Single Coat Inorganic Zinc Protection for Steel Bridges

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Printed in the United States of America

Preface

Inorganic zinc (IOZ) coatings (i.e., paints) are frequently used as a primer layer in paint systems for steel structures. These coatings can also be used alone, i.e., as a single component, to provide appropriate corrosion protection in some situations. This application of inorganic zinc coatings is referenced as single-coat inorganic zinc (SIOZ). This document is a synthesis study report on the use of SIOZ as the sole corrosion protection system for steel bridges.

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BACKGROUND

Overview

Inorganic zinc (IOZ) coatings (i.e., paints) are frequently used as a primer layer in paint systems for steel structures. These coatings can also be used alone, i.e., as a single component, to provide appropriate corrosion protection in some situations. This application of inorganic zinc coatings is referenced as single-coat inorganic zinc (SIOZ) and is the subject of this literature review. Below, background is provided on SIOZ with respect to the history, corrosion protection mechanisms, available options, advantages, and disadvantages. Later sections review the available publications discussing application, performance data, and repair.

Brief History of SIOZ

Modern zinc coatings originated with the work of Victor Nightingall, who patented a zinc coating in 1937 (Francis 2013a). Because Nightingall was an Australian, much of the use and study of zinc coatings has occurred in Australia and New Zealand. The first recorded use of this coating for a large industrial structure was piloted in 1938 and experience with the coating led the owner (Vacuum Oil Company) to expand the use of the zinc coating to pipelines and oil tank interiors and exteriors. Uses by other owners in the oil sector soon followed. Later, zinc coatings were used for highway bridges.

Key developments in the advancement of zinc coatings include the development of self-curing zinc coatings in the 1960s (beginning with water-based products, which were followed by solvent-based products). Also, the Australian/New Zealand standard on corrosion protection using paint (Standards Australia, 2002) included inorganic zinc coatings with a quantified time to first maintenance in different environments in 1994. Zinc coatings were introduced in the United States in 1949 by the Ameron Company. The first known use of SIOZ for highway bridges in the United States was by the Missouri and Virginia Departments of Transportation in 1993 and 1994, respectively.

Corrosion Protection Mechanism

Inorganic zinc coatings consist of powdered zinc in a silicate solution, and are therefore often referenced as inorganic zinc silicates. Like all paint systems, SIOZ coatings provide barrier protection to the underlying steel. In other words, for intact coatings, they prevent moisture, oxygen, and contaminants from reaching the surface of the substrate steel and therefore prevent corrosion. Furthermore, zinc reacts with oxygen, carbon dioxide, and water that are readily available in the atmosphere to form zinc salts. In favorable situations, these salts include zinc carbonate, zinc hydroxide, and zinc oxide, and are sometimes referenced as “white rust”. These salts fill surface pores, further increasing the barrier protection provided by SIOZ coatings.

The high amounts of zinc in these coatings also provide cathodic protection at any scratches, gaps, or other defects in the coating. This means that the zinc will preferentially corrode relative to the exposed steel due to zinc’s greater anodic potential (reflected by the relative positions of zinc and steel in the galvanic series). This property prevents undercutting of the coating, which is often observed in other damaged coatings.

In harsh environments, some differences to the basic corrosion mechanism outlined above may occur. For example, in the presence of sulfur dioxide or chlorides, zinc sulfate or zinc chloride are formed. These compounds have no protective function. While this is an obvious disadvantage, Biddle (2013) states the following: “in coastal exposures, salt catalyzes the polymerization of unreacted silicic acid groups, increasing the molecular weight and thus protection by the silicate matrix.”

A final consideration in the corrosion mechanism of SIOZ is the inorganic nature of the corrosion protection system. This offers the advantages of the corrosion protection mechanism being unaffected by ultraviolet radiation from sunlight, temperature (after initial curing), bacteria, fungus, etc. These features may extend the coating life relative to organic coatings.

Comparison of SIOZ Types

SIOZ coatings are available in two primary formulations: water-based (alkali silicates) and solvent-based (ethyl silicates). These two formulations have distinct chemistry, and therefore some important differences. One of these is the required curing conditions, with the alternative optimum and acceptable temperature and relative humidity ranges for the two formulations being summarized by Figure 1. Lofhelm et al. (2006) also found that solvent-based outperformed water-based in accelerated corrosion testing, although the translation of this to real-world performance is unknown as both formulations have performed well and similarly in field conditions (as further discussed in the Performance Section below).

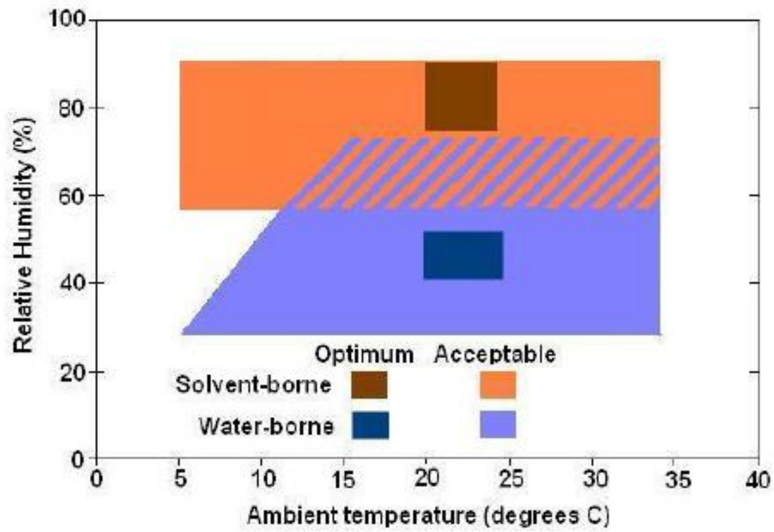


Figure 1. Optimum and Acceptable Curing Conditions for Solvent-Based and Water-Based SIOZ (Francis, 2013b).

