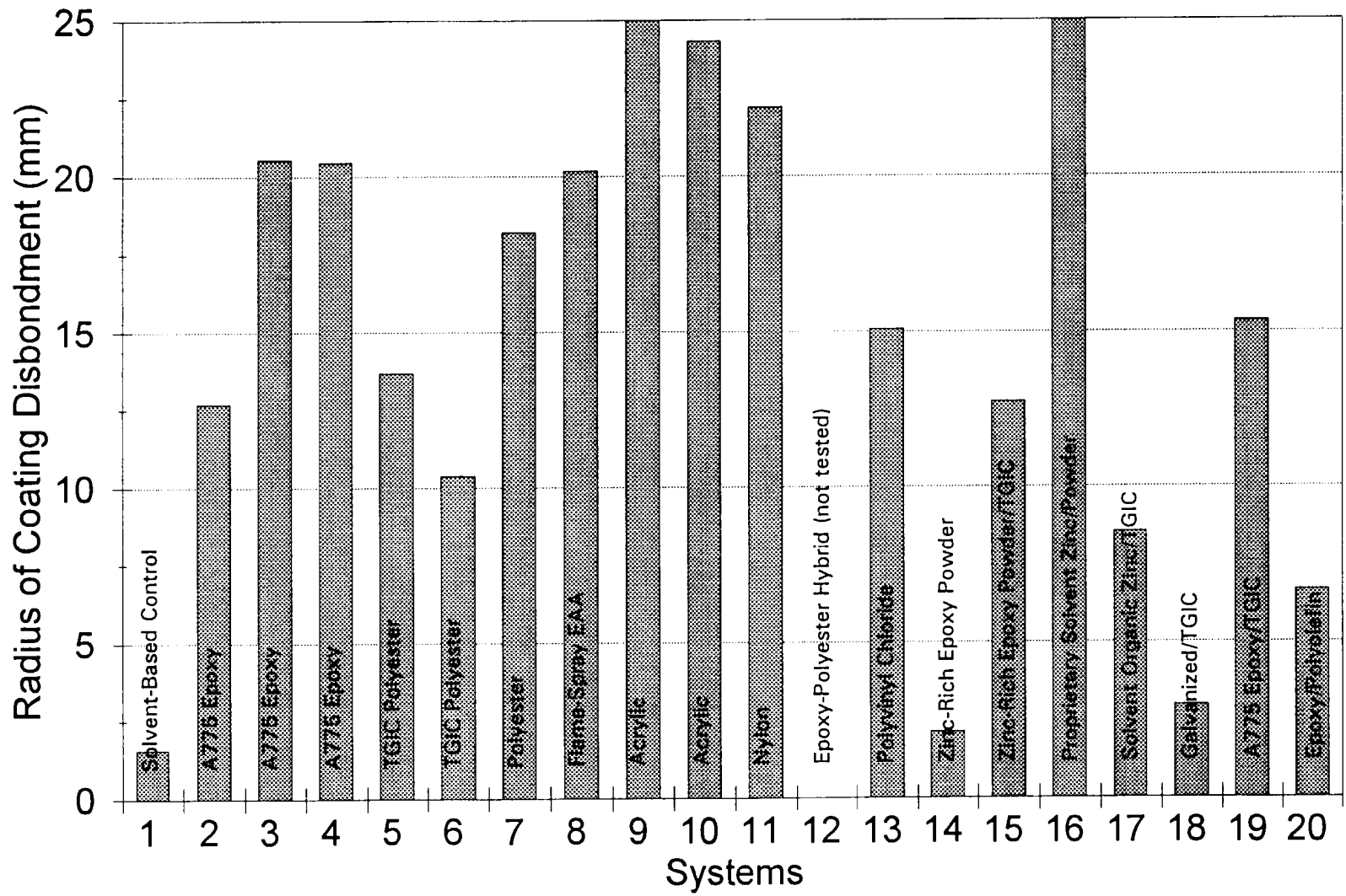


Figure 13. Radius of coating disbondment after cyclic salt fog/marine exposure.

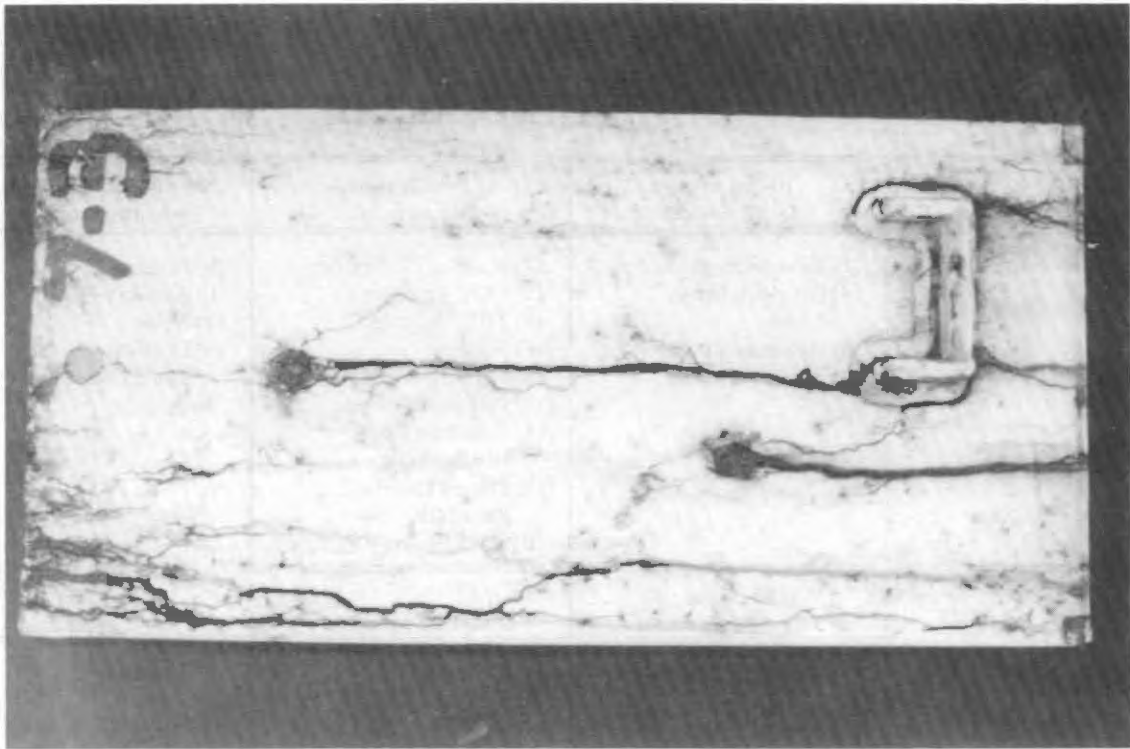


Figure 14. Proprietary polyester (system 7) cracked during salt fog/marine test.

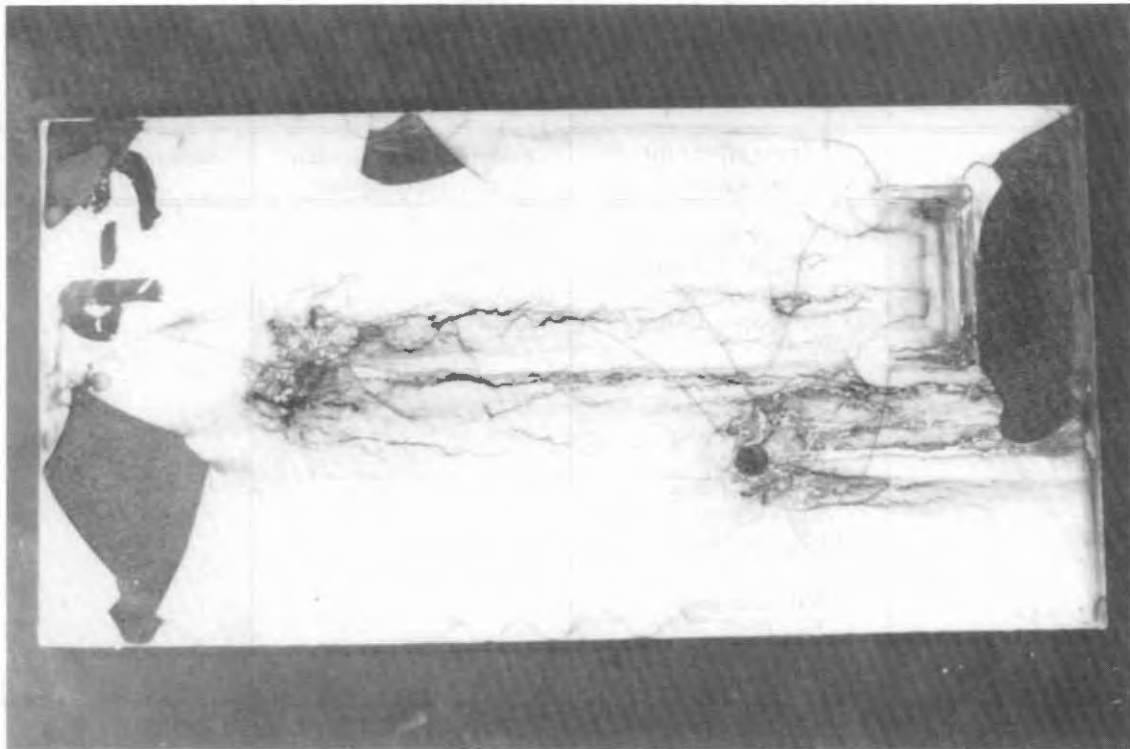


Figure 15. Acrylic (system 9) cracked during salt fog/marine exposure.

