

Coating Performance on Existing Steel Bridge Superstructures

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FOREWORD

This report documents a study that evaluated the corrosion protection performance of four coating systems applied to steel substrates with various chloride contamination levels. The purpose of the study was to identify coating systems that can provide extended service life for steel bridges with minimal surface preparation. This study helps estimate the amount of chloride contamination that coating systems can tolerate without premature failure. Owners, consultants, contractors, and technical experts interested in the durability of coatings applied to contaminated steel substrates may benefit from the information contained herein.

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Research and Development

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16. Abstract This study evaluated the performance of four coating systems applied on chloride-contaminated steel substrates. The purpose of the study was to identify coating systems that can provide extended service life for steel bridges with minimal surface preparation at a much reduced cost. The study helps estimate the amount of chloride contamination coating systems can tolerate without significant premature failure. The chloride contamination levels tested in this study were 0, 20, and 60 µg/cm ² . The coating systems tested were two 3-coat systems (one with inorganic zinc-rich primer and the other with organic zinc-rich primer), a 2-coat system with carbon nanotubes in its zinc-rich primer, and a 1-coat system of high-ratio calcium sulfonate alkyd. Coated panels were exposed to two conditions: accelerated laboratory testing and outdoor natural weathering. The 3-coat systems had the best corrosion protection performance among the tested specimens. The inorganic zinc primer performed slightly better than the organic zinc primer. The 2-coat system demonstrated the highest adhesion strength over all levels of chloride contamination.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1,000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	$\frac{5}{9}(F-32)$ or $\frac{5}{9}(F-32)+32$	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	$1.8C+32$	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS AND ABBREVIATIONS

ALT	accelerated laboratory testing
CIE	International Commission on Illumination
DFT	dry film thickness
FHWA	Federal Highway Administration
GU	gloss unit
HRCSA	high-ratio calcium sulfonate alkyd
NACE	National Association of Corrosion Engineers
ppm	parts per million
SSPC	Society for Protective Coatings
UV	ultraviolet

CHAPTER 1. INTRODUCTION

If left unprotected, some steel used in highway bridge superstructures is highly susceptible to corrosion when exposed to the environment. Steel corrodes when it is exposed to moisture and oxygen. The corrosion process is significantly accelerated in the presence of salts. Corrosion on highway bridges is predominantly caused by chloride ions from either deicing salts or natural chlorides present in certain environments.

Typical corrosion protection for steel bridges consists of applying a 3-coat paint (coating) system. The first coat contains a zinc-rich primer applied to the abrasive blast-cleaned surface. Because zinc is more reactive than iron, it acts as a sacrificing anode to provide cathodic protection to the steel substrate during the corrosion process. The intermediate coat is usually an epoxy that acts as a barrier to protect the primer coat. The top coat protects underlying layers of coating against deterioration caused by ultraviolet (UV) radiation and improves aesthetics. For a newly constructed and coated steel bridge, 3-coat systems have a service life of approximately 30 yr before field rehabilitation is required.⁽¹⁾

Conventional 3-coat systems have demonstrated exemplary durability in actual use on steel bridges as well as in laboratory studies. Some emerging 1- and 2-coat systems have also shown potential for durability. The cost of coating application can be significantly reduced when 1- or 2-coat systems are used. In addition to application cost savings, time and space savings are the other inherent advantages of 1- and 2-coat systems. The improved efficiency may benefit bridge fabricators in the shop as well as bridge builders and coating maintenance crews.

Surface preparation is an integral step in the coating process. It is common practice to apply coating to a clean steel surface to prevent premature failure caused by an inappropriately prepared substrate. The purpose of surface preparation is to remove any contaminants from the surface and create a specific roughness so the coating material can contact and adhere to the substrate. Abrasive blast cleaning achieves both goals simultaneously, and specific industry standards are used as guides.⁽²⁾ Studies have found that varying amounts of contaminants, particularly chlorides, are almost always present on abrasive blast-cleaned steel surfaces, especially existing structures being cleaned and prepared for recoating in the field.

No industrial standard exists for the maximum amount of salt that can be present on a steel surface before coating application.⁽²⁾ A universal definition of surface cleanliness is difficult to accomplish. Commonly used test methods involve extracting contaminants from the substrate surface and then analyzing the chemical components. Still, the substrate surface cannot be completely cleaned of contaminants. Also, many analytical methods used for determining contaminants are not accurate, especially when the concentration is at the parts per million (ppm) level or lower.

Previous Federal Highway Administration (FHWA) coating studies have focused on the performance of coatings applied on properly cleaned steel substrates.^(3,4) This study focused mainly on the performance of recoating or repair coating applied on existing bridges with the assumption that some chloride ions remained on the steel substrate after abrasive blast cleaning.

Where weathering (uncoated) steel bridges have not performed well in aggressive environments, maintenance coatings may provide desirable service life.⁽⁵⁾ A few panels made from A588 weathering steel were included in this study to test this hypothesis.

The objective of the study was to identify coating systems that can provide extended service life for steel bridges with minimal surface preparation at a much reduced cost. The experiments were composed of two parts:

- Investigate the long-term performance of select coating systems when applied to steel substrates with certain amounts of salts on standard size 102- by 152-mm (4- by 6-inch) steel panels. These panels were subjected to accelerated laboratory testing (ALT) or outdoor natural weathering exposure.
- Study coating systems on large 457- by 457-mm (18- by 18-inch) specimens with multiple attachments representing bridge details. These specimens were exposed only to natural weathering with water or saltwater spray.

This study evaluated the performance of coating systems when applied to chloride-contaminated steel substrates. It helped determine the amount of chloride contamination coating systems can tolerate without premature failure.

CHAPTER 2. MATERIALS AND PREPARATION

COATING MATERIALS

Selection of coating systems for this study was mainly based on previous FHWA studies and current industrial practices. (See references 3, 4, and 6–13.) Conventional 3-coat systems with either an inorganic or organic zinc-rich primer were chosen as benchmarks for evaluating other coating systems. A 1-coat system of high-ratio calcium sulfonate alkyd (HRCSA) was selected for testing because of its good performance in previous studies.^(3,4) It is a pigmented alkaline coating that resists corrosion because of its inherent alkalinity. The alkalinity neutralizes acidity and in turn sustains the passivity on the steel surface.⁽⁴⁾ The coating film remains viscoelastic and does not become brittle while developing a strong ionic bond with the steel substrate. Another positive attribute of the HRCSA coating is its hydrophobic surface. A new and promising 2-coat system was selected based on the attention it received after the Army Corps of Engineers studied it and applied it in the field.⁽⁶⁾ This system incorporates nanomaterial in the primer to improve its coating properties. The potential cost savings of the 1- and 2-coat systems was another incentive for their inclusion in this study. In summary, the four coating systems selected for evaluation were the following:

- A 3-coat system with an inorganic zinc-rich primer (layers listed in application order are inorganic zinc-rich primer, epoxy, and aliphatic polyurethane).
- A 3-coat system with an organic zinc-rich primer (layers listed in application order are organic zinc-rich primer, epoxy, and aliphatic polyurethane).
- A 1-coat system of HRCSA.
- A 2-coat system (layers listed in application order are zinc-rich primer with carbon nanotubes and urethane top coat).

SPECIMEN FABRICATION

Most steel used for this study was A36 steel. A few A588 weathering steel panels were also included. Two types of specimens were fabricated: standard size 102- by 152-mm (4- by 6-inch) panels (figure 1) and large 457- by 457-mm (18- by 18-inch) specimens with attachments (figure 2). The large specimen contained a welded 51-mm (2-inch) tall V-shaped angle, a 305-mm (12-inch) long inverted T-shaped joint bolted to the base plate, and a 406-mm (16-inch) angle also bolted to the base plate. Incorporating the complex geometric details onto the panel helped evaluate coating performance on crevices and interfaces created by the attachments.



Source: FHWA.

Figure 1. Photo. Standard size panel.



Source: FHWA.

Figure 2. Photo. Large panel.

SALT CONTAMINATION ON STEEL SUBSTRATE

Salt Concentration

The amount of soluble salts on steel substrates that coatings can tolerate has been studied and debated in the protective coating industry. A literature search was conducted to determine the salt concentration levels for this study. Society for Protective Coatings (SSPC)-TU 1 recognized that high-concentration salts are detrimental to protective coatings.⁽¹⁴⁾ They found that chloride greater than 50 $\mu\text{g}/\text{cm}^2$ or sulfate greater than 100 $\mu\text{g}/\text{cm}^2$ can lead to blistering and premature coating failure.¹ Their maximum recommended permissible concentration for chloride is 1–50 $\mu\text{g}/\text{cm}^2$ and for sulfate is 10–100 $\mu\text{g}/\text{cm}^2$. Palle et al. investigated Kentucky bridges and concluded that the maximum acceptable concentrations of soluble salts are very low (e.g., 10–50 $\mu\text{g}/\text{cm}^2$ for chlorides).⁽¹⁵⁾ If high soluble salt levels are encountered (i.e., greater than 30 $\mu\text{g}/\text{cm}^2$ for any types of soluble salts), they recommended that the bridge be given a washing test to ensure that the salt level can be reduced to about 10 $\mu\text{g}/\text{cm}^2$ before painting. Johnson stated that the U.S. Navy specified the limit for soluble chloride as 5 $\mu\text{g}/\text{cm}^2$ for nonimmersion service and 3 $\mu\text{g}/\text{cm}^2$ for immersion service.⁽¹⁶⁾ Some departments of transportation have used a limit of 10 $\mu\text{g}/\text{cm}^2$ to reduce the risk of premature failures.