The primary advantage of water-based SIOZ systems is that they do not contain volatile organic compounds, which may present adverse health effects and are therefore subject to increased regulations in some jurisdictions. A secondary advantage of water-based formulations is they are harder with better abrasion resistance (Francis, 2013b), although the importance of this advantage may be negligible in most bridge engineering applications. Water-based formulations also typically have slightly higher zinc content and higher specified dry film thickness (DFT).

Advantages

The primary advantages of SIOZ are a cost-effective and high-quality corrosion protection system. As discussed above, the corrosion protection mechanism provides both barrier protection, with the ability to improve performance over time due to the development of beneficial corrosion byproducts, and cathodic protection. As will be elaborated below, there is also reason to believe that SIOZ may provide superior corrosion protection relative to many other common systems. The cost-effectiveness of SIOZ results from both material savings due to the need for less coating and from fabrication cost savings due to the reduced time needed for one coat application as opposed to two or three in more typical paint systems. This results in reduced labor cost and the ability for increased fabrication throughput. Carlson (2020) compiled the data shown in Figure 2 from American Institute of Steel Construction fabricator members, which quantifies this cost savings. Figure 2 shows SIOZ (labeled 1-coat IOZ in Figure 2) to be the least expensive coating option, with only uncoated weathering steel (labeled UWS in Figure 2) options providing better economy. Helsel (2007) compared the life cycle costs of various zinc protection systems, including single- and multi-coat zinc coatings, galvanizing, and metallizing. In terms of life cycle costs, SIOZ was ranked second only behind galvanizing for shop applied systems; when field applied, SIOZ was ranked the best with the lowest life cycle costs.

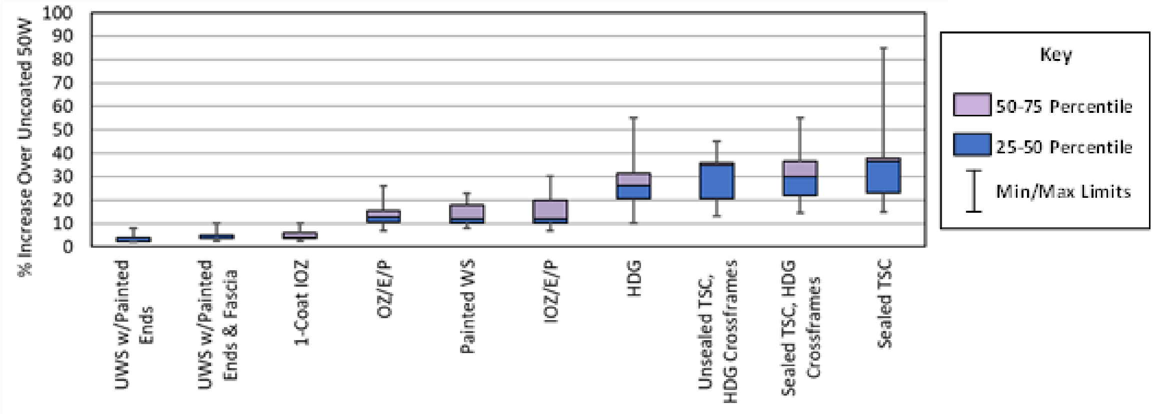


Figure 2. Relative Costs of Steel Corrosion Protection Systems (adapted from Carlson, 2020).

Other advantages of SIOZ include that it provides a hard coating, relative to many other paint systems. Furthermore, as mentioned above, water-based SIOZ coatings provide environmental benefits in that they do not contain volatile organic compounds.

Disadvantages

While a few technical disadvantages of SIOZ exist, most of these are issues that can be mitigated with proper fabrication. Two such disadvantages are sensitivity to surface preparation and curing conditions. The surface preparation requirements are a larger burden in field conditions than in shop conditions. Similarly, a disadvantage of SIOZ is a consequence of the initial porosity of coating. This porosity allows both for the absorption of contaminants (e.g., oils and greases) and difficulty of removing them. While removing contaminants in SIOZ is difficult, it is not impossible and recommended procedures do exist (as detailed in Wattyl, 1999). Regarding curing conditions, as shown by Figure 1, solvent-based SIOZ requires relatively high humidity levels to cure in a timely manner.

Another often reported disadvantage of inorganic zinc paints are their tendency to "mud crack", which is a fine pattern of cracks in the paint. This typically occurs when the coating thickness is excessive. Excessive thickness can result from simply over-spraying the coating. This is mostly a concern in internal corners where the laborer may make several overlapping passes of the corner in an effort to fully coat each connecting surface. Excessive thickness can also result in areas with too low of a blast profile. Wattyl (1999) has noted that this is a concern particularly at welds due to the increased hardness of the weld material. Other possible causes of mud cracking include high relative humidity combined with poor ventilation during application causing the outer layer to cure too quickly and products over the end of their shelf life (Wattyl, 1999).

Lastly, an additional possible subjective disadvantage is aesthetics. SIOZ is most commonly available in limited colors on the green to gray color spectrum, which may not be favorable for aesthetics reasons. Tinting with iron oxide for reddish tint is also possible. The aesthetic concerns may have been summarized best by Biddle (1993): "If zinc dust was available in a range of attractive colors, a one coat of inorganic zinc silicate paint would give long term protection to many facilities." To overcome the aesthetics concerns of SIOZ, the Texas Department of Transportation has standardized an IOZ primer with a breathable acrylic latex topcoat that can be readily tinted (Miller, 2019).