Table 4. Cyclic salt fog/marine exposure test summary.

Phenomena	<10-mm average for all surfaces	10- to 20-mm average for all surfaces	>20-mm average for more than one surface
Coating Disbondment	(1) Solvent-Based Control (14) Zinc-Rich Epoxy Powder (18) Galvanized/TGIC (20) Epoxy/Polyolefin	(2),(3),(4) A775 Epoxies (5) TGIC Polyester (6) TGIC Polyester (7) Polyester (8) Flame-Spray EAA (13) Polyvinyl Chloride (15) Zinc-Rich Epoxy Powder/TGIC (17) Solvent Organic Zinc/TGIC (19) A775 Epoxy/TGIC	(9) Acrylic (10) Acrylic (11) Nylon (16) Proprietary Solvent Zinc/Powder
Rusting	ASTM D610 "10" on all panels	ASTM D610 "9" or better on all panels	ASTM D610 less than "9" on at least one panel
	(1) Solvent-Based Control (2) Epoxy (11) Nylon (16) Proprietary Solvent Zinc/Powder (20) Epoxy/Polyolefin	(3),(4) A775 Epoxies (5) TGIC Polyester (6) TGIC Polyester (8) Flame-Spray EAA (10) Acrylic (13) Polyvinyl Chloride (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/TGIC (17) Solvent Organic Zinc/TGIC (18) Galvanized/TGIC (19) A775 Epoxy/TGIC	(7) Polyester (9) Acrylic
Blistering	ASTM D714 "10" on all panels	Scattered blisters on a few panels off the system	Blistering on all panels of the system
	(1) Solvent-Based Control (2),(3),(4) A775 Epoxies (5) TGIC Polyester (8) Flame-Spray EAA (9) Acrylic (11) Nylon (13) Polyvinyl Chloride (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/TGIC (16) Proprietary Solvent Zinc/Powder (17) Solvent Organic Zinc/TGIC (19) A775 Epoxy/TGIC (20) Epoxy/Polyolefin	(6) TGIC Polyester (7) Polyester (10) Acrylic (18) Galvanized/TGIC	

System number appears in parentheses followed by the generic type.

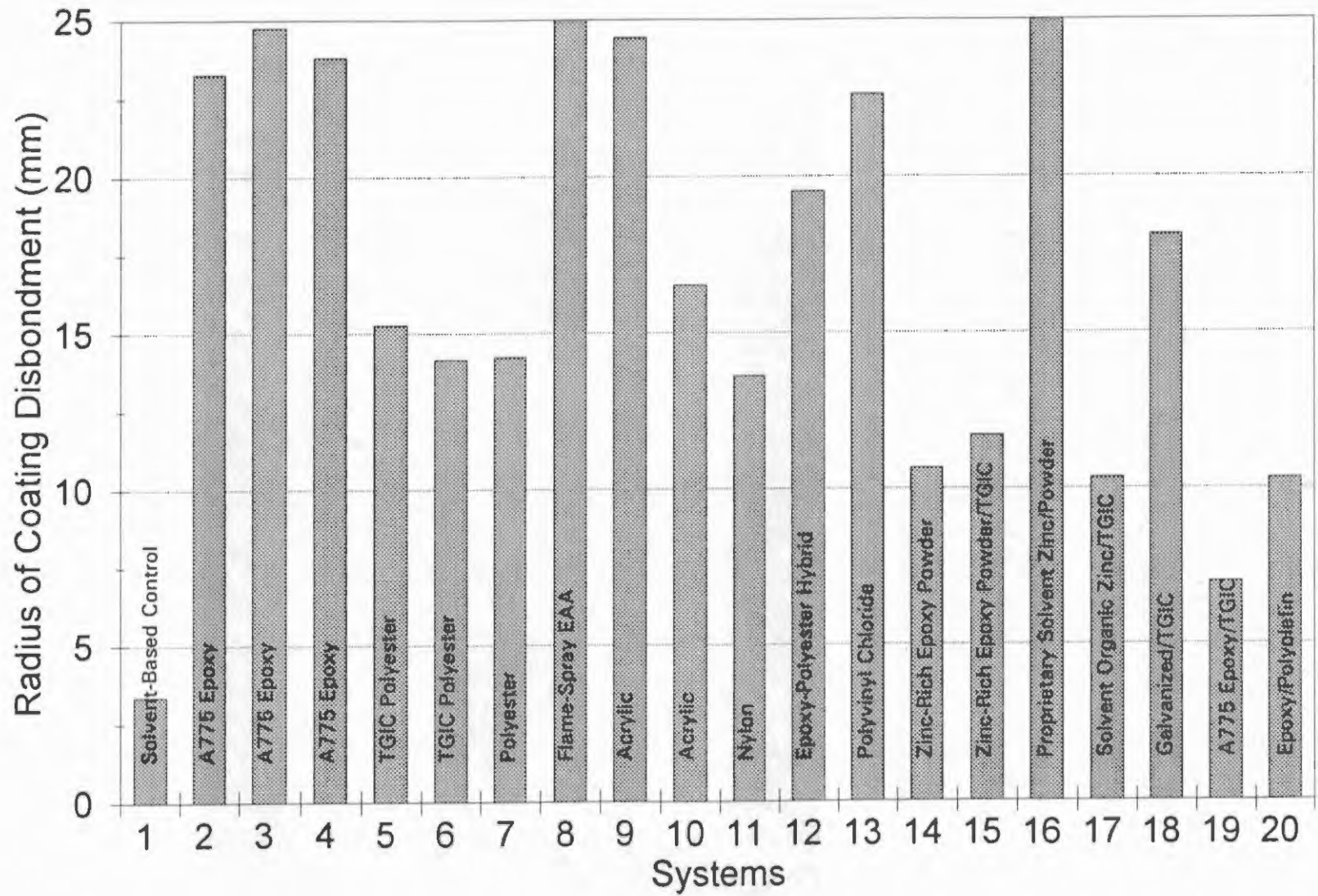


Figure 16. Radius of coating disbondment after cyclic high-pressure/high-temperature seawater immersion.

Cyclic High-Pressure/High-Temperature Seawater Exposure

Figure 16 shows average radius of coating disbondment for each system measured destructively after the complete 9-month exposure period. None of the powders outperformed the solvent-based control.

The proprietary polyester coating (system 7) cracked extensively during exposure. Figure 17 shows a representative panel after exposure. Figure 18 shows one of the A775 epoxy-coated panels (system 3) with rusting at pinholes. This system did not appear to flow properly during application. The film had a rough finish, with scattered pinholes. All other systems had an ASTM D610 rating of "8" or better for coated plane surfaces.

Panels from the PVC system were consistently blistered. Figure 19 shows a representative panel. Several systems had a few scattered blisters on some panels. They included a TGIC (system 6), both acrylics (systems 9 and 10), the epoxy-polyester hybrid (system 12), and the galvanized/ TGIC (system 18). None of the other systems had any blistering after the test.

Table 5 summarizes the results of the high-pressure/high-temperature testing.