Tator provided a comprehensive summary via a literature review. His findings are summarized in the following list.⁽¹⁷⁾

- Steinsmo and Axelsen suggested a maximum 2 $\mu\text{g}/\text{cm}^2$ sodium chloride equivalent to ensure coating performance for immersion in water or exposure to marine atmosphere.⁽¹⁸⁾
- Alblas and van Londen stated that a maximum chloride level of 2 $\mu\text{g}/\text{cm}^2$ can be taken as a safe critical value.⁽¹⁹⁾
- Mitschke concluded that chloride threshold levels vary considerably from 4 to 30 $\mu\text{g}/\text{cm}^2$ at 24°C (75°F) for modified epoxy linings.⁽²⁰⁾ For elevated service temperature, even 1 $\mu\text{g}/\text{cm}^2$ has an effect.
- Richards established a maximum salt surface contamination of 3.5 $\mu\text{g}/\text{cm}^2$.⁽²¹⁾
- For a zinc-rich 3-coat system, the European Commission established a maximum concentration of 40 $\mu\text{g}/\text{cm}^2$ for both chloride and sulfate.⁽²²⁾ For a zinc silicate primer, they established maximum concentrations of 10 $\mu\text{g}/\text{cm}^2$ for chloride and 40 $\mu\text{g}/\text{cm}^2$ for sulfate.
- Tator provided the following maximum concentrations: for saltwater immersion: 2–50 $\mu\text{g}/\text{cm}^2$ for chloride and 40–125 $\mu\text{g}/\text{cm}^2$ for sulfate; for freshwater immersion: 2–50 $\mu\text{g}/\text{cm}^2$ for chloride and 10–250 $\mu\text{g}/\text{cm}^2$ for sulfate; for atmospheric (industrial marine): 2–50 $\mu\text{g}/\text{cm}^2$ for chloride and 14–100 $\mu\text{g}/\text{cm}^2$ for sulfate.⁽¹⁷⁾

¹Surface concentration is presented in $\mu\text{g}/\text{cm}^2$ throughout this report, but if needed, the following conversion equation can be used: $1 \mu\text{g}/\text{cm}^2 = 2.28 \times 10^{-7} \text{ oz}/\text{in}^2$.

Based on these findings, chloride concentration between 5 and 10 $\mu\text{g}/\text{cm}^2$ is generally considered the threshold level for protective coating to achieve desirable service life performance.

Because chloride ions are the most corrosive and detrimental contaminant to the coated steel, they were the only contaminant applied to steel substrates for this study. The selected concentration range for the laboratory experiment was somewhat akin to conditions in the field. Sodium chloride solution was applied to steel panels to achieve the following chloride concentration levels on the surface:

- Control: chloride concentration less than 1 $\mu\text{g}/\text{cm}^2$.
- 20 $\mu\text{g}/\text{cm}^2$.
- 60 $\mu\text{g}/\text{cm}^2$.

Applying Chloride to the Surface

Steel panels and attachment parts were first cleaned with solvent to rid them of any oil and grease per SSPC-SP 1, *Solvent Cleaning*.⁽²³⁾ Then, all sides and edges of the panel were abrasive blast cleaned to meet the surface cleanliness requirements of SSPC-SP 10, *Near-White Metal Blast Cleaning*, resulting in a 51- to 76- μm (2- to 3-mil) angular surface profile.⁽²⁴⁾

The salt solution was evenly spread over the blast-cleaned steel surface using a glass rod. An oscillating fan facilitated the evaporation of water from the surface. The contamination procedure (found in appendix A) was based on appendix C of the National Association of Corrosion Engineers (NACE) International Standard Practice SP0508-2017, *Methods of Validating Equivalence to ISO 8502-9 on Measurement of the Levels of Soluble Salts*.⁽²⁵⁾ Chloride ions were introduced to the cleaned steel surface via a small volume of sodium chloride solution. To achieve the 20- $\mu\text{g}/\text{cm}^2$ chloride level, a 4,000-ppm chloride solution was used; to achieve the 60- $\mu\text{g}/\text{cm}^2$ chloride level, a 12,000-ppm chloride solution was used. The front face of the large 457- by 457-mm (18- by 18-inch) plate was divided into 228.5- by 228.5-mm (9- by 9-inch) quadrants. The calculated amount of doping solution was then placed at the center of each quadrant. For the standard size 102- by 152-mm (4- by 6-inch) panels, the solution was simply placed at the center of each panel. The hanging hole in the standard size panel was plugged before the solution was added so no liquid was lost in the process. The top margin of the standard size panel above the hole was not contaminated by the salt solution. For the large multipiece assembly specimen, the chloride solution was not applied to the surface of the welded V-shape attachment or within a quarter-inch perimeter around each of the five holes. The panels were wrapped with a plastic sheet after drying and stored in the laboratory at ambient temperature (20–25°C (68–77°F)) for no longer than 8 h before coating application.

Chloride levels on the doped steel panels were tested. The test procedure can be found in *Methodology for Analysis of Soluble Salts from Steel Substrates*.⁽²⁶⁾ Multiple extractions were taken from six panels for each doping level to determine chloride concentration variation. Results from the standard size 102- by 152-mm (4- by 6-inch) and large 457- by 457-mm (18- by 18-inch) panels are shown in table 1 and table 2, respectively.

Table 1. Chloride contamination on standard size steel panels.

Targeted Chloride Level ($\mu\text{g}/\text{cm}^2$)	Average Measured Chloride Concentration ($\mu\text{g}/\text{cm}^2$)	Standard Deviation ($\mu\text{g}/\text{cm}^2$)
20	14.8	1.8
60	47.2	3.9

Table 2. Chloride contamination on large steel panels.

Targeted Chloride Level ($\mu\text{g}/\text{cm}^2$)	Average Measured Chloride Concentration ($\mu\text{g}/\text{cm}^2$)	Standard Deviation ($\mu\text{g}/\text{cm}^2$)
20	15.8	3.6
60	35.8	7.9

Coating Application

Upon completing blast cleaning and salt contamination, trained coating applicators sprayed coatings onto the steel substrates in a controlled environment (figure 3 and figure 4). The base plate and individual parts of the large specimens were spray painted with the primer coat. After the primer cured for 24 h, the components were assembled. The edges, welds, bolts, and nuts were stripe painted (figure 5). The back sides of the panels were also painted with primer. Additional layers of coating were applied accordingly.

After the coatings were fully cured, some panels were scribed per ASTM D1654, *Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments*, as shown in figure 6 and figure 7.⁽²⁷⁾ The scribe line was about 51 mm (2 inches) long. On the front face of the large panel, three scribes were created, as shown in figure 8.



Source: FHWA.

Figure 3. Photo. Coating application for standard size panels.



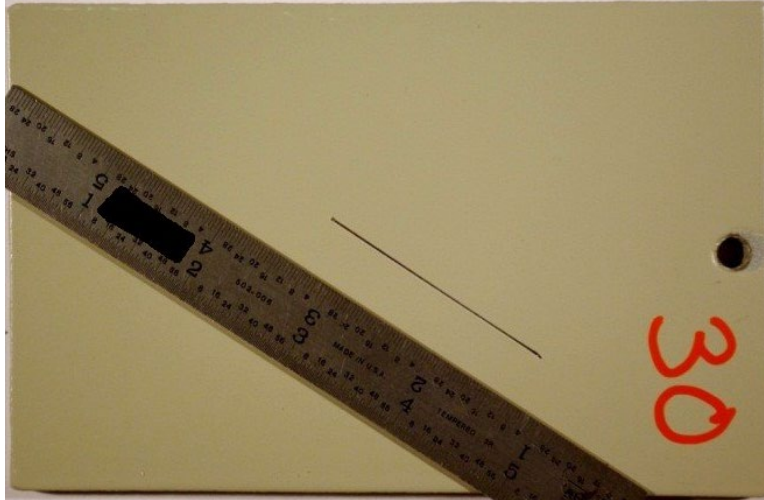
Source: FHWA.

Figure 4. Photo. Coating application for large panel attachments.



Source: FHWA.

Figure 5. Photo. Stripe coating the large panels.



Source: FHWA.

A. Standard size panel with a single-line scribe.



Source: FHWA.

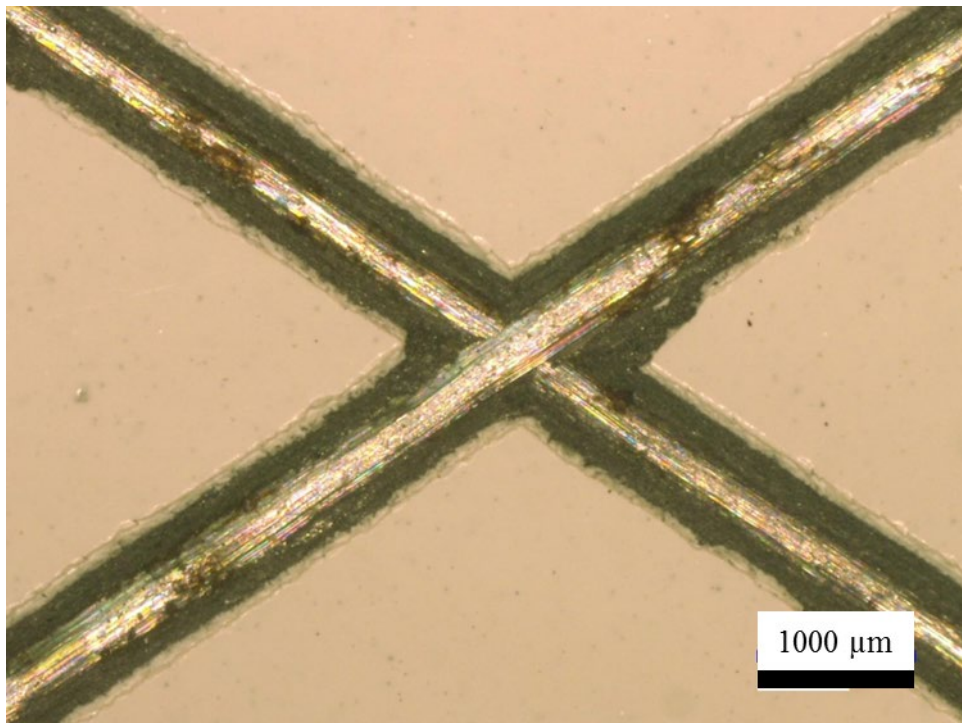
B. Standard size panel with a crossed-line scribe.

Figure 6. Photos. Standard size panels with single- and crossed-line scribes.



Source: FHWA.