APPLICATION

Surface Preparation

The surface preparation for SIOZ can be considered as following the four primary steps common to all liquid coatings: pretreatment, cleaning, blasting, and avoiding contamination prior to coating. Each of these steps are generally easier to perform and / or control in the shop versus in the field, but field application is also possible. The specific requirements for each of these steps for SIOZ are summarized below.

Surface Pretreatment

The first step in surface preparation is typically removing sharp edges and fabrication defects by grinding. The same is true for SIOZ. Sharp edges are defined by the American Association of State Highway and Transportation Officials and the National Steel Bridge Alliance (AASHTO / NSBA, 2002) as “able or appears to be able to cut human flesh”. This guide specification also states that thermally cut edges may require grinding prior to blasting in order to achieve the blast profile discussed below. On the other hand, Francis (2016, citing an undated study by Corbett evaluating corner build characteristics) states that edge treatment can be minimized for SIOZ in part because of their limited shrinkage during curing. It is not specified whether this statement applies to thermally cut edges.

Fabrication defects that should be removed by grinding commonly include items such as rough welds and weld spatter. Removal is typically performed in accordance with SSPC SP-3. Testing by the Florida Department of Transportation demonstrated the importance of this by performing salt fog testing of weld spattered plates coated with SIOZ (McCullough 2022). These specimens “failed the criteria for rust creep and scribe at approximately 40% of the test duration (5,000 hrs. in the salt fog)”. This was attributed to the uneven surface caused by the weld spatter providing anodes to accelerate the electrochemical corrosion process.

Cleaning

Cleaning simply involves removing oil, grease, and lubricants from the surface. Water-based systems are particularly sensitive to any oil on the surface (Francis, 2016) Removing oil and grease is generally performed using the same standards as for other coating systems, commonly in accordance with SSPC SP-1. AASHTO / NSBA (2002) gives specific guidance on the removal of lubricants.

Blasting

Blasting should be performed to a near white standard of cleanliness (e.g., SSPC SP-10, SSPC 2007a). This is the industry standard in the United States and in Australia and New Zealand, where the majority of the archival literature on SIOZ has been produced. It is noted that the specific definitions of near white blasting are slightly different in the SSPC and International Standards Organization (ISO 2007) standards, typically used in the United States versus Australia and New Zealand (respectively), with SSPC allowing only 5% of the surface area to contain staining but ISO allowing this on up to 15% of the surface. However, these two grades of cleanliness are generally thought to be compatible for practical purposes. The necessity of this level of cleanliness has somewhat been confirmed by testing done by the Florida Department of Transportation (McCullough 2022), who evaluated the performance of zinc coatings on test panels blasted to the SSPC SP-6 standard (i.e., commercial blast cleaning; SSPC 2017b). These specimens “failed the criteria for rust creep, scribe and blistering at approximately 20% of the test duration (5,000 hrs. in the salt fog) [and] failed the test criteria at 10% of the test duration (5,000 hrs. in tidal immersion) due to severe blistering”.

The required blast profile is also a matter of consideration. Requirements in various sources require a minimum of 25 (AASHTO / NSBA 2002) to 40 microns up to a maximum of 75 (AASHTO / NSBA 2002) to 80 microns (Francis, 2019). As noted above, AASHTO / NSBA (2002) points out that thermally cut edges may need pretreatment in order to achieve these requirements. Son et al. (2013) evaluated the differences in performance between a 20- and 70-micron blast profile and found that the higher blast profile reduced the presence of mud cracking of the coating. However, Francis (2016) claimed that that blast profile is less critical to performance than the act of blast cleaning.

Other blasting considerations include that: blasting of fasteners should be performed; that the blasting media should be angular to facilitate achieving the proper blast profile (steel grit, steel shot, blends of these two, and garnet have been specifically recommended in the AASHTO/ NSBA [2002] and draft Australian specifications [Francis, 2019]); and that the blast media should be thoroughly removed from the surface in a manner that avoids contamination of the cleaned surface, e.g., by compressed air or vacuuming.

Avoiding Contamination

After the above surface preparation steps, it is essential to avoid contamination of the surface prior to painting. The most common concerns in this aspect are chloride contamination and rusting due to exposure to moisture. Regarding moisture, Francis (2019) recommends avoiding surface preparation activities to the exposure of unfavorable weather conditions, including the specific requirement that the temperature must be at least 3 degrees (C, presumably) above the dew point, presumably to avoid water condensation on the steel. Chloride exposure can occur from either atmospheric exposure of new uncoated steel or prior exposure in the case of repainting projects. Francis (2016) states that the maintenance of a near white surface is a sufficient indicator for non-problematic levels of chloride exposure. More quantitative guidance on this topic is given by AASHTO / NSBA (2002) and the National Aeronautics and Space Administration (NASA, 2016) who specify that the chloride level prior to coating should not exceed 7 and 5 micrograms / cm^2, respectively.

Curing Conditions

Ambient conditions such as temperature and humidity are critical factors affecting the performance of SIOZ coatings. These factors can affect the time to cure (which affects schedule) and, of greater importance, the chemical reactions that occur during curing – resulting in different final chemical compositions and therefore performance of the paint. Therefore, it is necessary that ambient conditions are suitable for coating application. If they are not, it is necessary to change the coating type or wait until the ambient conditions become favorable. Some general requirements and the reasons for these requirements are given below on three main factors: temperature, humidity, and the rate of atmospheric transport (i.e., wind and / or ventilation conditions). Furthermore, individual coating manufacturers supply the required conditions for use of their products. However, it should be recognized that while all conditions within these ranges should result in an acceptable outcome, Salome (2013) highlights that variation in performance within these ranges can result.