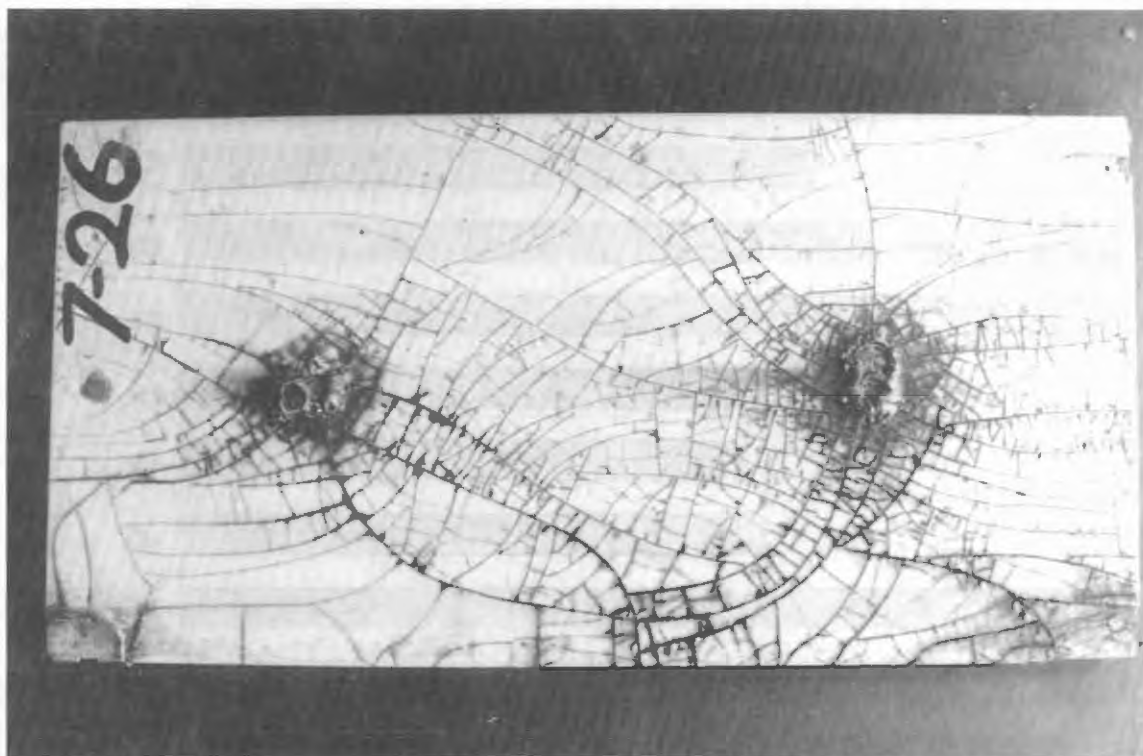


Figure 17. Proprietary polyester (system 7) after cyclic immersion testing.

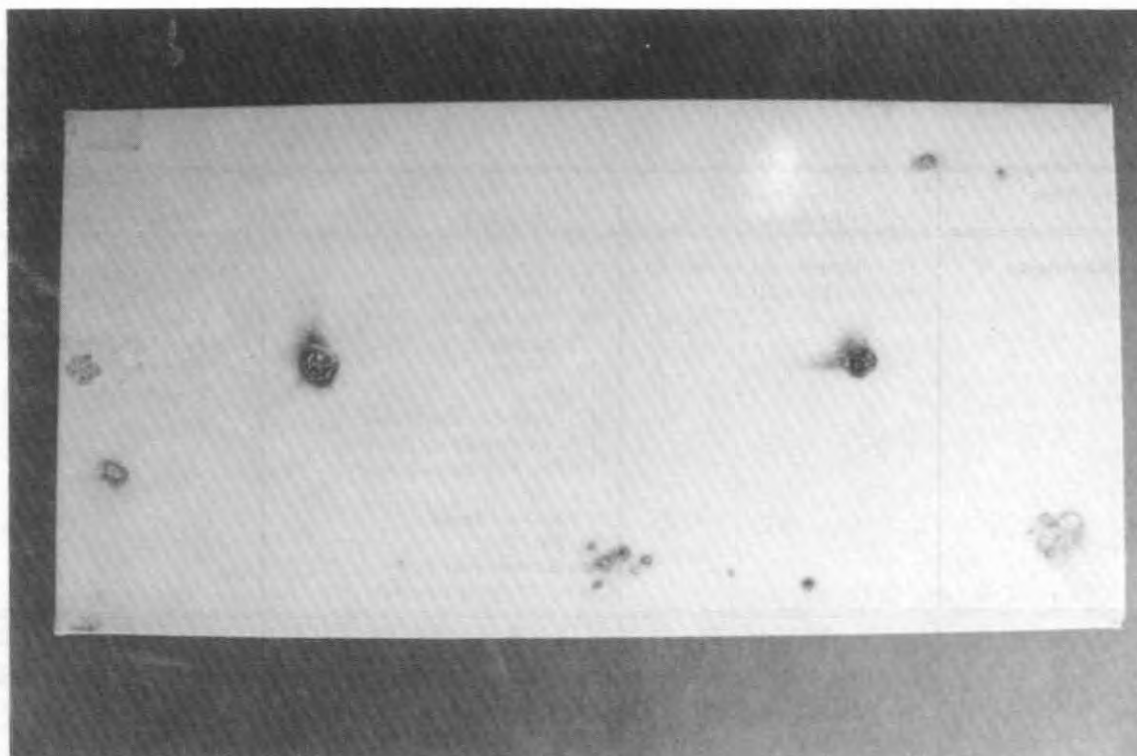


Figure 18. A775 (system 3) epoxy coating after cyclic immersion testing.

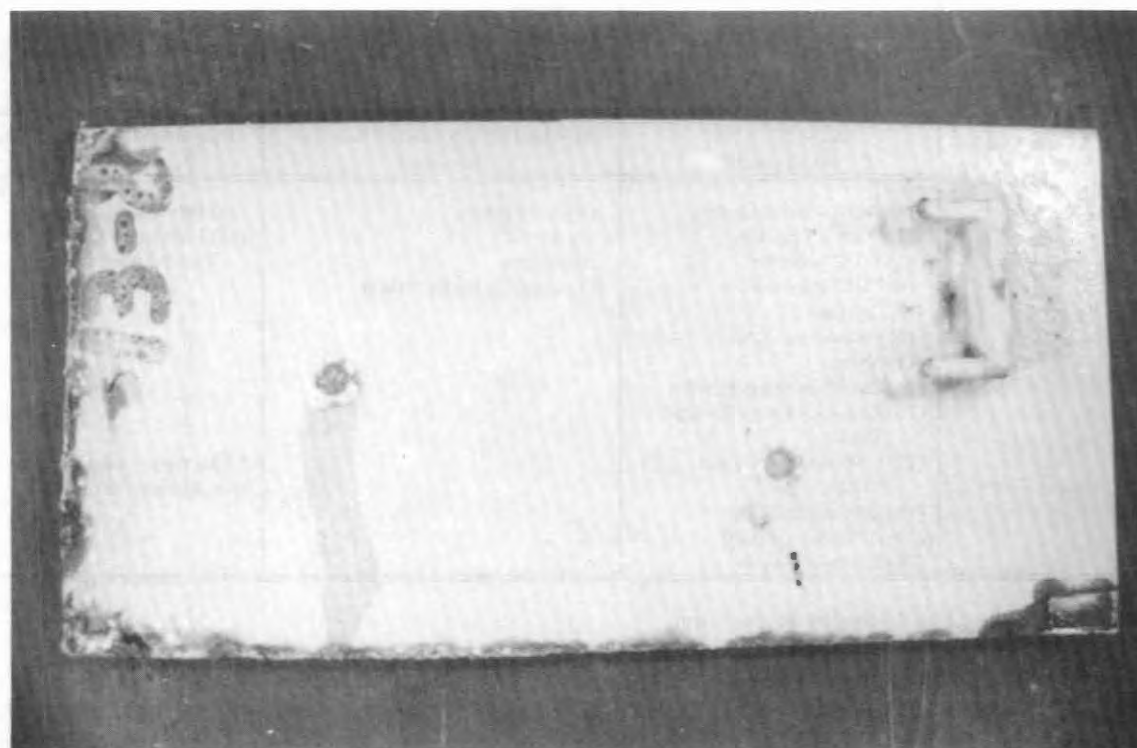


Figure 19. PVC (system 13) coated test panel after cyclic immersion testing.

Table 5. Cyclic high-pressure/high-temperature seawater immersion test summary.