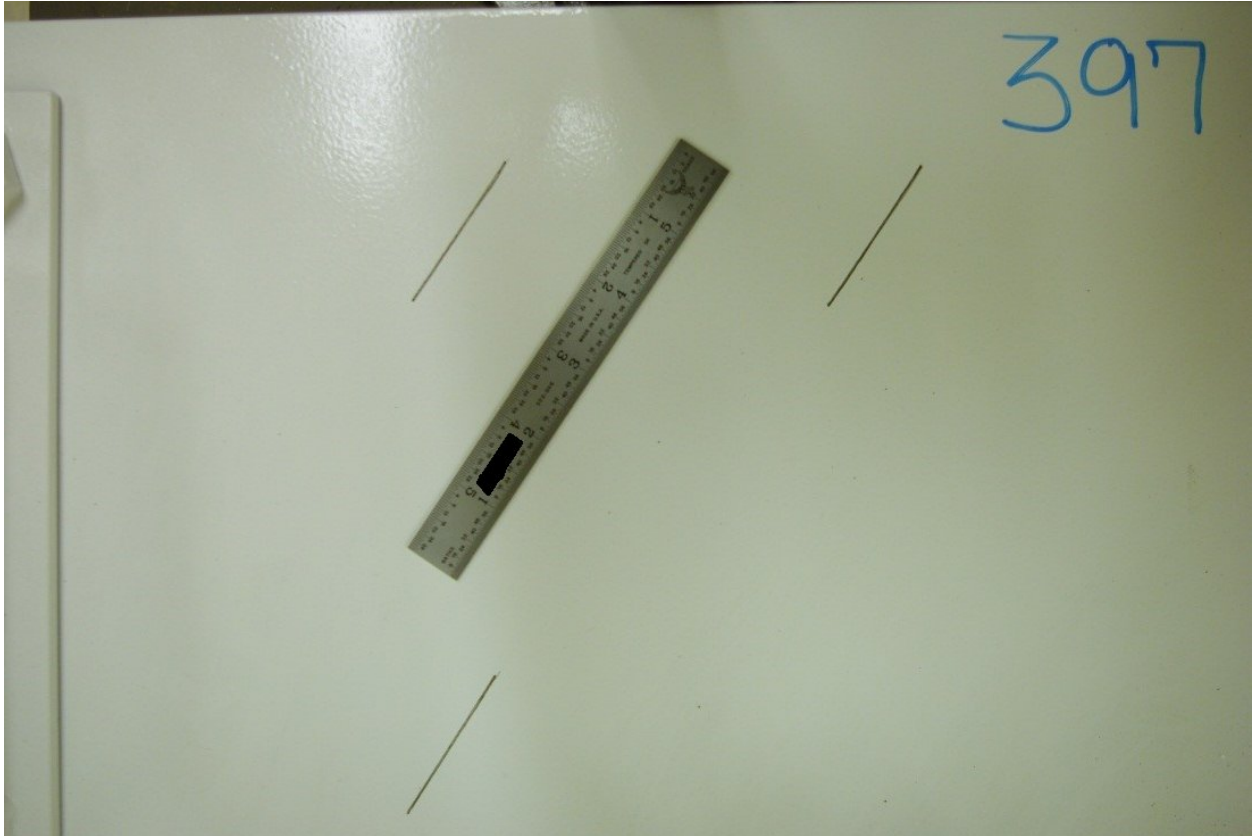
A. Microscopic image of a single-line scribe.



Source: FHWA.

B. Microscopic image of a crossed-line scribe.

Figure 7. Photos. Microscopic images of single- and crossed-line scribes.



Source: FHWA.

Figure 8. Photo. Three scribes on a large panel.

EXPOSURE CONDITIONS

Accelerated Laboratory Testing

The ALT was based on ASTM D5894, *Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal*.⁽²⁸⁾ Each test cycle started by placing the panels in a freezer (figure 9) for 1 d. The panels were then subjected to alternating exposures in a UV/condensation chamber (figure 10) and a salt/fog chamber (figure 11). The Harrison mixture in the ASTM standard takes too long to affect the coated panels, so based on the procedure in the FHWA 100-yr coating study, the salt concentration for the salt/fog chamber was modified to increase its corrosivity.⁽³⁾ Each test cycle lasted 360 h, and 14 test cycles were performed, which totaled a cumulative exposure time of 5,040 h. The procedure for one 360-h cycle was as follows:

- Freezing: -23°C (-10°F) for 24 h.
- UV/condensation cycle: 4 h UV with 340 nm irradiance at 60°C (140°F), followed by 4 h condensation at 40°C (104°F). Repeat 21 times for a total of 168 h.
- Prohesion cycle: 1 h fog at ambient temperature $20\text{--}25^{\circ}\text{C}$ ($68\text{--}77^{\circ}\text{F}$) with a salt solution of 0.35-percent ammonium sulfate and 0.5-percent sodium chloride, followed by 1 h dry at 35°C (95°F). Repeat 84 times for a total of 168 h.



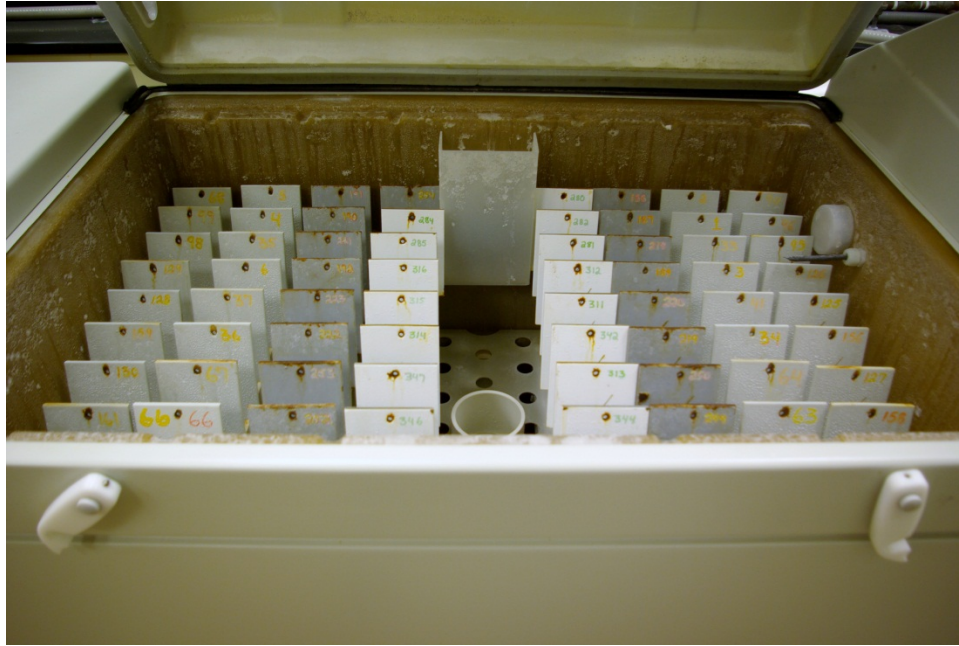
Source: FHWA.

Figure 9. Photo. Panels in a freezer.



Source: FHWA.

Figure 10. Photo. UV weathering chambers.



Source: FHWA.

Figure 11. Photo. ALT panels in the salt/fog chamber.

Outdoor Natural Weathering Exposure

The natural weathering exposure test was based on ASTM D1014-18, *Standard Practice for Conducting Exterior Exposure Tests of Paints and Coatings on Metal Substrates*, with a few changes.⁽²⁹⁾ Panels were placed on wooden racks inclined at 30° facing south and exposed to the local outdoor environment, as shown in figure 12. The ASTM standard orientation angle of 45° was not used because previous FHWA studies used a 30° orientation and the laboratory wanted to maintain the continuity of the test regimen. Weather permitting, the specimens were sprayed once a day, five days a week with either saltwater spray or water spray. A solution containing 0.5-percent sodium chloride and 0.35-percent ammonium sulfate was used for the saltwater spray, and tap water was used for the water spray. About every 6 mo, the coated panels were brought back to the laboratory for testing, and the latest data gathered represented the results after 54 mo of exposure.



Source: FHWA.

Figure 12. Photo. Outdoor panel rack.

CHAPTER 3. EVALUATION OF COATING PERFORMANCE

Measurements were performed on the coated panels to characterize a variety of performance-related properties. These measurements were the basis for quantitative evaluation of the coating systems as the panels went through ALT or natural exposure conditions. The measurements included the physical and chemical properties of coatings, such as color, gloss, and adhesion. Measurement of rust creepage was used to evaluate a coating system's corrosion resistance at a scribe in the coating film.

DRY FILM THICKNESS

Dry film thickness (DFT) is an important measurement for determining a coating or coating system's performance. If the dry film is too thin, the underlying substrate will not be protected; if it is too thick, solvents may become entrapped in the coating. Coatings may also crack or not properly cure if they are too thick. DFT measurements for each coating system were taken before ALT and outdoor natural weathering exposure to verify that the coating was applied correctly. Measurements were taken with an electronic thickness gauge following ASTM D7091, *Standard Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals*, and the SSPC-PA 2 standard method, *Measurement of Dry Coating Thickness with Magnetic Gages*.^(30,31)

The measured and manufacturer's recommended DFT values on the standard size panels are listed in table 3. The measured DFTs were within the manufacturer's recommended range except for the 1-coat system. The DFT of the 1-coat system was not measured immediately after coating application because of the softness of the coating film.

Table 3. Measured and recommended DFT on standard size panels.

Coating System	Status	Primer	Intermediate	Top
3-coat with inorganic zinc	Measured	91 μm (3.6 mil)	94 μm (3.7 mil)	84 μm (3.3 mil)
	Recommended	51–76 μm (2–3 mil)	76–127 μm (3–5 mil)	76–127 μm (3–5 mil)
3-coat with organic zinc	Measured	99 μm (3.9 mil)	97 μm (3.8 mil)	81 μm (3.2 mil)
	Recommended	76–127 μm (3–5 mil)	76–127 μm (3–5 mil)	76–127 μm (3–5 mil)
2-coat	Measured	150 μm (5.9 mil)	NA	81 μm (3.2 mil)
	Recommended	51–76 μm (2–3 mil)	NA	76–127 μm (3–5 mil)
1-coat	Measured	135 μm (5.3 mil)	NA	NA
	Recommended	254–305 μm (10–12 mil)	NA	NA

NA = not applicable.

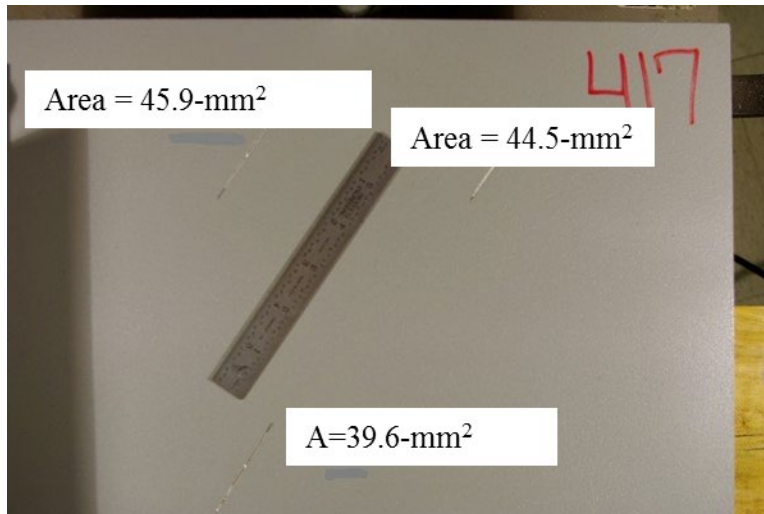
The DFT on the large panels was measured at 22 locations:

- Face—8 locations.
- V joint—4 locations.
- Angle—6 joints.
- T joint—4 locations.