Temperature is important because it affects both chemical reaction rates and the rate of evaporation of solvents. These two effects are often competing, as increased temperature increases both the reaction rate and the rate of evaporation. Therefore, faster reaction rates are coupled with faster evaporation. Hence, once too much water has evaporated, which is necessary for the curing reactions, curing reactions will cease. The governing temperature in these processes is the temperature of paint, which is most closely related to surface temperature as opposed to ambient temperature. Salome (2013) has stated that 18 to 27 degrees C is an optimum temperature for the application of both water-based and solvent-based SIOZ (independent of humidity; the coupled effect of humidity and temperature is discussed below). Consistent with this recommendation are: (1) the findings of Eccleston (2013), who found that 32 degrees C resulted in an unsatisfactory cure of solvent-based SIOZ, and (2) the draft Australian specifications (Francis, 2019) which states that SIOZ coatings should not be applied if the ambient temperature is below 10 degrees C or the surface temperature is above 35 degrees C.

Humidity is important because it affects the rate of evaporation, with higher humidity resulting in slower rate of evaporation. In this aspect, water- and solvent-based SIOZ function differently. Because of the water inherent to the water-based SIOZ, these paints cure by water evaporation and therefore lower humidity is ideal for these products. Salome (2013) states a relative humidity of 40 to 60 percent is ideal for water-based SIOZ.

Conversely, curing of solvent-based SIOZ requires moisture (i.e., the presence of water molecules in the ambient environment) and therefore higher humidity is necessary for these products. Salome (2013) gives an optimum relative humidity range for solvent-based SIOZ to be 60 to 90 percent. Salome notes that relative humidity greater than 90 percent does not affect the curing reactions (e.g., final product) but curing time will be extended. Eccleston (2013) also found that lower humidity within the optimum range can slow curing time. Specifically, while 60 and 80 percent relative humidity both resulted in satisfactory curing, the time taken to reach steady-state conditions in the specimens at 60 percent relative humidity was three times that of the specimens at 80 percent relative humidity. Furthermore, the specimens at 80 percent relative humidity were speculated to have a more complete cure based on both abrasion resistance and the chemical species contained in the final product.

Consistent with Salome's recommendations on optimum humidity, Eccleston (1998) reported that at a lower humidity of 40 percent relative humidity, full cure of solvent-based SIOZ may never be achieved. NASA (2016) stipulates that solvent-based SIOZ may not be applied at these humidity levels. The draft Australian specifications (Francis, 2019) have a slightly more stringent recommendation that the relative humidity should not be less than 50 percent during application or initial curing stages of solvent-based SIOZ. A more thorough discussion of the effects of temperature and humidity appear below in the Performance Section of this review.

The combined effects of temperature and humidity are also relevant considerations. One reason for this is that decreases in temperature at constant humidity can result in condensing conditions that are detrimental to paints during or immediately following application. For this reason, multiple sources recommend consideration of the dew point.

For example, NASA (2016) requires avoiding painting operations within 3 degrees C of the dew point. Furthermore, because the curing of SIOZ is dependent on evaporation and humidity and temperature both affect evaporation, Salome (2013) gives specific recommendations on the optimum interaction of these two variables. For water-based SIOZ, these are a surface temperature of 20 to 25 degrees C and a relative humidity between 40% and 50%. Salome states that in these conditions, "curing to water resistance can be achieved in about 2 hours". For solvent-based SIOZ, Salome (2013) does not further refine the separate temperature and humidity recommendations given above, but provides combinations of temperature and humidity outside the optimum ranges listed above that should be avoided. Francis (2013b) provides similar recommendations for temperature and relative humidity combinations, as previously presented in Figure 1.

Wind and ventilation conditions affect curing because curing is a diffusion process. In the absence of air currents, this is a relatively slow diffusion process because the air immediately surrounding the paint becomes saturated with the evaporating compounds. When air currents are present, diffusion can proceed more quickly. For this reason, NASA (2016) requires that "spray application methods shall not be used when wind speed exceeds 25 km/hr (15 mph) in the area where the coating is being applied".

Dry Film Thickness

As with all coatings, SIOZ can suffer from being applied too thin or too thick. From a minimum thickness perspective, one need is that the thickness is large enough to provide barrier protection. The minimum thickness also should be large enough to provide cathodic protection throughout the lifetime of the structure as the zinc is consumed into other corrosion products. In practical terms, the minimum thickness is also a quality control consideration, where it should be acknowledged that a uniform thickness is unrealistic to achieve. For these reasons, some specifications allow an actual DFT of 80 percent of the specified minimum if the average actual DFT exceeds the specified minimum. This should be considered when choosing a minimum thickness. DFT ranges between 100 to 150 microns (4 to 6 mils) are regularly cited in the existing literature. However, specific product suppliers may have alternative recommendations for specific products.

The concern regarding a DFT that is too thick is primarily fine cracks in the coating, often referenced as "mud cracking". Maximum thicknesses to prevent this phenomenon are reviewed in detail in the Performance Section below, which results in the general conclusion that a conservative upper-bound DFT is 200 microns (8 mils) based on the findings of Son et al. (2013). This is a conservative maximum from the perspective that higher DFT have been used without the occurrence of mud cracking in several situations. Furthermore, it should be noted that there is much greater concern regarding DFT that is too low compared to too high. A DFT that is too low will directly impact the corrosion protection capabilities of the SIOZ. In contrast, mud cracking has not been associated with any significant effect on performance.

A secondary concern regarding a DFT that is too thick is simply economical inefficiencies of using more product than needed. Lastly, a third concern regarding too thick DFT is increased curing time. This may impact project schedules. Additionally, for field applications, increased curing time also translates to greater probability for curing conditions to become unfavorable.