Phenomena	<10-mm average for all surfaces	10- to 20-mm average for all surfaces	>20-mm average for more than one surface
Coating Disbondment	(1) Solvent-Based Control (19) A775 Epoxy/TGIC	(2) A775 Epoxy (5) TGIC Polyester (6) TGIC Polyester (7) Polyester (10) Acrylic (11) Nylon (12) Epoxy-Polyester Hybrid (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/ TGIC (17) Solvent Organic Zinc/TGIC (18) Galvanized/TGIC (20) A775 Epoxy/Polyolefin	(3),(4) A775 Epoxies (8) Flame-Spray EAA (9) Acrylic (13) Polyvinyl Chloride (16) Proprietary Solvent Zinc/Powder
Rusting	ASTM D610 "10" on all panels	ASTM D610 "8" or better on all panels	ASTM D610 less than "8" on at least one panel
	(1) Solvent-Based Control (2) A775 Epoxy (11) Nylon (16) Proprietary Solvent Zinc/Powder (20) Epoxy/Polyolefin	(3),(4) A775 Epoxies (5) TGIC Polyester (6) TGIC Polyester (8) Flame-Spray EAA (9) Acrylic (10) Acrylic (12) Epoxy-Polyester Hybrid (13) Polyvinyl Chloride (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/ TGIC (17) Solvent Organic Zinc/TGIC (18) Galvanized/TGIC (19) A775 Epoxy/TGIC	(7) Polyester
Blistering	ASTM D714 "10" on all panels	Scattered blisters on a few panels of the system	Blistering on all panels of the system
	(1) Solvent-Based Control (2),(3) A775 Epoxies (5) TGIC Polyester (6) TGIC Polyester (7) Polyester (8) Flame-Spray EAA (11) Nylon (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/ TGIC (17) Solvent Organic Zinc/ TGIC (18) Galvanized/TGIC (19) A775 Epoxy/TGIC (20) Epoxy/Polyolefin	(4) A775 Epoxy (9) Acrylic (10) Acrylic (12) Epoxy-Polyester Hybrid	(13) Polyvinyl Chloride (16) Proprietary Solvent Zinc/Powder* * This system was removed after 3 months of testing.

System number appears in parentheses followed by the generic type.

Anodic Disbondment Testing

Table 6 summarizes the results of the anodic disbondment testing. Three categories for the amount of coating disbondment were developed to summarize the data. Blistering of the coatings around the holidays was the primary mode of failure. Removal of the blisters revealed a black corrosion product. The pH of the fluid in the blisters was more acidic than the bulk solution (observations consistent with those of Sagues and Powers).⁽³⁾

Table 6. Anodic disbondment test results summary.

<6.35-mm Cutback	6.35- to 19-mm Cutback	9-mm Cutback
(4) A775 Epoxy (5) TGIC Polyester (6) TGIC Polyester (7) Polyester (12) Epoxy-Polyester Hybrid (14) Zinc-Rich Epoxy Powder (15) Zinc-Rich Epoxy Powder/TGIC (18) Galvanized/TGIC	(2),(3) A775 Epoxies (11) Nylon (19) A775 Epoxy/TGIC	(8) Flame-Spray EAA (9) Acrylic (10) Acrylic (13) Polyvinyl Chloride (16) Proprietary Solvent Zinc/Powder (17) Solvent Organic Zinc/TGIC

System number appears in parentheses followed by the generic type.

TASK D - ELECTROCHEMICAL AC IMPEDANCE TESTING

Electrochemical ac impedance testing produces results that are cumbersome to analyze. A detailed presentation of the analyses are beyond the intent of this report. For simplicity, the impedance data were reduced to indicate the percent of the film that appears to have absorbed water. Table 7 summarizes the results of this analysis. Systems 4, 6, 7, 11, and 16 experienced the most significant water penetration. All other systems experienced water penetration of less than 50 percent of the coating thickness.

Table 7. Water penetration test results summary.

Penetration of less than 15% of the original coating thickness	Penetration of the original coating thickness between 15% and 50%	Penetration of more than 50% of the original coating thickness
(2),(3) A775 Epoxies (5) TGIC Polyester (8) Flame-Spray EAA (12) Epoxy-Polyester Hybrid (13) Polyvinyl Chloride (14) Zinc-Rich Epoxy Powder	(9) Acrylic (10) Acrylic (15) Zinc-Rich Epoxy Powder/TGIC (17) Solvent Organic Zinc/ A775 Epoxy (18) Galvanized/A775 Epoxy (19) A775 Epoxy/TGIC	(4) A775 Epoxy (6) TGIC Polyester (7) Polyester (11) Nylon (16) Proprietary Solvent Zinc/Powder

System number appears in parentheses followed by the generic type.

TASK E - ACCELERATED TESTING OF COATED REBAR

Table 8 summarizes quality assurance/quality control testing of rebars conducted before exposure. Figure 20 shows the number of holidays detected using two different holiday detectors versus the measured film thickness for the rebars used for testing. The graph suggests that it is very difficult to meet both the coating thickness criteria and the holiday requirements. This difficulty may be because the powder coating applicator used spray equipment rather than the more common fluidized bed equipment. The graph also demonstrates the increased sensitivity of the higher voltage detector.

Table 8. QC data for exposure test rebars.

Coating	Beam	Average DFT, μm	Pencil Scratch Hardness	1000-V Holidays per meter	67.5-V Holidays per meter
A775 Epoxy (System 2)	1	303.02	H	0.82	0.82
	2	323.60	2H	1.64	2.46
	3	272.03	2H	9.84	4.10
A775 Epoxy (System 3)	1	123.44	3H	>150.00	50.85
	2	154.18	3H	>150.00	31.17
	3	150.37	3H	>150.00	41.83
TGIC Polyester (System 6)	1	142.49	2H	>150.00	31.99
	2	148.59	3H	60.70	32.81
	3	265.43	3H	55.77	31.17
Epoxy-Polyester Hybrid (System 12)	1	419.86	4H	1.64	0.82
	2	470.66	3H	1.64	0.82
	3	466.34	3H	0.00	0.00
Zinc-Rich Epoxy Powder (System 14)	1	371.86	4H	N/A	0.82
	2	390.14	4H	N/A	0.00
	3	397.76	5H	N/A	0.00
Organic Zinc/A775 Epoxy (System 17)	1	251.21	2H	124.67	24.61
	2	259.08	3H	53.31	13.94
	3	107.01	2H	32.81	22.15