DFT measurements on the large panels are shown in table 4. The measured DFTs were within the manufacturer’s recommended DFT range except for the 1-coat system. The recommended DFT for application of the 1-coat system on prepared steel is 250–300 μm (10–12 mil), whereas the average DFT on the coated panels ranged from 80 to 103 μm (3.1–4.1 mil). The V-shaped attachment on the large panel had thinner DFTs than other parts of the panel. Some 1-coat panels developed many surface blisters and rust pits in addition to significant rust creepage at the scribe. The original coating condition is shown in figure 13-A. Significant coating failure developed after 3 yr of exposure, as shown in figure 13-B. The poor performance could be attributed to the insufficient DFT.

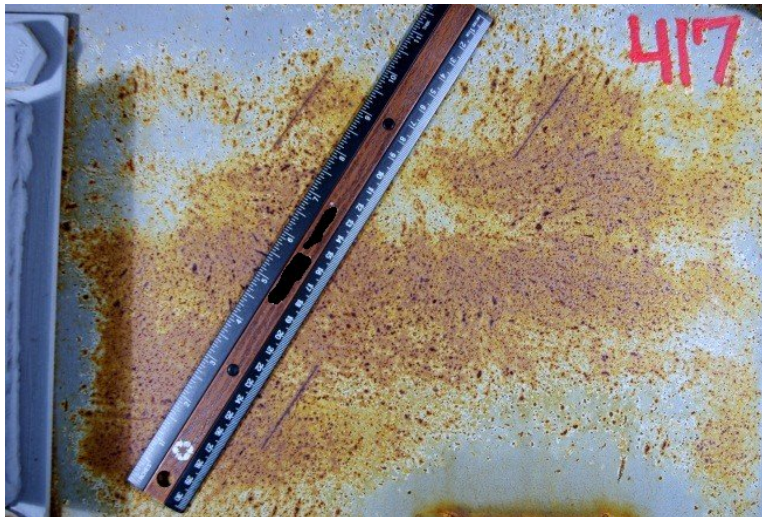
Table 4. DFT on large panels.

Item	3-Coat with Inorganic Zinc	3-Coat with Organic Zinc	2-Coat	1-Coat
Face	301 μm (11.9 mil)	296 μm (11.7 mil)	274 μm (10.8 mil)	89 μm (3.5 mil)
V joint	217 μm (8.5 mil)	245 μm (9.6 mil)	174 μm (6.8 mil)	80 μm (3.1 mil)
Angle	265 μm (10.4 mil)	306 μm (12.0 mil)	210 μm (8.3 mil)	87 μm (3.4 mil)
T joint	291 μm (11.5 mil)	327 μm (12.9 mil)	207 μm (8.2 mil)	103 μm (4.1 mil)



Source: FHWA.

A. Original coating condition on a 1-coat large panel.



Source: FHWA.

B. Coating failure on the 1-coat large panel 3 yr later.

Figure 13. Photos. Original coating condition and coating failure on the 1-coat large panel 3 yr later.

GLOSS

Gloss is a measure of a surface's capability to reflect light, and the level of reflection is measured in gloss units (GUs). Gloss is important for predicting coating durability. Gloss reduction is an indication that the coating film has degraded. All coatings lose gloss over time, but high-quality UV-resistant top coatings can provide long-term gloss retention in a properly applied coating system.

A gloss meter measures the luminous reflectance of a coated surface and compares it with a black glass standard. Following ASTM D523-14, *Standard Test Method for Specular Gloss*, gloss was measured at 20° and 60° on the coated panels.⁽³²⁾

Gloss Reduction of ALT Panels

Gloss reduction values after 14 cycles are shown in table 5. The 3- and 2-coat systems had about the same level of gloss reduction. The 1-coat system had the most gloss reduction.

Table 5. Gloss reduction of ALT panels.

Coating System	Original Gloss (GU)		Gloss after 14 Cycles (GU)		Gloss Reduction (%)	
	20°	60°	20°	60°	20°	60°
3-coat with inorganic zinc	5.3	28.4	3.0	18.9	-44	-33
3-coat with organic zinc	5.1	27.8	2.8	18.3	-45	-34
2-coat	14.2	50.6	7.4	35.6	-48	-30
1-coat	1.3	10.3	0.4	1.2	-69	-89

Gloss Reduction of Outdoor Panels

Gloss reduction values of the outdoor panels are presented in table 6 (saltwater spray) and table 7 (water spray). The coating systems had significant gloss reduction after 54 mo of exposure to saltwater spray. The 1-coat system exhibited relatively more gloss reduction than the other coating systems. In general, saltwater spray caused more gloss reduction than water spray.

Table 6. Gloss reduction of outdoor panels with saltwater spray.

Coating System	Original Gloss (GU)		Gloss after 54 Mo (GU)		Gloss Reduction (%)	
	20°	60°	20°	60°	20°	60°
3-coat with inorganic zinc	5.3	28.4	1.0	4.3	-81	-85
3-coat with organic zinc	5.1	27.8	1.0	4.1	-81	-85
2-coat	14.2	50.6	10.8	24.4	-24	-52
1-coat	1.3	10.3	0.3	0.9	-76	-92

Table 7. Gloss reduction of outdoor panels with water spray.

Coating System	Original Gloss (GU)		Gloss after 54 Mo (GU)		Gloss Reduction (%)	
	20°	60°	20°	60°	20°	60°
3-coat with inorganic zinc	5.3	28.4	2.6	19.0	-51	-33
3-coat with organic zinc	5.1	27.8	2.8	19.7	-46	-29
2-coat	14.2	50.6	6.6	34.9	-53	-31
1-coat	1.3	10.3	0.4	1.5	-73	-85

COLOR

Corrosion-resistant coatings on bridges must provide utilitarian surfaces as well as a pleasing appearance. It is essential for a coating to maintain its color for a long time without fading or chalking. Coatings with high color retention are valued because they are indicative of corrosion resistance, weatherability, and durability.

The International Commission on Illumination (CIE) lab color system (also known as the CIE $L^*a^*b^*$) was used for color measurement. L^* , a^* , and b^* represent the three coordinates of the three-dimensional lab color space. The CIE parameters are defined based on the values they represent, and those values identify colors as follows:

- $L^* = 0$ represents black, and $L^* = 100$ represents diffuse white.
- Positive values of a^* represent green, and negative values represent magenta.
- Positive values of b^* represent blue, and negative values represent yellow.

A 45°/0° colorimeter was used to measure the color of the coated panels based on ASTM D2244-09A, *Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates*.⁽³³⁾ Three locations were measured for each standard size test panel, and three locations were measured on the front face of each large test panel. Three color readings were obtained from each location. The color difference (ΔE) of the test panels before and after the test was calculated using the equation in figure 14:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

Figure 14. Equation. Formula for calculating the color difference.

Where:

$\Delta L^* = L^*$ after test – L^* before test.

$\Delta a^* = a^*$ after test – a^* before test.

$\Delta b^* = b^*$ after test – b^* before test.

Color Change of ALT Panels

The color changes of the ALT panels, indicated by ΔE , are presented in table 8. After 14 cycles, the inorganic zinc 3-coat system had the best color retention, as indicated by the low ΔE value. The organic zinc 3-coat system had significant color reduction. The 2-coat system had the worst color retention, but visual examination revealed that the color reduction might have been attributed to rust stains on the coating panels. The 1-coat system showed noticeable color change.

Table 8. Color change of ALT panels.

Coating	Original			After 14 Cycles						
	L^*	a^*	b^*	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE
3-coat with inorganic zinc	71.99	-1.59	5.25	70.03	-0.28	9.45	-1.96	1.32	4.20	4.81
3-coat with organic zinc	71.97	-1.74	5.34	68.38	0.83	14.35	-3.60	2.57	9.01	10.04
2-coat	95.89	-1.66	2.28	88.93	2.23	20.22	-6.96	3.89	17.95	19.64
1-coat	60.22	-1.41	-0.28	54.86	0.87	6.42	-5.36	2.28	6.71	8.88

Color Change of Outdoor Panels

The color retention characteristics of the outdoor panels were different from those of the ALT panels. For the outdoor panels sprayed with salt water, the color change after 54 mo is shown in table 9. No visually noticeable color change was present on the panels except for those with the 1-coat system.

Table 9. Color change of outdoor panels with saltwater spray.

Coating	Original			After 54-Mo Exposure						
	L^*	a^*	b^*	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE
3-coat with inorganic zinc	71.99	-1.59	5.25	74.55	-0.69	4.07	2.56	0.90	-1.18	2.96
3-coat with organic zinc	71.97	-1.74	5.34	74.64	-0.65	4.13	2.66	1.10	-1.20	3.12
2-coat	95.89	-1.66	2.28	94.11	-0.37	2.87	-1.78	1.29	0.60	2.27
1-coat	60.22	-1.41	-0.28	44.98	0.42	1.34	-15.24	1.83	1.62	15.44

Except for the 1-coat panels, the outdoor panels subjected to water spray changed in color only slightly after 54 mo of exposure, as shown in table 10. No distinctive difference in color change was found between the water-sprayed panels and the saltwater-sprayed panels.

Table 10. Color change of outdoor panels with water spray.

Coating	Original			After 54-Mo Exposure						
	L^*	a^*	b^*	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE
3-coat with inorganic zinc	71.99	-1.59	5.25	72.77	-0.80	4.17	0.77	0.79	-1.08	1.55
3-coat with organic zinc	71.97	-1.74	5.34	72.35	-0.79	4.30	0.38	0.95	-1.04	1.46
2-coat	95.89	-1.66	2.28	92.28	-0.42	2.75	-3.61	1.24	0.48	3.84
1-coat	60.22	-1.41	-0.28	45.73	0.53	1.47	-14.49	1.94	1.75	14.72

ADHESION

Adhesion is frequently considered the most prominent requirement for a corrosion-resistant coating. Strong adhesion is essential for a coating's integrity because it prevents damage from thermal gradients and osmosis.