Other Application Best Practices

Various sources have compiled and published other recommended best practices and / or requirements for the application of SIOZ (e.g., AASHTO/NSBA 2002, Francis 2013a and 2019, NASA 2016). These include information on topics such as: mixing instructions, methods of application, methods for identifying and repairing defects, methods to test curing, and storage following coating application. Other best practices include monitoring and documenting ambient conditions every four hours (AASHTO / NSBA 2002; Francis 2019) as well as continued compliance with all product-specific requirements provided by the specific product manufacturer such as shelf life and curing conditions.

PERFORMANCE

Performance Compared to Other Corrosion Protection Systems

Comparison to Organic Zinc

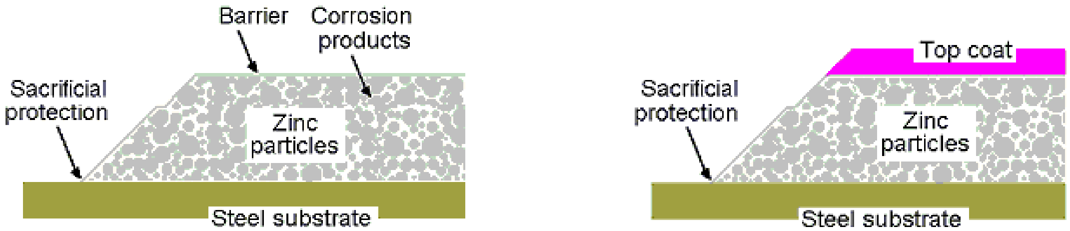
Extensive comparison between IOZ and organic zinc coatings has been performed by NASA (Calle, 2019). Test panels with both coating types were exposed in a marine environment at NASA's Beachside Corrosion Test Site for up to 10 years. This evaluation concluded that IOZ primers were "the best choice to provide long-term corrosion protection of launch structures and ground support equipment". This was at least partially attributed to the difference in conductivity of the two coating types, with the matrix of the organic coatings (e.g., epoxy, vinyl, etc.) providing an undesirable insulating effect to the zinc particles that inhibited galvanic protection.

Comparison to Other Single-Coat Paint Systems

Morcillo et al. (1990) and Feliu et al. (2001) have evaluated the performance of SIOZ compared to polyamide epoxies. Morcillo et al. found that solvent-based (ethyl silicate) SIOZ with two different zinc contents (84 and 50% by weight) had superior cathodic protection compared to polyamide epoxies (with 93 and 78% zinc by weight) based on scanning electron microscopy of specimens subjected to accelerated corrosion testing. In a later study by Feliu et al., six different paint systems were evaluated: one ethyl silicate with zinc only, two ethyl silicates with various proportions of partial zinc and partial conductive extender equal to the total mass of zinc in the zinc only formulation, and three polyamide epoxies. These specimens were subjected to an atmospheric exposure in an urban environment for ten years then assessed based on impedance and polarization measurements. All specimens were found to produce corrosion potential measurements indicative of galvanic corrosion after 10 years of exposure, though the galvanic protection was decreasing with time at different rates for the different specimens. The epoxy coating systems were generally concluded as providing better performance, but these coatings also generally had higher zinc contents than the ethyl silicates, and no control cases with equivalent zinc content exist. All of the epoxies and the highest zinc content ethyl silicate formulation (84 percent zinc) were free of rust after 10 years. In contrast, the ethyl silicates with partial zinc (72 percent or less) experienced rust formation.

Comparison to Multi-Coat Paint Systems

Given the corrosion protection mechanism and advantages of SIOZ discussed above, inorganic zinc coatings arguably perform best when used alone, without additional coatings. This is because both the barrier and cathodic protection abilities of SIOZ are diminished when inorganic zinc coatings serve as a primer in a multi-coat paint system. From the barrier protection standpoint, applying a topcoat prevents the formation of the protective zinc compounds that form and act to decrease the porosity that would otherwise occur when SIOZ is exposed to the atmosphere, as depicted by Figure 3. The cathodic protection benefits of SIOZ have also been demonstrated to be lessened when inorganic zinc coatings are top coated (Paton, 1973). Calle (2019) provides photographic evidence of this for IOZ specimens exposed to a marine environment for 8 years in Figure 4. Calle also notes that several SIOZ panels in the same environment for 50 years show "complete corrosion protection of the carbon steel".



(a*) without topcoat*

(b) with topcoat

Figure 3. Protection mechanisms in a zinc-rich coating (Francis 2013c).

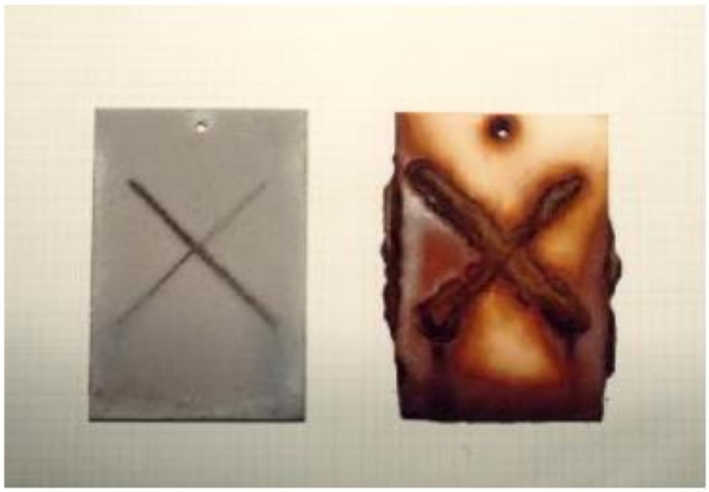


Figure 4. SIOZ without a top coat (left) and IOZ top coated with epoxy and urethane (right) after 8 years of atmospheric exposure in marine environment (Calle 2019).