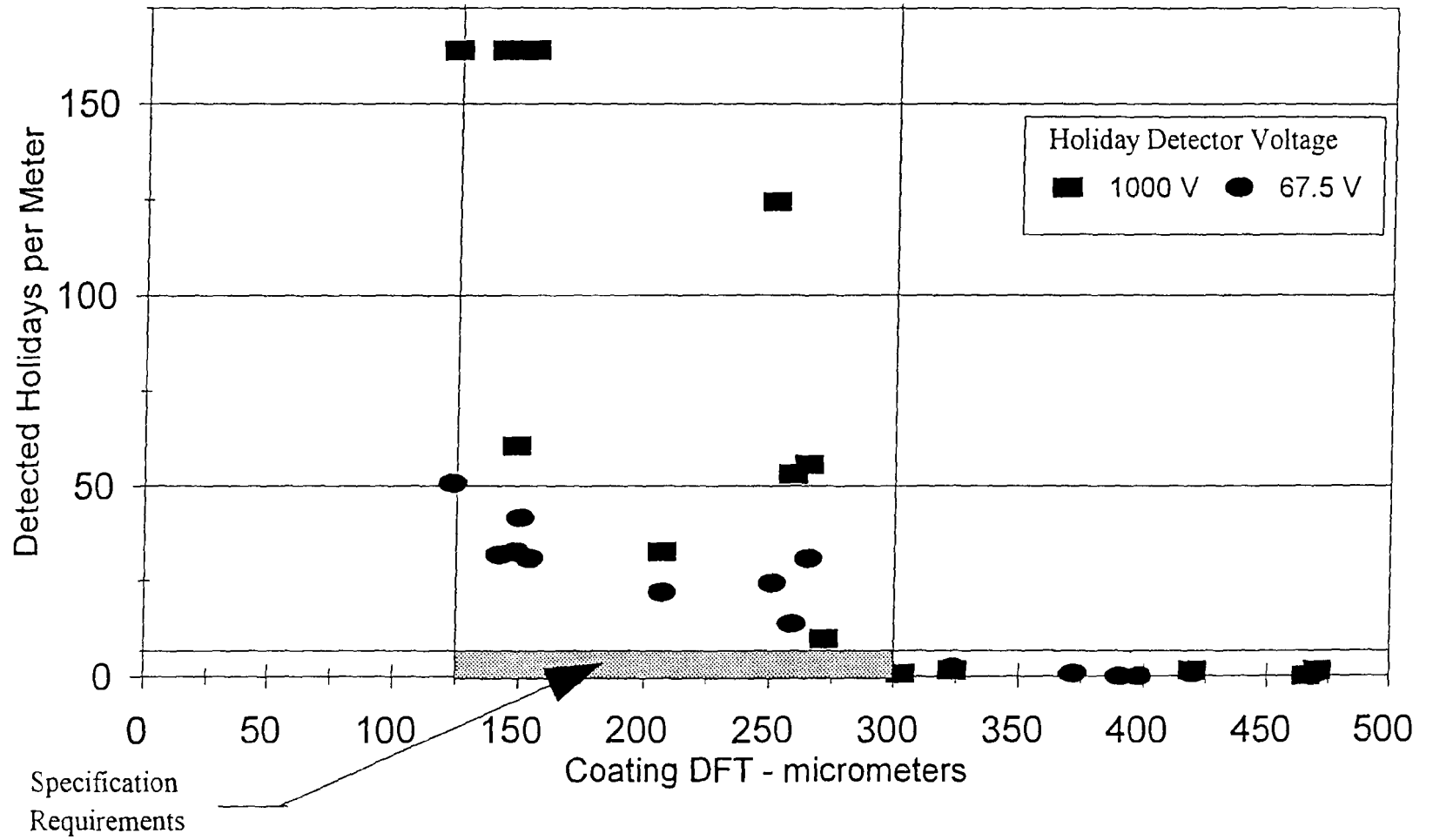


Figure 20. Detected holidays at various coating thicknesses from rebar QC data.

After approximately 18 months of exposure, two beams were removed. The concrete was carefully broken from around the reinforcing bars so the coating could be inspected. Figure 21 shows the bars from beam 1. The left ends of the rebars were intentionally not coated. The uncoated sections of the rebars that were more than 12.7 mm (0.5 in) from the coating edge were successfully passivated by the concrete and were not corroding. The rebars were corroding where the coating edge appeared to prohibit the concrete from adequately passivating the steel. The same coatings in both beams exhibited similar modes of failure, though beam 2 appeared less corrosive than beam 1. This may be due to the slightly increased thickness of the coatings on the beam 2 rebars (see table 8).

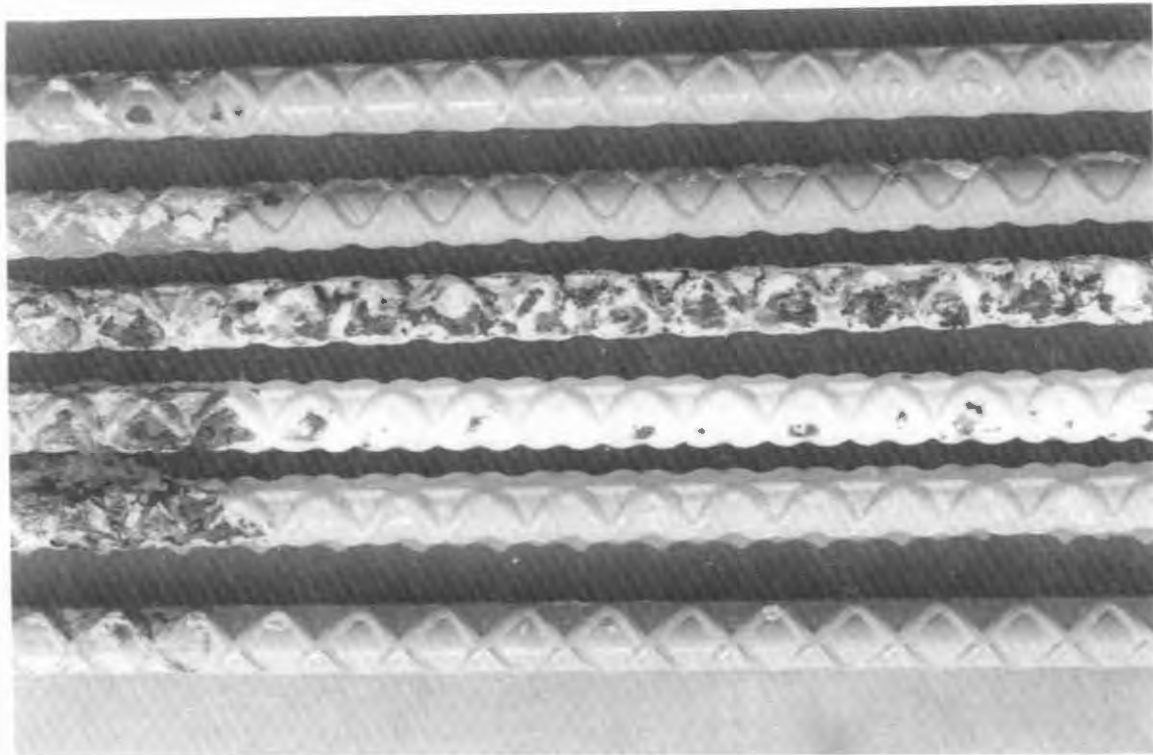


Figure 21. Coated rebars removed from beam. [From top to bottom (systems in parentheses): A775 Epoxy (2), [300 μm (12 mils)]; A775 Epoxy (3), [150 μm (6 mils)]; TGIC Polyester (6); Epoxy-Polyester Hybrid (12); Zinc-Rich Epoxy Powder (14); Solvent Organic Zinc/A775 Epoxy (17).]

Table 9 shows the results of coating tests performed on the rebar after exposure.

Table 9. Post-exposure rebar coating inspection.

Coating	Beam	Pinhole Rust Spots per Meter	Pencil Scratch Hardness (change from initial)	Coating Cutback, mm
A775 Epoxy (System 2)	1	7.38	F (1 softer)	22.23
	2	6.56	H (1 softer)	20.64
A775 Epoxy (System 3)	1	69.72	B (5 softer)	>50
	2	24.61	H,F (2.5 softer)	>50
TGIC Polyester (System 6)	1	74.64	4B (7 softer)	>50
	2	60.70	4H (1 harder)	>50
Epoxy-Polyester Hybrid (System 12)	1	58.23	H (3 softer)	>50
	2	58.23	H (2 softer)	>50
Zinc-Rich Epoxy Powder (System 14)	1	11.48	4H (no change)	4.76
	2	5.74	4H (no change)	7.14
Solvent Organic Zinc/A775 Epoxy (System 17)	1	8.20	F (2 softer)	>50
	2	4.92	F (3 softer)	>50

The following summarizes the performance of each tested rebar coating.

A775 Epoxy (system 2). The coating retained its glossy green color and thickness near the original application [250 to 525 μm (10 to 21 mils)]. The coated sections of the bar had pinhole-type corrosion in a few isolated locations. Density of this corrosion was very light. The most significant corrosion on the bar was located on the uncoated sections of the bar within 12.7 mm (0.5 in) of the coated sections. There were no blisters on the coating. The coating was not easily damaged during the breaking of the concrete cover. Pencil scratch hardness indicated slight softening of the coating.

A775 Epoxy (system 3). This coating retained its thickness near the original application [150 μm (6 mils)]. Figure 22 shows areas of the two A775 epoxy-coated bars after exposure. Note that the top bar was measured to be about 25 μm (1 mil) thinner than the bottom bar (see table 8). The coating was very thin and had a "porous" appearance. Corrosion covered the coated sections of the bar in a medium to dense pinhole-type pattern. Small blisters containing fluid were observed on the coated sections of the bar. Frequency of these blisters was approximately 49.2/linear meter (15/linear foot). This value correlates well with the number of holidays observed using the 67.5-V holiday detector. The pH of the fluid in the blisters was approximately 6, only slightly acidic. The coating was moderately susceptible to damage during the breaking of the concrete cover. Pencil scratch hardness showed that this material softened more than the system 2 epoxy.