The coating's adhesion strength was measured with a portable adhesion tester following ASTM D4541-09, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*.⁽³⁴⁾ Three locations on the standard size coated panels were tested. The adhesion strength of the coating systems is shown in table 11. The introduction of chloride on the steel surface adversely affected the initial adhesion strength of the 3-coat system with inorganic zinc primer. Without chloride, the average initial adhesion strength was 15 MPa (2,141 psi); the panels with 20 $\mu\text{g}/\text{cm}^2$ of chloride had an average initial adhesion strength of 12 MPa (1,810 psi), a 15-percent loss in adhesion strength. The panels with 60 $\mu\text{g}/\text{cm}^2$ of chloride had an average initial adhesion strength of 11 MPa (1,581 psi), a 30-percent loss in adhesion strength. For the 1-coat system, the average initial adhesion strength was 4 MPa (586 psi) without salt contamination. At 60 $\mu\text{g}/\text{cm}^2$ of chloride contamination, the average initial adhesion strength decreased to 3 MPa (464 psi), a 21-percent loss in strength. Surface salt contamination had no significant effect on initial adhesion strength for the 3-coat system with organic zinc primer and the 2-coat system.

Adhesion Strength of ALT Panels

After 14 cycles of ALT, the 3-coat system with inorganic zinc primer did not exhibit significant change in adhesion strength on panels with chloride contamination levels at 20 and 60 $\mu\text{g}/\text{cm}^2$. The 3-coat system with organic zinc primer upheld adhesion strength at the 20- $\mu\text{g}/\text{cm}^2$ chloride contamination level but sustained a 19-percent loss at 60 $\mu\text{g}/\text{cm}^2$. For the 2-coat system, the control panels lost 23-percent adhesion strength, panels with 20 $\mu\text{g}/\text{cm}^2$ of chloride lost 33 percent, and panels with 60 $\mu\text{g}/\text{cm}^2$ of chloride lost 37 percent. The chloride did not significantly affect the adhesion strength of the 1-coat system.

Table 11. Adhesion test results of the coated panels exposed to ALT.

Coating	Chloride Level	Initial Adhesion (MPa (psi))	Adhesion after 5,040-H Exposure (MPa (psi))	Change (%)
3-coat with inorganic zinc	No chloride	15 (2,141)	19 (2,692)	26
	20 µg/cm ²	12 (1,810)	13 (1,834)	1
	60 µg/cm ²	11 (1,581)	12 (1,705)	8
3-coat with organic zinc	No chloride	19 (2,771)	19 (2,803)	1
	20 µg/cm ²	19 (2,802)	19 (2,776)	-1
	60 µg/cm ²	18 (2,645)	15 (2,141)	-19
2-coat	No chloride	23 (3,318)	18 (2,562)	-23
	20 µg/cm ²	23 (3,388)	16 (2,262)	-33
	60 µg/cm ²	23 (3,313)	14 (2,094)	-37
1-coat	No chloride	4 (586)	4 (593)	1
	20 µg/cm ²	4 (542)	5 (673)	24
	60 µg/cm ²	3 (464)	3 (477)	3

Adhesion Strength of Outdoor Panels

After 54 mo of natural exposure, pull-off adhesion tests were performed on the standard size unscrubbed panels. Table 12 shows the results from saltwater-sprayed panels. The chloride contamination level did not adversely affect the 3-coat system with inorganic zinc primer. The chloride contamination level affected the 3-coat system with organic zinc primer, causing its adhesion strength to decrease as the chloride levels increased. The 2-coat system had slight reduction in its adhesion when chloride contamination was 20 µg/cm², but the loss in adhesion strength when contamination was 60 µg/cm² was significant. The 1-coat system’s adhesion strength did not decrease after 54 mo.

Table 12. Adhesion strength of saltwater-sprayed panels.

Coating	Chloride Level	Initial Adhesion (MPa (psi))	Adhesion after 54-Mo Exposure (MPa (psi))	Change (%)
3-coat with inorganic zinc	No chloride	15 (2,141)	12 (1,772)	-17
	20 µg/cm ²	12 (1,810)	11 (1,660)	-8
	60 µg/cm ²	11 (1,581)	14 (1,975)	25
3-coat with organic zinc	No chloride	19 (2,771)	20 (2,851)	3
	20 µg/cm ²	19 (2,802)	17 (2,506)	-11
	60 µg/cm ²	18 (2,645)	13 (1,944)	-26
2-coat	No chloride	23 (3,318)	20 (2,872)	-13
	20 µg/cm ²	23 (3,388)	22 (3,149)	-7
	60 µg/cm ²	23 (3,313)	16 (2,284)	-31
1-coat	No chloride	4 (586)	4 (630)	7
	20 µg/cm ²	4 (542)	4 (636)	17
	60 µg/cm ²	3 (464)	3 (466)	1

The pull-off test results from the water-sprayed panels are presented in table 13. For the 3-coat system with organic zinc primer and the 2-coat system, the adhesion strength decreased after 54 mo, and panels with more chloride on their substrate had lower adhesion strength. However, adhesion of the 3-coat system with inorganic zinc primer was not adversely affected by the chloride contamination level. The 1-coat system was able to sustain its adhesion when the chloride level was 20 $\mu\text{g}/\text{cm}^2$, but the loss in adhesion strength was significant at 60 $\mu\text{g}/\text{cm}^2$.

Table 13. Adhesion strength of water-sprayed panels.

Coating	Chloride Level	Initial Adhesion (MPa (psi))	Adhesion after 54-Mo Exposure (MPa (psi))	Change (%)
3-coat with inorganic zinc	No chloride	15 (2,141)	17 (2,401)	12
	20 $\mu\text{g}/\text{cm}^2$	12 (1,810)	12 (1,758)	-3
	60 $\mu\text{g}/\text{cm}^2$	11 (1,581)	14 (2,030)	28
3-coat with organic zinc	No chloride	19 (2,771)	19 (2,693)	-3
	20 $\mu\text{g}/\text{cm}^2$	19 (2,802)	15 (2,223)	-21
	60 $\mu\text{g}/\text{cm}^2$	18 (2,645)	13 (1,875)	-29
2-coat	No chloride	23 (3,318)	21 (3,105)	-6
	20 $\mu\text{g}/\text{cm}^2$	23 (3,388)	21 (2,979)	-12
	60 $\mu\text{g}/\text{cm}^2$	23 (3,313)	20 (2,861)	-14
1-coat	No chloride	4 (586)	5 (686)	17
	20 $\mu\text{g}/\text{cm}^2$	4 (542)	5 (634)	17
	60 $\mu\text{g}/\text{cm}^2$	3 (464)	3 (403)	-13

RUST CREEPAGE

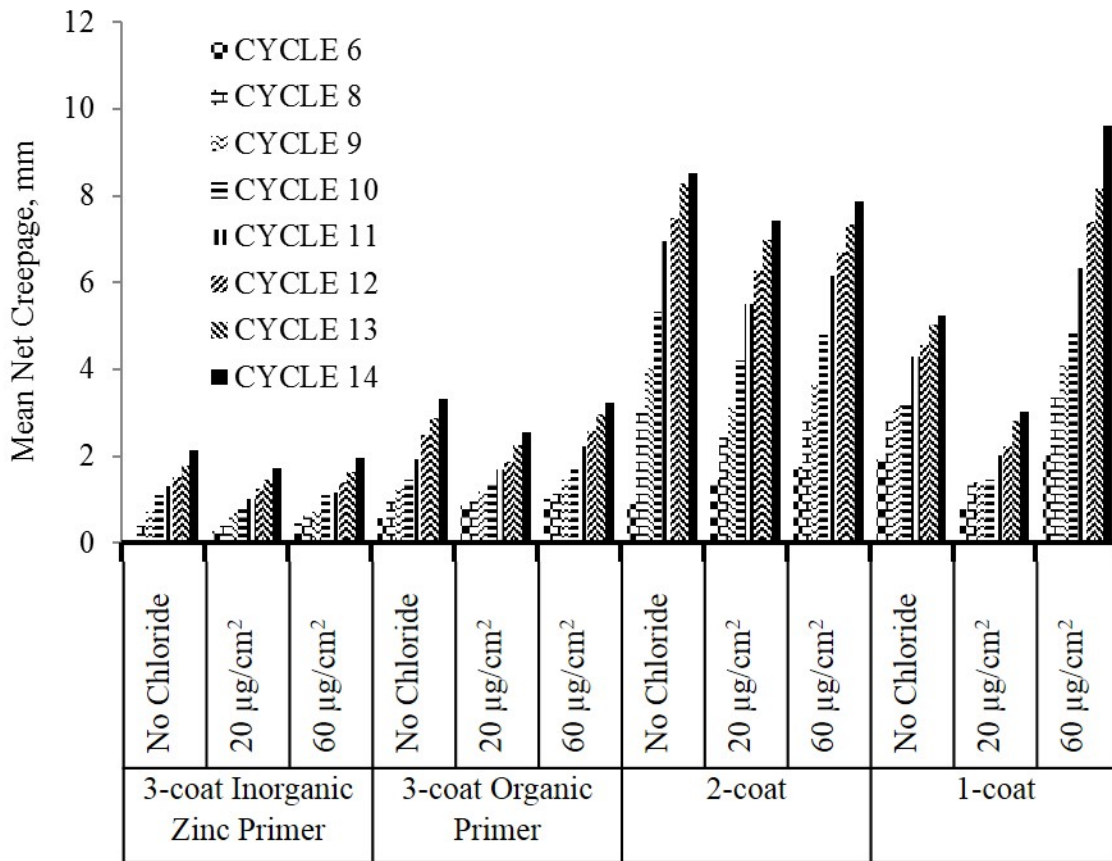
Rust creepage measurement is a quantitative method for evaluating the loss of adhesion at a scribe line, development of blistering, and corrosion damage to the coating. Rust creepage at the scribe was measured in general accordance with ASTM D7087-05A, *Standard Test Method for an Imaging Technique to Measure Rust Creepage at Scribe on Coated Test Panels Subjected to Corrosive Environments*.⁽³⁵⁾ The rust creepage area from the scribe line was traced with a fine soft pencil. The panel was then digitally photographed, and image-analyzing software was used to calculate creepage areas. The procedure is detailed in appendix B. Mean creepage distance was reported as the nominal creepage for the coating system.