Szokolik (2013) reports accelerated corrosion testing (alternating salt fog and environmental chamber) of 11 SIOZ and 12 multicoat paint systems. This testing showed that the SIOZ systems performed better than systems with topcoats based on a combined evaluation system based on DFT (which was found to be unchanged), hardness (all of which increased during testing), adhesion, and undercutting / pitting (of which the SIOZ systems had none). Similarly, in accelerated corrosion testing (salt fog) of scribed panels by Lofhelm et al. (2013), multi-coat systems had rusting in the scribe, while alternative formulations of SIOZ (further discussed below) did not. Laliberte et al. (2005) evaluated numerous corrosion protection systems using three different testing methods: 120 cycles of the J2334 cyclic corrosion testing methodology (which involves salt, humid, and dry cycles), salt fog testing, and a marine atmospheric exposure. The corrosion protection systems included SIOZ, four different formulations of zinc-rich primer with top coats, and numerous other systems. Comparing the zinc-rich primer alone to those that had top coats, better performance was observed without top coats in the marine atmospheric exposure, the same or better performance was observed as a result of the cyclic corrosion testing, and worse performance was observed in the salt fog testing (counter to the findings of the previous studies). Therefore, it is concluded that the only potential benefit to additional coating layers is aesthetic (as other paint systems are available in a wider range of color and gloss options).

Comparison to Galvanizing and Metallizing

SIOZ coatings have been compared to galvanizing because of the similarity of their corrosion protection mechanisms. It has been argued that SIOZ coatings are more durable than galvanizing (Szokolik, 2013; Baxter, 2013). The basis of this argument is that the exposed zinc on a galvanized surface can go into solution relatively easily. In contrast, in SIOZ, the zinc particles are bound within the silicate matrix, which slows down the rate of zinc loss. Baxter (2013) states that this difference is most prominent in severe environments in the presence of salt water.

This difference in performance is reflected by the National Association of Corrosion Engineers (NACE) (Brevoort and Roebuck 1993) and Australia / New Zealand guidelines on time to first maintenance as reported by Francis (2003b). Specifically, the NACE recommendations give the same time to first maintenance for galvanizing and 75 microns (3 mils) of SIOZ in all listed environment types except for a longer time to first maintenance for SIOZ compared to galvanizing in a seacoast marine environment. The Australia / New Zealand Guidelines give time to first maintenance for two different SIOZ applications: one having a DFT of 65 to 75 microns (3 mils) and the other having a DFT of 100 to 150 microns (4 to 6 mils). The SIOZ with the lower DFT ranges is recommended only for mild to moderate environments and a low time to first maintenance is predicted in this situation. Comparing the time to first maintenance of 100 to 150 microns of SIOZ to galvanizing, SIOZ is predicted to have a longer life in marine and severe marine environments, is not recommended for industrial environments, and is predicted to have the same life in all other environments. Figure 5 and Figure 6 give the quantitative values predicted in each of these scenarios.

System	Environment			
	Mild/Rural	**Moderate (industrial)**	**Seacoast marine**	**Severe heavy industrial**
Class 2½/ 75 µm IZS	27	17	15	12
Hot Dip Galvanize	27	17	13	12

IZS: Inorganic zinc silicate.

Figure 5. Time to First Maintenance (years) for SIOZ and Galvanizing by Environment (Brevoort and Roebuck 1993)

System		**Environment**				
		Mild/ Moderate	**Tropical**	**Industrial**	**Marine**	**Severe marine**
MP1A	Class 2½/ 65-75µm IZS-SB	5 - 10	NR	NR	NR	NR
LP3	Class 2½/ 100-150µm IZS-WB	10 - 20	10 - 20	NR	10 - 20	10 - 20
GZ	Hot Dip Galvanize	10 - 20	10 - 20	2 - 5	5 - 10	NR

IZS-SB: Inorganic zinc - solvent borne, IZS-WB: Inorganic zinc - water borne, NR: Not recommended.

Figure 6. Time to First Maintenance (years) for SIOZ and Galvanizing by Environment in AS / NZ3 2312 (Francis 2013b).

Lofhelm (2013) provided data supporting this difference in performance using salt fog testing per American Society of Testing and Materials G85 Annex A5 (ASTM, 2019a) at 2000, 4000, and 6000 hours on scribed water-based and solvent-based SIOZ as well as galvanized panels. Panels were evaluated based on DFT measurements, degree of corrosion in the scribe, degree of blistering, and adhesion. Comparison of the water-based and solvent-based systems is discussed in the following section, but both of these results were considered to be superior to the galvanized panels. The galvanized panels showed light rusting on the panel surfaces, while the SIOZ panels did not. Furthermore, galvanized then coated specimens (i.e., duplex system) suffered from a loss of the initial adhesion between the galvanized and liquid coating.

One location where galvanizing has been reported to outperform SIOZ coatings is along edges. Galvanizing does not thin at edges and maintains a relatively constant thickness across surfaces. SIOZ coatings are prone to edge thinning, although the effect is less pronounced compared to non-zinc coatings (Francis, 2013b). Francis (2013b) also compares SIOZ and galvanizing in terms of cost (Figure 7) and other coatings properties (Figure 8).