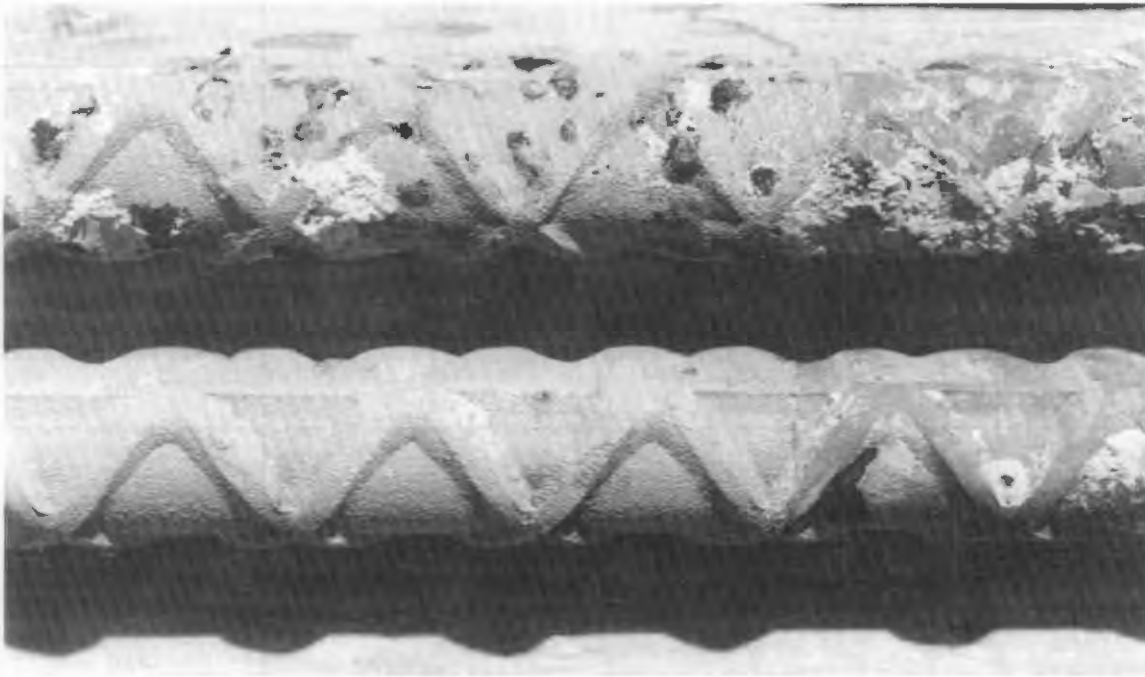


Figure 22. A775 (system 3) epoxy coatings after exposure.
[Beam 1 exposure (top); beam 3 exposure (bottom).]

TGIC Polyester (system 6). This coating appeared to disintegrate during exposure. The alkalinity of the concrete saponified the polyester material. After exposure, the coating was measured to be 20 to 30 μm (0.8 to 1.2 mils) — significantly thinner than the original 127- μm (5-mil) thickness. The coating had a number of pinholes and severe cracking. Corrosion was severe enough to connect several pinhole initiation spots. There were no blisters on the coating. The coating was very susceptible to damage during the breaking of the concrete since it was easily cracked and easily disbonded. Post-exposure pencil scratch hardness data had a significant amount of scatter.

Epoxy-Polyester Hybrid (system 12). This coating was also severely cracked and easily disbonded from the substrate. Pinhole corrosion was moderately severe, but not severe enough that areas of corrosion were connected. There were no blisters on the coating. The coating was very susceptible to damage during the breaking of the concrete due to its tendency to crack. The coating material softened during exposure.

Zinc-Rich Epoxy Powder (system 14). This coating was only corroding within 25.4 mm (1 in) from the uncoated sections of the bar. There were no blisters on the coating. The coating was not easily damaged during the breaking of the concrete cover. This was the only coating material that did not show signs of softening after exposure.

Solvent Organic Zinc/A775 Epoxy (system 17). No corrosion or blistering of the coating was observed. The coating was susceptible to damage during the breaking of the concrete as several nicks and abrasions were observed. The epoxy topcoat cut back easily from the solvent organic zinc primer. The epoxy topcoat softened during exposure. Note that the topcoat is the same A775 material as system 2, but it exhibited more softening as the topcoat for system 17.

DISCUSSION OF POWDER COATING MATERIALS

There are several different types of powder coatings available commercially today. Table 10 presents some powder coating performance information for generic materials. The physical and performance characteristics of the generic resin types are generally the same as for solvent-based coatings. Powder coating resins are classified into two categories: thermoset and thermoplastic. The types of commercially used powder coatings tested in this program are described below.

Table 10. Generic powder coating performance.

Thermoset Powder Coatings	
Epoxy	good electrical insulation, corrosion protection, and mechanical properties; poor exterior weatherability (i.e., chalks and yellows)
Acrylic	good durability, thin film coatings, better alkali resistance than polyester, brittle at high film builds
Urethane Polyester	good exterior durability, thin film coatings
TGIC Polyester	good exterior durability, slightly thicker than the urethane polyesters, less chemical and solvent resistance than urethane polyester
Epoxy-Polyester Hybrid	similar to epoxy except poor solvent and alkali resistance
Thermoplastic Powder Coatings	
Ethylene Acrylic Acid	good chemical resistance and flexibility, good abrasion and impact resistance, less solvent resistance than other thermoplastics, poor weatherability (i.e., chalks)
Nylon	abrasion, wear and impact resistance; good toughness; low coefficient of friction
Polyvinyl Chloride	durable, flexible, soft, poor weatherability (i.e., chalks)
Polypropylene	inert, poor adhesion without modification
Polyethylene	good chemical resistance, toughness, electrical insulation, and release properties
Thermoplastic Polyester	good adhesion and exterior weatherability

THERMOSET POWDERS

This category of powder coatings is the most popular and has been used since powder coating technology began. The powders are applied to a part at the desired thickness and heated to chemically crosslink the polymer and form a durable permanent film. Typical thermosetting powder resins include epoxies, polyesters, and acrylics. These are widely used for highway applications.

Epoxy Powder

Epoxy coatings are the most common of all functional powder coatings. They provide good mechanical strength and corrosion protection, however their high aromatic content reduces their light and heat stability. As a result, epoxies tend to chalk when exposed to sunlight and are not recommended for outdoor exposure where aesthetics are a concern. The decreased heat stability causes coating process curing variables to be of increased concern.

The American Society for Testing and Materials (ASTM) specification A775 provides a performance standard for epoxy powder coatings to be used for concrete reinforcing bars (rebars). This program included testing of three epoxy powder coatings meeting A775 to show the variability in coating performance among coatings meeting the same specification. Lilly Green-Bar powder epoxy for rebar (system 2) and Skotchkote 213 (system 3) were selected because of their widespread use. These coatings meet AASHTO designation M284/M284-87I, ASTM D3963-86, and ASTM A775-90 as confirmed by Valley Forge Laboratories in April 1991. These materials are qualified products in most States. Skotchkote 213, manufactured by 3M, is used on many reinforced concrete bridges, including some in marine environments. A 3M developmental epoxy, XC6159 (system 4), was also tested. It is being designed to have improved adhesion, particularly under hot, wet conditions. It has been evaluated by Valley Forge Laboratory per ASTM A775-90.

The epoxy-based powder coatings had poor gloss- and color-retention properties when compared to the other powder coatings tested over the exposure periods. The epoxy powders chalked in the natural marine atmosphere exposure tests. Epoxy-coated natural marine exposure, cyclic salt fog/marine exposure, and cyclic high-pressure/high-temperature seawater immersion test panels had worse underfilm corrosion than most other systems. Of special note are the differences in application of the three products. As shown in appendix I, the applicator used the same application condition for all three epoxies. However, the finished systems 3 and 4 had a rougher appearance and thinner film than system 2. Inspection with a high-voltage holiday detector showed scattered pinholes in system 4 panels. This demonstrates the sensitivity of generically similar materials to application conditions.

Acrylic

Acrylics are thermosetting powder coatings that provide good exterior durability. Their impact resistance and flexibility are not as good as polyesters, but they are claimed to have good corrosion protection characteristics. A majority of the acrylics used in industry today are of the urethane type.

Two acrylic powders were selected for testing. EVTECH provided a white acrylic powder coating for testing (system 9). Pratt and Lambert's Vitralon acrylic powder (system 10) was also provided for testing.

The two acrylic powder coating systems tended to crack during the accelerated and exposure tests. This is primarily the result of the high applied thickness. Acrylics are generally applied as decorative materials at relatively low thicknesses [e.g., 25 to 75 μm (1 to 3 mils)]. The materials in this program were being evaluated at higher film builds [e.g., 175 to 300 μm (7 to 12 mils)] than recommended by the acrylic manufacturers. The EVTECH acrylic cracked more than the Vitralon acrylic. The gloss retention for both systems was good, but second to the polyester powder coating systems tested.

Polyester

Polyesters can be subdivided into two major types — urethane and TGIC (triglycidyl isocyanurate)-cured. Cost and availability of raw materials are the most significant factors affecting the formulation (and thus performance) of polyester coatings in general. TGIC polyester provides excellent color and gloss retention and good corrosion protection. This resin-type material is currently used by Maryland DOT for coating steel safety appurtenances where there are aesthetic concerns. Urethane crosslinked polyester powders provide a smooth-finish coating that demonstrates good adhesion, weatherability, and corrosion protection. While the urethane coatings provide a smoother finish than TGIC crosslinked polyesters, bubbles and blisters tend to appear at higher film thicknesses.