Rust Creepage on ALT Panels

Rust creepage at the scribe line was measured periodically for the ALT panels. The results are summarized in table 14, and figure 15 presents these data in graph form. For each coating system, the panels are categorized according to the amount of chloride added to the steel surface.

Table 14. Rust creepage development on ALT panels.

Coating	Chloride Level	2,160 h (mm (mil))	2,880 h (mm (mil))	3,240 h (mm (mil))	3,600 h (mm (mil))	3,960 h (mm (mil))	4,320 h (mm (mil))	4,680 h (mm (mil))	5,040 h (mm (mil))
3-coat with inorganic zinc	No chloride	0.0 (0.0)	0.5 (19.7)	0.7 (27.6)	1.1 (43.3)	1.3 (51.2)	1.5 (59.1)	1.8 (70.9)	2.1 (82.7)
	20 µg/cm ²	0.3 (11.8)	0.6 (23.6)	0.7 (27.6)	0.9 (35.4)	1.0 (39.4)	1.3 (51.2)	1.5 (59.1)	1.7 (66.9)
	60 µg/cm ²	0.5 (19.7)	0.6 (23.6)	0.8 (31.5)	1.1 (43.3)	1.2 (47.2)	1.4 (55.1)	1.6 (63.0)	2.0 (78.7)
3-coat with organic zinc	No chloride	0.6 (23.6)	1.0 (39.4)	1.2 (47.2)	1.4 (55.1)	1.9 (74.8)	2.5 (98.4)	2.9 (114.2)	3.3 (129.9)
	20 µg/cm ²	0.9 (35.4)	1.0 (39.4)	1.2 (47.2)	1.4 (55.1)	1.7 (66.9)	1.9 (74.8)	2.3 (90.6)	2.5 (78.7)
	60 µg/cm ²	1.0 (39.4)	1.2 (47.2)	1.5 (59.1)	1.8 (70.9)	2.2 (86.6)	2.6 (102.4)	3.0 (118.1)	3.2 (126.0)
2-coat	No chloride	0.9 (35.4)	3.1 (122.0)	4.0 (157.5)	5.3 (208.7)	7.0 (275.6)	7.5 (295.3)	8.3 (326.8)	8.5 (334.6)
	20 µg/cm ²	1.5 (59.1)	2.4 (94.5)	3.2 (126.0)	4.2 (165.4)	5.5 (216.5)	6.3 (248)	7.0 (275.6)	7.4 (291.3)
	60 µg/cm ²	1.7 (66.9)	2.9 (114.2)	3.6 (141.7)	4.8 (189.0)	6.2 (244.1)	6.7 (263.8)	7.3 (287.4)	7.9 (311.0)
1-coat	No chloride	1.9 (74.8)	2.9 (114.2)	3.2 (126.0)	3.2 (126.0)	4.3 (169.3)	4.6 (181.1)	5.0 (196.9)	5.2 (204.7)
	20 µg/cm ²	0.8 (31.5)	1.4 (55.1)	1.4 (55.1)	1.5 (59.1)	2.0 (78.7)	2.2 (86.6)	2.8 (110.2)	3.0 (118.1)
	60 µg/cm ²	2.0 (78.7)	3.4 (133.9)	4.1 (161.4)	4.9 (192.9)	6.3 (248.0)	7.4 (291.3)	8.2 (322.8)	9.6 (378.0)



Source: FHWA.
1 mm = 39 mil.

Figure 15. Chart. Rust creepage development on ALT panels.

In general, the 3-coat system with inorganic zinc primer had the least creepage, and chloride contamination on the steel surface had little or no impact on the development of creepage. The 3-coat system with organic zinc primer had a slightly larger amount of creepage. After six cycles (2,160 h) of testing, the 3-coat with inorganic zinc primer panels with 20 µg/cm² of chloride developed a net creepage of 0.3 mm (11.8 mil), whereas panels with 60 µg/cm² of chloride developed a net creepage of 0.5 mm (19.7 mil). The control panels without additional chloride did not develop any creepage. After 5,040 h, the 3-coat panels with inorganic zinc primer developed a net creepage between 1.7 and 2.1 mm (66.9 and 82.7 mil), whereas the 3-coat panels with organic zinc primer developed a net creepage between 2.5 and 3.3 mm (78.7 and 129.9 mil). The 2- and 1-coat systems developed significant creepage. After 5,040 h, the 2-coat system developed a net creepage between 7.4 and 8.5 mm (291.3 and 334.6 mil). The 1-coat panels developed a net creepage between 3.0 and 9.6 mm (118.1 and 378.0 mil).

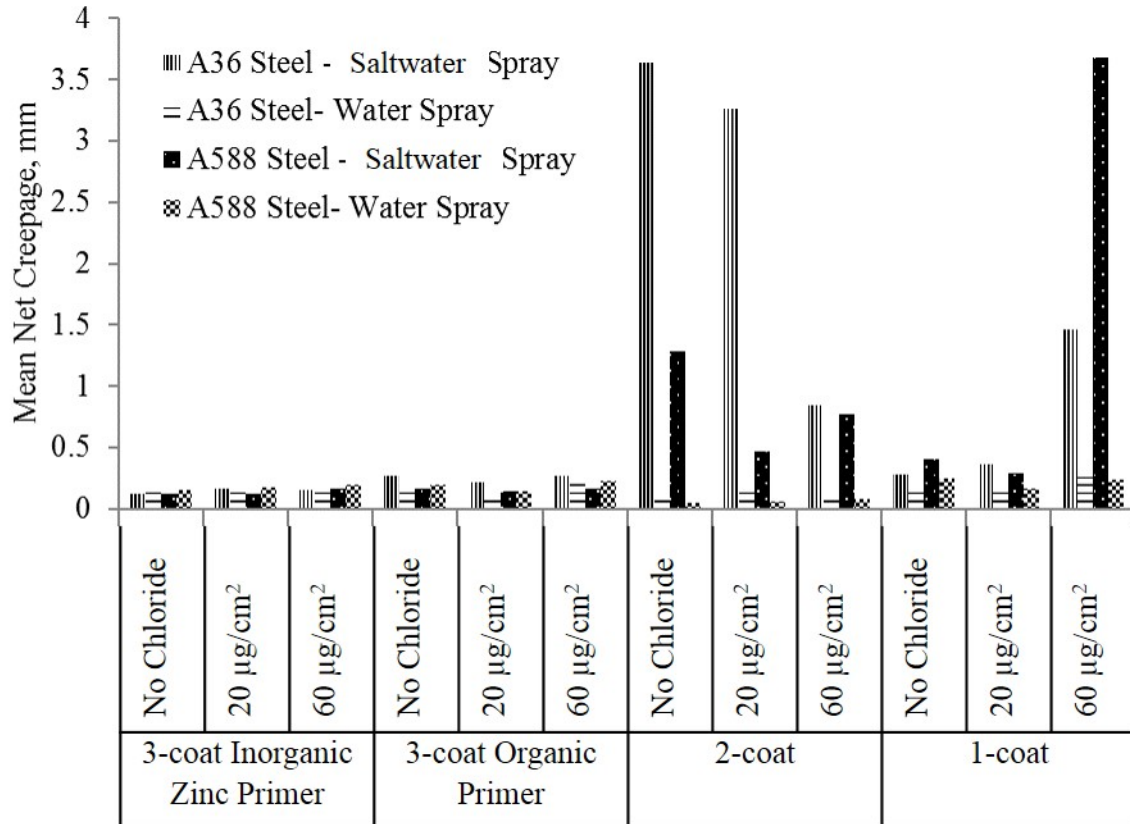
Rust Creepage on Outdoor Panels

The data in table 15 represent the rust creepage development on the standard size panels after 54 mo of outdoor exposure, and figure 16 shows these data in graph form. Of the two 3-coat

systems, the coating with inorganic zinc primer had slightly less creepage than the one with organic zinc primer. Both coating systems demonstrated excellent resistance to rust creepage development regardless of chloride contamination, type of spray, or type of steel substrate. The 2- and 1-coat systems were sensitive to saltwater spray, but they had less rust creepage under water spray. With saltwater spray, the 2-coat system had significant creepage development; however, noticeably less creepage occurred on A588 weathering steel panels than on A36 steel panels. With saltwater spray, the 1-coat system developed significant rust creepage at the high chloride contamination level. Among all panels with water spray, the rust creepage on the A588 steel panels exhibited similar trends as that on the A36 steel panels, as shown in figure 16. In general, the creepage was not significant after 54 mo of outdoor exposure.

Table 15. Rust creepage development on standard size outdoor panels after 54-mo exposure.

Coating	Chloride Level	A36 Steel: Saltwater Spray (mm (mil))	A36 Steel: Water Spray (mm (mil))	A588 Steel: Saltwater Spray (mm (mil))	A588 Steel: Water Spray (mm (mil))
3-coat inorganic zinc	No chloride	0.12 (4.72)	0.14 (5.51)	0.12 (4.72)	0.16 (6.30)
	20 $\mu\text{g}/\text{cm}^2$	0.17 (6.69)	0.14 (5.51)	0.13 (5.12)	0.17 (6.69)
	60 $\mu\text{g}/\text{cm}^2$	0.16 (6.30)	0.14 (5.51)	0.16 (6.30)	0.20 (7.87)
3-coat organic zinc	No chloride	0.26 (10.24)	0.17 (6.69)	0.17 (6.69)	0.19 (7.48)
	20 $\mu\text{g}/\text{cm}^2$	0.22 (8.66)	0.11 (4.33)	0.14 (5.51)	0.14 (5.51)
	60 $\mu\text{g}/\text{cm}^2$	0.26 (10.24)	0.23 (9.06)	0.16 (6.30)	0.22 (8.66)
2-coat	No chloride	3.63 (142.91)	0.10 (3.94)	1.28 (50.39)	0.05 (1.97)
	20 $\mu\text{g}/\text{cm}^2$	3.27 (128.74)	0.15 (5.91)	0.47 (18.50)	0.06 (2.36)
	60 $\mu\text{g}/\text{cm}^2$	0.85 (33.46)	0.07 (2.76)	0.77 (30.31)	0.08 (3.15)
1-coat	No chloride	0.28 (11.02)	0.18 (7.09)	0.40 (15.75)	0.25 (9.84)
	20 $\mu\text{g}/\text{cm}^2$	0.36 (14.17)	0.19 (7.48)	0.29 (11.42)	0.17 (6.69)
	60 $\mu\text{g}/\text{cm}^2$	1.46 (57.18)	0.26 (10.24)	3.68 (144.88)	0.24 (9.45)



Source: FHWA.
1 mm = 39 mil.