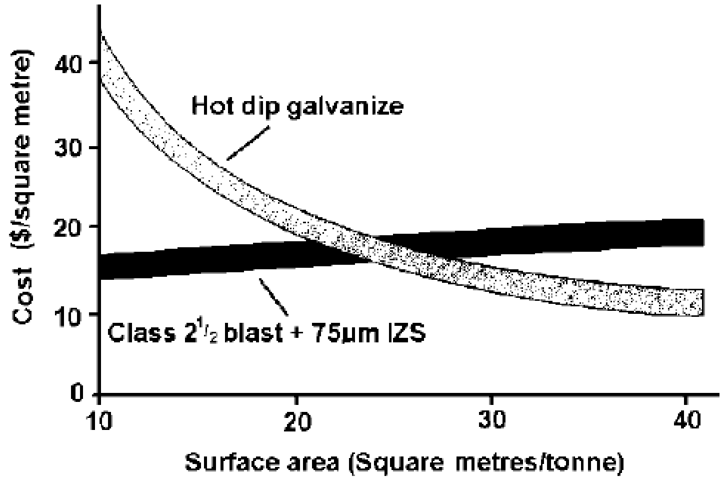


Figure 7. Cost Comparison of Galvanizing and SIOZ based on Surface Area (Francis 2013b).

Property	Galvanizing	Inorganic zinc
Hardness/toughness	Excellent	Excellent
Abrasion resistance	Excellent	Excellent
Max temperature - dry	200 - 250°C	400°C
Resistance to:		
• Marine environments	Yes	Yes
• Humidity	Yes	Yes
• Oil and solvents	Yes	Yes
• Acid	No	No
• Alkali	OK below pH 12	OK below pH 10
• Fungi, mould, etc	Unaffected	Unaffected
• Fire	Resistant	Resistant
Coating Application:		
• Minimum surface preparation	Pickle	Class 2½ blast
• Can suffer warpage during application	Possible	No
• Typical thickness (microns)	50-150	50-200
• Thickness at corners and edges	Same or greater	Same or less
• Temperature/ humidity requirements for cure	No	Yes
• Ease of topcoating	Complex	Acceptable
• Inspection (QA) requirements	Simple	Complex
• Ease and appearance of repair	Complex and poor	Simple and good
Applications:		
• Faying surfaces	Must be roughened	Acceptable
• Small items - fasteners, etc	Ideal	No
• Large or existing structures	No	Ideal
• Complex structures	Complete coverage	Difficult

Figure 8. Comparison of Other Coating Properties for Galvanizing and SIOZ (Francis 2013b).

There is comparatively less information available comparing SIOZ and thermal spray (i.e., metalized) coatings. The conceptual behavior of these two corrosion protection systems is even more similar than SIOZ and galvanizing because in both systems zinc particles are suspended in a matrix. The most quantitative information available comparing metallizing and SIOZ is time to first maintenance estimates given by Mandeno and Sutherland (2013), which show the same times to first maintenance for 100 to 150 microns (4 to 6 mils) of SIOZ compared to 100 microns of metallizing.

Performance of Alternative SIOZ Systems

Salt fog testing per ASTM G85 Annex A5 (ASTM, 2019a) was used to compare the performance of water-based and solvent-based SIOZ (Lofhelm 2013). After 6000 hours, scribed panels were evaluated based on DFT measurements, degree of corrosion in the scribe, degree of blistering, and adhesion. Results of this testing were that the solvent-based SIOZ coatings were considered to be "faultless". The water-based SIOZ was also considered to provide good performance but had corrosion that was attributed to "edge effect… and/or from poor application during test panel application".

Francis (2013b) compares the field performance of water-based versus solvent-based SIOZ. Based on comparing the field performance of sixteen SIOZ bridges, most of which were coated with water-based SIOZ, it was concluded that differences in performance were more likely due to differences in DFT rather than differences in performance of the two alternative types of SIOZ for the mild environments in which these bridges were located. Hemmings and Demirdjian (2013) discuss the alternative solvent-based and water-based SIOZ recommendations in New Zealand, for which the solvent-based recommendations were more stringent. They argue that this is based on less experience with solvent-based SIOZ, and not diminished performance.

Performance in Field Conditions

Two studies (Mandeno 2017, Francis and Szokolik 2013) have reviewed the field performance of SIOZ bridges. Specifically, Mandeno (2017) compares the performance of two New Zealand bridges coated with water-based IOZ as the sole corrosion protection system. Both bridges were constructed 7 years prior to the publication date and after that timespan, one of the bridges was performing well and the other was not. The difference was attributed to improper curing between the multiple IOZ coats and / or the addition of 20% extra water (as recommended by the manufacturer) to the second coat of the bridge that was not performing well. The bridges were located in similar environments, so this was not believed to be a factor influencing the difference in performance.

Francis and Szokolik (2013) reviewed the condition of the coatings on sixteen bridges with water-based SIOZ coatings in a similar environment near Melbourne, Australia (described as upper C2, "perhaps extending into upper C3" based on the ISO (2017) environment classifications, i.e., the environments were not particularly severe). Age range of the bridges was 3 to 37 years and DFT of the SIOZ coatings ranged from 35 to 375 microns (1 to 15 mils). Bridges with other coating systems (red lead and micaceaous iron oxide / aluminum pigment systems) in the same environment were also evaluated. Comparing the two coating types, the results generally showed that the SIOZ coatings produced three or more times the life of the alternative coatings (even with lower DFT). It was also reported that maintenance of the SIOZ coatings was easier because rust of these coatings tended to be limited to the surface, whereas more extensive rusting of the substrate was observed in the alternative coating systems. Therefore, surface preparation for repainting was stated as being easier for the SIOZ coatings.