Three polyesters for exterior applications were tested. Corvel 30-1007 (system 5) is a white TGIC-cured polyester manufactured by Morton Powder Coatings. Lilly supplied a white TGIC-cured polyester powder coating for testing (system 6). The Lilly TGIC was also used as the topcoat on the two-coat systems. Lilly proprietary polyester for structural components (system 7) was designed by Lilly to replace TGIC crosslinked polyesters. It was designed to perform comparably and reduce health risks commonly associated with TGIC. The powder contains a proprietary crosslinking agent that is not a TGIC or a urethane. It was tested for comparison to the TGIC materials.

As expected, due to characteristics of the resin type, the gloss retention of the polyester powder coatings in the natural marine environment was better than all other powders tested. The gloss retention of Lilly TGIC was better than that of the other two polyesters tested. The underfilm corrosion resistance of the polyesters was better than that of the epoxy powders in the natural marine environment, and about the same as the epoxy powders in the two accelerated tests.

Epoxy-Polyester Hybrid

Hybrids are mixtures of epoxy and polyester resins. They are claimed to offer improved resistance to over-bake yellowing and ultraviolet degradation when compared with epoxies. Hybrids are generally not recommended for outdoor applications as they are still susceptible to the chalking characteristic of epoxies.

In order to test the generic material of an epoxy-polyester hybrid powder coating for comparative purposes, Ferro VEDOC VH 1215 was chosen for testing (system 12). This system performed on average with the other powders in the accelerated tests. The coating had poor gloss retention in the natural marine environment. The material's underfilm corrosion resistance was better than the epoxies, but not as good as the polyesters.

Zinc-Rich Epoxy Powder

A zinc-rich epoxy powder offers sacrificial corrosion protection (galvanic) due to a material that can be applied using powder coating technology. The material is an epoxy with zinc added as an anti-corrosive pigment. When a corrosive electrolyte (moisture) electrically connects the zinc-rich coating with the steel substrate, the zinc will sacrificially corrode to protect the steel. As with all zinc-rich epoxy coatings, the substrate must be free of all contaminants for optimal adhesion and corrosion control. The performance of such coatings will obviously be related to the zinc content of the coating. Both the quantity of zinc and its dispersion within the film are important in its ability to provide sacrificial corrosion protection.

For the present testing, Morton Powder Coatings provided ZR1000 zinc-rich epoxy coating (system 14). It has a zinc loading of approximately 60 percent by weight. This coating, applied at thicknesses be-

tween 175 and 350 μm (7 and 14 mils), provided the best atmospheric corrosion control of all of the powders tested. However, as with all epoxy coatings, the material chalked heavily.

THERMOPLASTIC POWDERS

Thermoplastic powders do not form a solvent-resistant solid crosslinked film like thermosetting powders. They can be remelted for repairs or alterations to the coating while retaining all of the physical and corrosion-control properties of thermosetting powder coatings. Thermoplastic powders are generally applied at higher film builds than thermosetting powders and are used more for corrosion protection rather than aesthetics.

Envelon (Ethylene Acrylic Acid)

Technological advances have led to powder formulation for application by thermal spray methods. This allows for field application of powder coatings, which is especially desirable for maintenance applications. An ethylene acrylic acid (EAA) copolymer has been developed by Dow for such an application. The EAA copolymer is most like a polyethylene in its chemical resistance and tactile properties. It has acrylic functional groups attached to the polyethylene chain to give adhesive bond properties not typical of polyethylene. Both ionic and mechanical bonds contribute to the bond strength of the coating with the ionic bonds being predominant. This coating can also be applied by electrostatic spray and fluidized bed processes.

Envelon (trade name for EAA) was applied by UTP Welding, a company specializing in flame-spray operations. The coating (system 8) was tested as a proprietary single-coat system applied using flame-spray equipment. The flame-spray coating was only applied to one side of the test panels. The applicator felt that reheating of the powder when applying the material to the reverse side of the panel would damage the initially coated side. This illustrates the type of geometry considerations required when using such systems. In general, similar test panels have been prepared with both sides coated using a flame-spray technique. This can be facilitated using two applicators (one from each side) or with materials that are not as sensitive to reheating. The backs of these panels were subsequently masked with a solvent-based epoxy system.

Envelon's resistance to underfilm corrosion was average compared to the other powder coatings tested, showing about 12.7 mm (0.5 in) of undercutting after each test. The gloss and color retention of the exposed coating was below average. The initial bright yellow color of the coating faded significantly during each test.

Nylon

Nearly all nylon powders are based on the type 11 resin. Nylon powders are claimed to produce finishes with good abrasion and wear resistance, good exterior durability, and excellent corrosion protection. An interesting use of nylon powders is to provide lubricity on faying surfaces. Nylon typically has a low coefficient of friction.

A Morton Nylon 11-based material (system 11) was tested as a representative of nylon-based powder coatings. This coating performed below average for resisting underfilm corrosion and retaining gloss when compared to the other powder coatings tested.

Polyvinyl Chloride

The results of a 1974 study performed by the National Bureau of Standards for the Federal Highway Administration indicated that "both epoxy and polyvinyl chloride coatings, if properly applied, should adequately protect steel reinforcing bars from corrosion."⁽⁴⁾ The state of the art at that time prohibited polyvinyl chloride (PVC) coatings from being applied at the thicknesses required to maintain pull-out strength of rebar in concrete.

The Thermoclad Company markets a PVC powder that can be applied at 175- μm (7-mil) thicknesses (system 13). An epoxy-acrylic emulsion primer was recommended to improve adhesion of the powder coating material to the substrate. System 13 was a poor performer in the natural marine exposure testing. The coating had significant amounts of underfilm corrosion and poor gloss and color retention. Because of its poor performance in initial tests, PVC was not tested as a rebar coating.

DUPLEX SYSTEMS

The complementary merits of two different coatings can be exploited with a duplex system. Two separate layers of powder coating are applied to form a duplex system. Six duplex systems were tested. Four systems consisted of a zinc-based primer (for improved corrosion protection) and a weatherable powder topcoat (for aesthetics). The remaining two systems consisted of an epoxy primer (to promote improved adhesion) and a weatherable powder topcoat (for aesthetics).

The duplex systems consisting of two powder materials were applied with electrostatic spray equipment. The first powder is sprayed onto the preheated part. This is immediately followed by the second powder material. The part is then oven cured. Because of the application technique, a certain amount of fusion between the two powders occurs. However, the application technique makes it difficult to control thicknesses. Thicknesses less than 25 μm (10 mils) were difficult to achieve.

Zinc-Based Primer

Epoxiplate ZR1000 was tested with a topcoat of Lilly TGIC polyester powder (system 15). JMK Enterprises provided a powder-topcoated system with an inorganic zinc primer (system 16). A Unocal organic zinc primer was topcoated with Lilly TGIC (system 17). Lilly TGIC was also topcoated over galvanized steel (system 18).

TGIC-topcoated galvanized steel has practical as well as performance considerations. In the event that powders are deemed suitable for highway safety appurtenances, it is possible that structures already galvanized (e.g., guardrail) will be replaced with powder-coated structures. A significant cost savings may be realized if an existing galvanized part is powder coated.

As a group, the zinc-based systems were the most resistant to underfilm corrosion of all powder coatings tested. Adhesion of the powder topcoat was a significant problem for the JMK system. Although the steel panels were protected from corrosion, the powder topcoat was very easily disbonded from the inorganic zinc primer during and after each exposure test. Systems 14 and 18 were superior at stopping underfilm corrosion in the natural marine environment. System 15 had a relatively thin layer of the zinc-rich epoxy powder under the Lilly TGIC powder topcoat, so unlike system 14, it developed some underfilm corrosion during the tests. The zinc-rich epoxy (system 14) lost gloss and chalked in the natural marine environment. The zinc systems topcoated with Lilly TGIC powder had superior gloss retention (systems 15, 17,

and 18). Variations in performance of these zinc-based systems illustrate differences among various uses of zinc in a powder coating system (i.e., liquid zinc-loaded versus galvanized coating, etc.).

Epoxy Primer

Lilly rebar epoxy was topcoated with Lilly TGIC polyester for one of the duplex systems (system 19). DuVal (a DuPont and Valspar joint venture) epoxy-polyolefin was also tested as a duplex system (system 20).

The DuVal system was only applied to one side of the test panels. Due to time constraints between application of the two powders (required by the manufacturer), the applicator could only apply the material to one side of the panel at a time. The coating manufacturer felt that reheating the panel to apply coating to the back would damage the coating on the front. The back sides of the panels were subsequently masked with a solvent-based epoxy system.