Figure 16. Chart. Rust creepage development on standard size outdoor panels after 54-mo exposure.

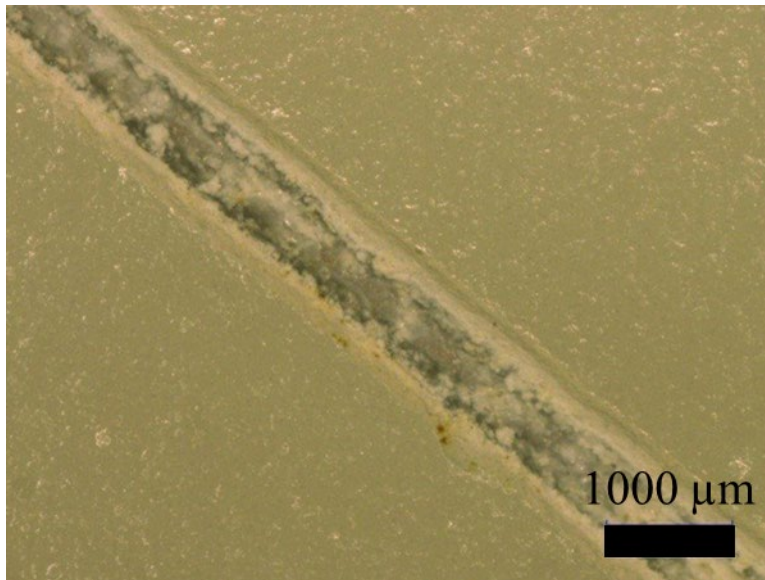
Rust creepage on the large panels after 54 mo of outdoor exposure is shown in table 16. The saltwater-sprayed 1-coat panel with 60 µg/cm² of chloride on the A36 steel substrate had significantly higher rust creepage than other panels of the same coating system, which can be partially attributed to the insufficient DFT. The water-sprayed panels did not show any significant rust creepage regardless of coating system, chloride contamination, type of spray, or steel type. The 3-coat systems remained relatively intact under saltwater spray, whereas the 1- and 2-coat systems had significantly higher rust creepage. The results are similar to those for the standard size panels.

Table 16. Rust creepage development on large outdoor panels after 54-mo exposure.

Coating	Chloride Level	A36 Steel: Saltwater Spray (mm (mil))	A588 Steel: Saltwater Spray (mm (mil))	A36 Steel: Water Spray (mm (mil))
3-coat inorganic zinc	No chloride	0.29 (11.42)	0.22 (8.66)	0.04 (1.57)
	20 µg/cm ²	0.29 (11.42)	0.32 (12.60)	0.06 (2.36)
	60 µg/cm ²	0.22 (8.66)	0.58 (22.83)	0.18 (7.09)
3-coat organic zinc	No chloride	0.33 (12.99)	0.24(9.45)	0.11 (4.33)
	20 µg/cm ²	0.72 (28.35)	0.13 (5.12)	0.08 (3.15)
	60 µg/cm ²	0.21 (8.27)	0.53 (20.87)	0.04 (1.57)
2-coat	No chloride	13.94 (548.82)	4.86 (191.34)	0.45 (17.72)
	20 µg/cm ²	11.44 (450.39)	0.84 (33.07)	0.05 (1.97)
	60 µg/cm ²	13.43 (528.74)	3.29 (129.53)	0.21 (8.27)
1-coat	No chloride	2.82 (111.02)	4.85 (190.94)	0.45 (17.72)
	20 µg/cm ²	4.48 (176.38)	1.87 (73.62)	0.28 (11.02)
	60 µg/cm ²	20.00 (787.40)	6.46 (254.33)	0.51 (20.08)

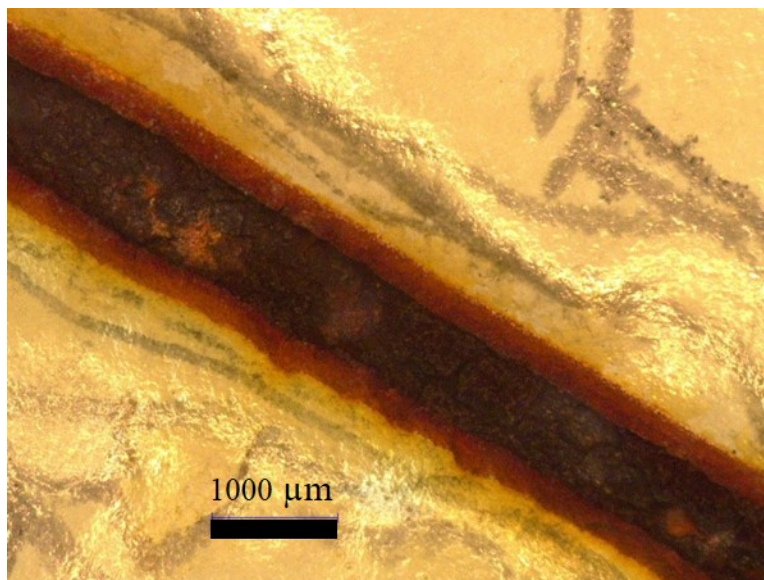
Visualization of Rust Creepage Development

Gradual growth of rust creepage along the scribe line is visible in photos and microscopic images, such as figure 17. With a magnification of 50 or higher, the rust creepage and blistering can be observed in clear detail.



Source: FHWA.

A. Scribe after 1 cycle.



Source: FHWA.

B. Scribe after 14 cycles.

Figure 17. Photos. Scribes after 1 and 14 cycles.

The rust creepage was significantly different among the coating systems. The findings from the images agreed with the measured creepage data. The 3-coat with inorganic zinc had the least creepage, and the chloride contamination did not affect the creepage development. The 3-coat with organic zinc had slightly more creepage. The 2- and 1-coat systems developed significant creepage.

MICROSCOPIC EXAMINATION AND DIGITAL PHOTOGRAPHY

A microscope was used to examine coated panels with surface defects. For instance, spot rust was examined under the microscope to determine whether it was caused by a protruding metal particle or a holiday in the coating. Surface conditions were documented via microphotographs. Digital photographs were taken to document the initial surface conditions of each panel and after each test cycle to assess rust creepage.

DETECTION OF COATING DEFECTS

Coating defects were identified following ASTM D5162-08, *Standard Practice for Discontinuity (Holiday) Testing of Nonconductive Protective Coating on Metallic Substrates*.⁽³⁶⁾ A low-voltage discontinuity (holiday) detector senses the electrically conductive defects, such as holidays, pinholes, voids, and protruding metal particles. The number of defects on each panel was recorded for quality control.

Additionally, the coated panels were visually examined to identify other types of defects. Standard test procedures were generally followed when such examinations were performed. For instance, ASTM D714-02, *Standard Test Method for Evaluating Degree of Blistering of Paints*, describes the procedures to determine the size and density of blistering on a coated panel, and ASTM D610-08, *Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces*, provides guidelines for classifying and determining the extent of rusts on a coated surface.^(37,38)

CHAPTER 4. CONCLUSIONS

This study investigated the performance of four coatings applied to chloride-contaminated steel substrate. The following conclusions were drawn from this study:

- The 3-coat systems performed better than the 1- and 2-coat systems under ALT and outdoor weathering conditions.
- The 1-coat film (HRCSA) remained soft for a long time after application and was prone to damage during transportation and handling. Some panels had DFTs that were substantially lower than the manufacturer's recommended value, which might have contributed negatively to the coating's performance.
- The 2-coat system demonstrated the highest adhesion strength over all levels of contamination.
- Based on the comprehensive performance evaluation, the 3-coat systems had the best corrosion protection performance.
- The presence of chloride on the steel substrate affected the coating performance. The 3-coat systems showed better tolerance of chloride than the 2- and 1-coat systems. The 3-coat system with inorganic zinc primer had the best tolerance of chloride.
- The 3-coat systems can tolerate chloride contamination levels up to $60 \mu\text{g}/\text{cm}^2$ without substantial effect on creepage development. The inorganic zinc primer performed slightly better than the organic zinc primer.
- Spraying salt water did not affect the performance of the 3-coat systems. The 2-coat panels subjected to saltwater spray developed significant rust creepage, whereas the panels exposed to water spray did not exhibit noticeable creepage.
- Among the 2-coat large panels subjected to saltwater spray, the A588 steel panels developed significantly less rust creepage than the A36 steel panels. This may be due to the self-sealing properties of the corrosion product formed by A588 steels.
- Outdoor weathering simulates the natural exposure conditions experienced by steel bridges in service, but the testing time must be significantly longer than ALT.

APPENDIX A. PROCEDURE FOR SODIUM CHLORIDE SOLUTION DEPOSITION

CALCULATING THE REQUIRED VOLUME OF SODIUM CHLORIDE SOLUTION

The concentration of the solution is expressed as ppm, which means grams of substance per million grams of total solution. The density of a dilute aqueous solution is close to 1.00 g/mL, and 1 g of water is approximately equal to 1 mL of water. One gram is one million micrograms. Therefore, 1 ppm ($\mu\text{g/g}$) is equivalent to 1 $\mu\text{g/mL}$, and the 4,000-ppm solution has a concentration of chloride ions of 4,000 $\mu\text{g/mL}$.

Figure 18 is the equation for calculating the volume of solution to achieve a certain level of contamination on the surface:

$$\text{Volume (mL)} = \frac{\text{Concentration of salt on surface } (\mu\text{g/cm}^2) \times \text{Area (cm}^2\text{)}}{\text{Concentration of doping solution } (\mu\text{g/mL})}$$

Figure 18. Equation. General equation for calculating the volume of salt solution to contaminate the steel surface.

The volume (V) calculation for the 20- $\mu\text{g/cm}^2$ doping level with a 4,000-ppm NaCl solution (chloride concentration of 4,000 $\mu\text{g/mL}$) on a 102- by 152-mm (4- by 6-inch) panel is shown in figure 19:

$$V = \frac{20 \mu\text{g/cm}^2 \times 154.8\text{cm}^2}{4,000 \mu\text{g/mL}} = 0.77 \text{ mL}$$

Figure 19. Equation. Volume for the 20- $\mu\text{g/cm}^2$ doping level with a 4,000-ppm solution on a 102- by 152-mm (4- by 6-inch) panel.