The DuVal system performed well in the natural marine exposure and cyclic accelerated tests. It was categorized as being one of the best performers for each test. The Lilly rebar epoxy/Lilly TGIC polyester system had corrosion resistance similar to the epoxy systems (systems 2, 3, and 4) in all tests, except in the cyclic high-pressure/high-temperature seawater exposure test where it outperformed the epoxies. The gloss retention of system 19 was good (typical of TGIC polyester).

APPENDIX I. SUMMARY OF POWDER COATING APPLICATION REPORTS

System No.	Commercial Description	Substrate/Surface Preparation	Target DFT (µm)	Preheat Time (min)	Preheat Temp (°C)	Cure Time (min)	Cure Temp (°C)	Actual DFT (µm)
Proprietary Single-Coat Powder Systems (13 Systems)								
2	Lilly Greenbar Epoxy	A36 Steel, White Metal Blast	178-229	30	221	none	none	153-254
		A36 Steel, White Metal Blast	254-356	30	221	none	none	254-381
		Steel Rebar, White Metal Blast	178-229	30	221	none	none	178-254
3	Skotchkote 213	A36 Steel, White Metal Blast	254-356	30	221	none	none	229-279
		A36 Steel, White Metal Blast	178-229	30	221	none	none	178-279
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	221	none	none	254-406
		Steel Rebar, White Metal Blast	178-229	30	221	none	none	152-178
4	3M XC6159	A36 Steel, White Metal Blast	254-256	30	221	none	none	254-356
		A36 Steel, White Metal Blast	178-229	30	221	none	none	152-267
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	221	none	none	203-330
		Steel Rebar, White Metal Blast	178-229	30	221	none	none	152-229
5	Corvel 30000 Series	A36 Steel, White Metal Blast	254-356	40	221	30	204	254-356
		A36 Steel, White Metal Blast	178-229	40	232	20	204	152-254
		Steel Rebar, White Metal Blast	178-229	40	232	40	204	178-229

System No.	Commercial Description	Substrate/Surface Preparation	Target DFT (µm)	Preheat Time (min)	Preheat Temp (°C)	Cure Time (min)	Cure Temp (°C)	Actual DFT (µm)
6	Lilly TGIC for Structural Components	A36 Steel, White Metal Blast	254-356	40	232	30	204	178-356
		A36 Steel, White Metal Blast	178-229	30	232	30	204	178-292
		A588 Weathering Steel, White Metal Blast	254-356	40	232	30	204	254-406
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-305
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	10	204	203-305
7	Lilly Proprietary Polyester for Structural Components	A36 Steel, White Metal Blast	254-356	30	221	30	204	254-381
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	10	204	216-356
		A588 Weathering Steel, White Metal Blast	254-356	40	232	30	204	254-406
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-279
8	Flame-Spray EAA	A36 Steel, White Metal Blast	154-356	Applied by UTP Welding, Inc.				352-498
		A588 Weathering Steel, White Metal Blast	254-356					348-458
9	EVTECH Acrylic	A36 Steel, White Metal Blast	254-356	30	232	30	204	229-406
		A36 Steel, White Metal Blast	178-229	30	232	30	204	152-279
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	30	204	229-356
		A588 Weathering Steel, White Metal Blast	254-356	30	232	30	204	229-381
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-279
10	Vitalon Acrylic Powder	A36 Steel, White Metal Blast	254-356	30	232	30	204	229-381
		A36 Steel, White Metal Blast	178-229	30	232	30	204	178-254
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	30	204	229-381
		Steel Rebar, White Metal Blast	178-229	45	232	45	204	178-279

System No.	Commercial Description	Substrate/Surface Preparation	Target DFT (µm)	Preheat Time (min)	Preheat Temp (°C)	Cure Time (min)	Cure Temp (°C)	Actual DFT (µm)
11	Morton Nylon	A36 Steel, White Metal Blast	254-356	30	204	20	221	254-457
		A36 Steel, White Metal Blast	178-229	30	204	20	221	178-279
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	60	260	none	none	254-381
		A588 Weathering Steel, White Metal Blast	254-356	60	260	none	none	254-356
		Steel Rebar, White Metal Blast	178-229	60	288	none	none	178-279
12	Ferro VH Series Hybrid Powder	A36 Steel, White Metal Blast	254-356	30	232	30	204	254-406
		A36 Steel, White Metal Blast	178-229	30	232	30	204	178-254
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	30	204	229-381
		A588 Weathering Steel, White Metal Blast	254-356	30	232	30	204	254-356
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-279
13	Thermoclad DURAVIN	Cold-Rolled A36 Steel, Zinc Phosphate	254-356	none	none	10	221	254-356
		A588 Weathering Steel, White Metal Blast	254-356	none	none	10	221	203-305
		A36 Steel, White Metal Blast	254-356	none	none	20	221	254-406
		A36 Steel, White Metal Blast	178-229	none	none	20	221	178-279
		Steel Rebar, White Metal Blast	178-229	none	none	20	232	203-356
14	Epoxiplac ZR1000, Zinc-Rich Epoxy Powder	A36 Steel, White Metal Blast	254-356	30	232	30	204	356-457
		A36 Steel, White Metal Blast	178-229	30	232	30	204	178-279
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-279

System No.	Commercial Description	Substrate/Surface Preparation	Target DFT (µm)	Preheat Time (min)	Preheat Temp (°C)	Cure Time (min)	Cure Temp (°C)	Actual DFT (µm)
Duplex Systems (6 Systems)								
15	Epoxyplate ZR1000/Lilly TGIC	A36 Steel, White Metal Blast	254-356	30	232	30	204	152-203
		A36 Steel, White Metal Blast	178-229	30	232	30	204	102-152
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	30	204	203-305
		A588 Weathering Steel, White Metal Blast	254-356	30	232	30	204	203-279
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	127-178
16	Proprietary Solvent Zinc/Powder	A36 Steel, White Metal Blast	254-356	Applied by JMK Enterprises (Proprietary)				219-310
		A36 Steel, White Metal Blast	178-229					208-335
		A588 Weathering Steel, White Metal Blast	254-356					216-348
		Steel Rebar, White Metal Blast	178-229					200-300
17	Unocal Primer/Lilly TGIC	A36 Steel, White Metal Blast	254-356	30	232	30	204	203-305
		A36 Steel, White Metal Blast	178-229	30	232	30	204	203-279
		A588 Weathering Steel, White Metal Blast	254-356	30	232	30	204	203-330
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-254
18	Galvanized/Lilly TGIC	A36 Steel, White Metal Blast	254-356	30	232	30	204	203-381
		A36 Steel, White Metal Blast	178-229	30	232	30	204	203-305
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	30	204	203-381
		A36 Steel, White Metal Blast	178-229	30	232	30	204	178-305
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-254

System No.	Commercial Description	Substrate/Surface Preparation	Target DFT (μm)	Preheat Time (mins)	Preheat Temp (°C)	Cure Time (min)	Cure Temp (°C)	Actual DFT (μm)
19	Lilly Rebar Epoxy/Lilly TGIC	A36 Steel, White Metal Blast	254-356	30	232	30	204	356-584
		A36 Steel, White Metal Blast	178-229	30	232	30	204	330-406
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	30	232	30	204	254-356
		A588 Weathering Steel, White Metal Blast	254-356	30	232	30	204	356-457
		Steel Rebar, White Metal Blast	178-229	30	232	45	204	178-305
20	DuVal	A36 Steel, White Metal Blast	254-356	20	304	3	260	406-635
		A36 Steel, White Metal Blast	254-356	20	304	3	260	330-508
		A588 Weathering Steel, White Metal Blast	254-356	20	304	3	260	457-508
		Cold-Rolled A36 Steel, Zinc Phosphate	254-356	20	304	3	260	406-559



**APPENDIX II. SOLVENT-BASED CONTROL SYSTEM
APPLICATION DATA**

Coating	Dry Film Thickness	VOC	RH	Dew Point	Surface Temperature
IOZ Primer	76-102 μm or 38-64 μms^*	264 g/L (2.2 lb/gal)	70%	19° C	24° C
High-Build Epoxy	127-152 μm or 64-89 μms^*	195 g/L (1.62 lb/gal)	70%	18° C	24° C
Polyurethane Topcoat	76-102 μm or 38-64 μms^*	300 g/L (2.5 lb/gal)	60%	18° C	25° C

* Depending on 305 μm (178 μms) total nominal DFT.



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