Use 0.8 mL in consideration of liquid remaining on the glass rod.

Figure 20 shows the volume calculation for the 60- $\mu\text{g/cm}^2$ doping level with a 12,000-ppm NaCl solution on a 102- by 152-mm (4- by 6-inch) panel:

$$V = \frac{60 \mu\text{g/cm}^2 \times 154.8\text{cm}^2}{12,000 \mu\text{g/mL}} = 0.77 \text{ mL}$$

Figure 20. Equation. Volume for the 60- $\mu\text{g/cm}^2$ doping level with a 12,000-ppm solution on a 102- by 152-mm (4- by 6-inch) panel.

Use 0.8 mL in consideration of liquid remaining on the glass rod.

The volume calculation for the 20- $\mu\text{g/cm}^2$ doping level with a 4,000-ppm NaCl solution on a 457- by 457-mm (18- by 18-inch) panel (divided into four 228.5- by 228.5-mm (9- by 9-inch) quadrants) is shown in figure 21:

$$V = \frac{20 \mu\text{g}/\text{cm}^2 \times 522.6\text{cm}^2}{4,000 \mu\text{g}/\text{mL}} = 2.61 \text{ mL}$$

Figure 21. Equation. Volume for the 20 $\mu\text{g}/\text{cm}^2$ doping level with a 4,000-ppm solution on a 457- by 457-mm (18- by 18-inch) panel.

Use 2.65 mL in consideration of liquid remaining on the glass rod.

The volume calculation for the 60- $\mu\text{g}/\text{cm}^2$ doping level with a 12,000-ppm NaCl solution on a 457- by 457-mm (18- by 18-inch) panel (divided into four 228.5- by 228.5-mm (9- by 9-inch) quadrants) is shown in figure 22:

$$V = \frac{60 \mu\text{g}/\text{cm}^2 \times 522.6\text{cm}^2}{12,000 \mu\text{g}/\text{mL}} = 2.61 \text{ mL}$$

Figure 22. Equation. Volume for the 60- $\mu\text{g}/\text{cm}^2$ doping level with a 12,000-ppm solution on a 457- by 457-mm (18- by 18-inch) panel.

Use 2.65 mL in consideration of liquid remaining on the glass rod.

APPLYING SOLUTIONS TO TEST PANEL SURFACES

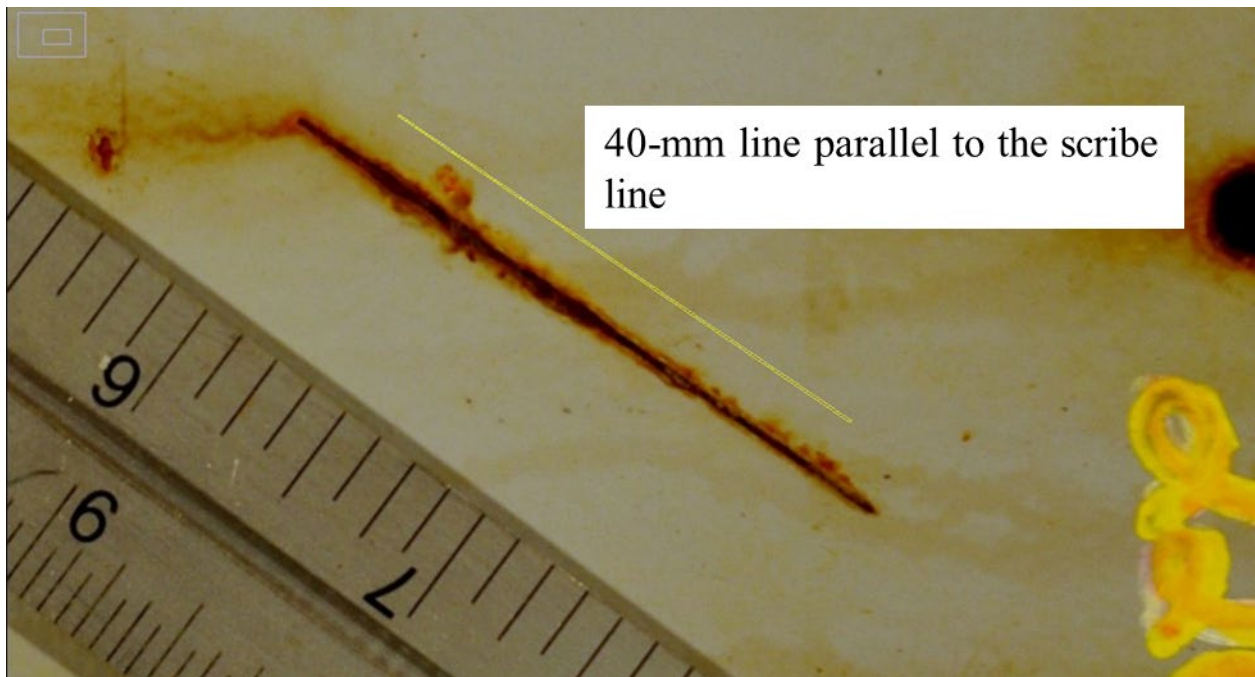
Salt solution was applied to the steel panels following the procedures described in appendix C, “Recommended Preparation of Test Panels and Methods for Applying Salt Solution to Test Panels, Drawdown Method,” of the NACE International Standard Practice SP0508-2010, *Methods of Validating Equivalence to ISO 8502-9 on Measurement of the Levels of Soluble Salts.*⁽²⁵⁾

- The appropriate amount of doping solution was delivered to the center of the 102- by 152-mm (4- by 6-inch) panel or 228.5- by 228.5-mm (9- by 9-inch) quadrant on the large panel using a graduated pipette. Only the front sides of the panels were treated with the salt solutions. The quarter-inch hanging hole in the 102- by 152-mm (4- by 6-inch) panels was plugged before delivering the solution to the panel surfaces to prevent loss of liquid volume. The area above the hole along the top edge of the 102- by 152-mm (4- by 6-inch) panels, welded V angle, and quarter-inch perimeter of the five holes on the 457- by 457-mm (18- by 18-inch) large panels were avoided during the chloride contamination process.
- The delivered solution was immediately spread evenly over the panel (quadrant) using a 6-mm (0.25-inch) glass rod. The rod was continuously passed (but not rotated) over the panel or quadrant surface to maintain a uniform distribution. A gentle stream of air flow generated by an oscillating fan blew over the surface to accelerate water evaporation during and after application of the solution. The panels were stored at laboratory conditions (20°C (68°F) to 25°C (77°F) and 50 percent or less humidity) before coating application.
- Panels were treated with the doping solutions the day before applying the primer. The treated panels contained a layer of flash rust that was coated over by the primer.

APPENDIX B. PROCEDURE FOR RUST CREEPAGE MEASUREMENT

To perform rust creepage measurement using ImageJ software, follow these steps:⁽³⁹⁾

- Open file.
- Magnify the image using the magnifying glass.
- Write the panel ID, test cycle, dates, and so forth. Use the text tool to write, and then click EDIT>DRAW to etch the text on the image.
- Set scale by clicking ANALYZE>SET SCALE.
- Mark the length by drawing a 40-mm (1.6-inch) straight line parallel to the rusted scribe line, as shown in figure 23. Place the marking line outside the rust creepage area. Position the line at the middle of the scribe line.

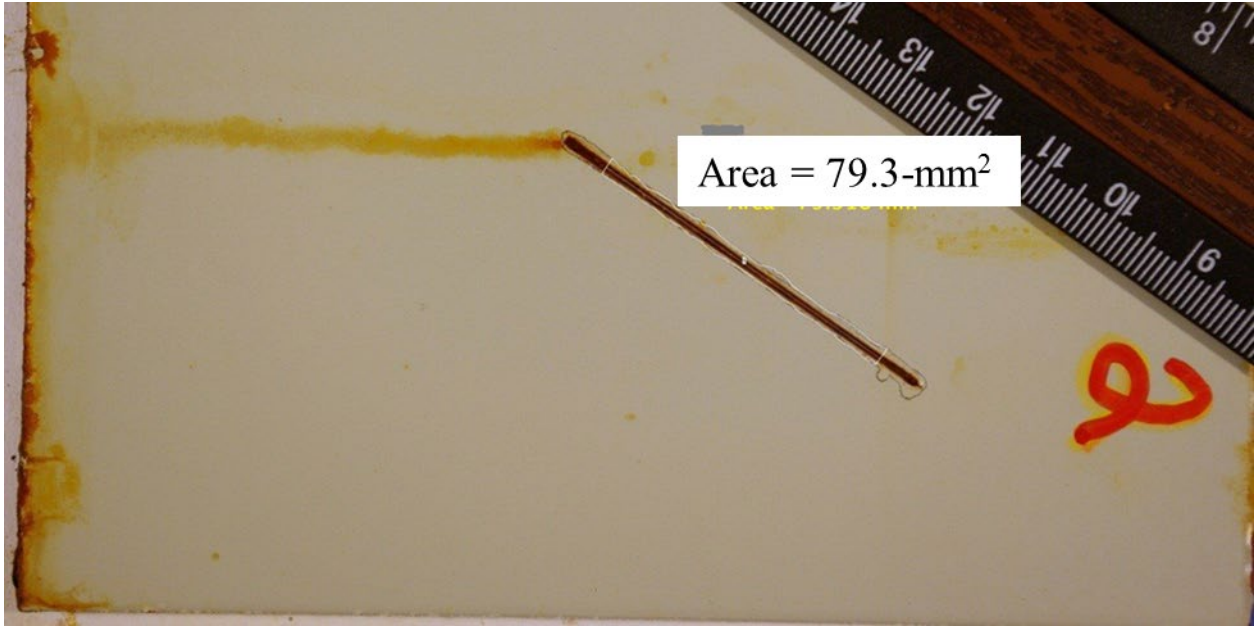


Source: FHWA.

Figure 23. Photo. Drawing a line parallel to the scribe.

- Sketch the creepage outline (for better results, use fine lines, such as size 1). Use polygon selections, as shown in figure 24.
- Measure the area of the polygon by clicking ANALYZE>MEASURE.
- Label the area by clicking ANALYZE>LABEL.

- Write the value of the area in square millimeters with the text tool, and then click EDIT>DRAW.
- Save the new file.



Source: FHWA.

Figure 24. Photo. Outlining the rust creepage area.

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