Francis and Szokolik (2013) also compared the extent of the rusting (as assessed by ASTM D610, 2019b) of the sixteen SIOZ bridges as a function of age of the bridge and DFT. This data was used to conclude that DFT above 75 microns (3 mils) may result in an expected lifespan of 30 or 40 years before corrosion initiates. Furthermore, rusted areas were generally associated with areas that were believed to be improperly coated (i.e., that were missed or too thin) at the time of application. Lastly, Francis and Szokolik also critiqued the use of the ASTM D610 procedures for field evaluation of SIOZ coating, as follows:

> *"The ASTM D-610 system assumes that breakdown will occur over a surface in a scattered manner. While this is often the case with conventional coatings, inorganic zinc coatings tend to break down in localized areas, usually where coating thickness was inadequate. This difference is very important in maintenance programs, as localized breakdown is far easier to maintain than scattered breakdown. For example, a surface with 10 per cent scattered breakdown would need complete coating removal and coating reinstatement, but 10 per cent breakdown in one localized area could easily be fixed by spot repair. In fact, localized breakdown will be far easier and cheaper to repair than scattered breakdown, whatever the amount."*

Performance As a Function of Controlled Variables

Dry Film Thickness

The DFT of SIOZ coatings is an important parameter governing its performance. Thicker coatings are generally thought to provide better performance, up to the point where the coating becomes overly thick, which results in fine hairline cracks in the coating. This is often referred to as mud cracking. For these reasons, there is often a maximum specified coating thickness, e.g., 125 to 150 microns (5 to 6 mils). Individual coatings manufacturers may have alternative product-specific recommendations.

The desire to increase the maximum allowable DFT motivated research on this topic by Son et al. (2013). In this study, five different SIOZ coatings with recommended thickness between 75 and 125 microns (3 to 5 mils) and maximum DFT between 150 and 200 microns (6 and 8 mils) were evaluated for mud cracking and corrosion resistance (using accelerated seawater immersion and condensation testing per ASTM D870 and D4585 [ASTM 2015 and 1999, respectively) when higher DFT were applied. The influences of the surface profile were also considered, with a 70 μm surface profile resulting in more favorable results compared to a 20 μm surface profile. The results also differed depending upon whether visual inspection or 10X microscopic inspection was used to identify mud cracking. For the 70 μm surface profile, maximum thicknesses of 140 to 260 microns (6 to 10 mils) were found for the five different formulations when performing a microscopic inspection and maximum thicknesses of 220 to 307 microns (9 to 12 mils) were found using a visual evaluation from a distance of 30 cm. Because the cracks were not found to penetrate through the entire thickness of the coating (the depth of the cracks was "about 50 microns") and that the corrosion testing found that the mud cracked specimens had performance "excellent and equal to the intact coating" after 7 days of testing, a lower bound thickness of 200 microns (8 mils, coupled with full blasting that achieves a 70 μm surface profile) resulting from the visual inspection method was recommended as an appropriate maximum DFT value.

Similarly, Francis and Szokolik (2013) summarized field evaluations of SIOZ coatings. In these evaluations the maximum DFT value measured was 375 microns (15 mils), with no mud-cracking observed. Based on this finding, Francis and Szokolik suggest that there is far more serious risk associated with the DFT being too low because this "certainly reduces the protective life of an inorganic zinc" than the DFT being too high.

Curing Conditions

It is generally known that SIOZ is sensitive to curing conditions and suppliers of commercial products will provide product-specific recommendations. Eccleston (2013) studied the chemical process governing these recommendations by measuring the rate of change in the number of organic or ethoxy groups attached to the silicon atom during the curing process of solvent-based SIOZ using gas chromatography and also measuring the abrasion resistance. Temperature and humidity were separately varied, while all other parameters remained constant. Varying the humidity at 40, 60, and 80% relative humidity at a constant temperature of 25 degrees C gave the same acceptable outcome at the completion of curing for the two highest levels of humidity, but the curing time for the samples at 60% relative humidity was thrice that of the samples at 80% relative humidity. The 40% relative humidity samples did not result in a satisfactory cure, as would be expected based on Figure 1. The effects of water immersion were also evaluated. This evaluation found that water immersion benefitted the specimens that were cured under good conditions, but not the ones cured under poor conditions. This suggests that water immersion is not a remedy for poor curing conditions.

The temperature was varied at 20, 25, and 32 degrees C. The 32 degrees C specimens resulted in an unsatisfactory cure, which was attributed to the rate of evaporation of the solvent increasing; this resulted in an inadequate duration at which sufficient moisture was available for the curing process. The authors point out similar problems may exist in windy conditions. Therefore, spraying with water when temperatures are excessive or strong winds are present was suggested as a remedy to this problem. Both the 25- and 20-degree C specimens gave the same acceptable outcome at the completion of curing, but the curing time for the samples at 25 degrees C was 2.5 times that of the samples at 20 degrees C.

Environment

Jaeger et al. (2013) evaluated test panels with five different formulations of SIOZ in five different environments using x-ray diffraction. Four of the SIOZ types contained a potassium silicate matrix with varying zinc contents; the fifth SIOZ formulation contained a lithium silicate matrix and the highest zinc content (88% compared to a maximum of

86% in the potassium silicates). Two of the environments were real-world atmospheric exposures: a "light industrial" environment for seven years and a marine environment for four years. In the marine environment, specimens were also subjected to intermittent submersion. The remaining two environments were laboratory accelerated corrosion testing consisting of salt fog (1050 hours) and immersion testing. The results showed a greater variation between the five different SIOZ formulations in the marine atmospheric exposure compared to the light industrial atmospheric exposure. This is likely caused by the greater severity of the marine environment. However, it was noted that the differences were much less for the lithium silicate, suggesting that this is a more durable coating type for aggressive climates. Variation in zinc content through the thickness of the coating after testing also indicated the consumption of zinc. Lastly, it was noted that the accelerated corrosion testing results differed dramatically from the real-world conditions in terms of the chemical species that existed in the samples after testing.

The Florida Department of Transportation has also performed testing for evaluating the performance of high zinc coatings in the environments within their jurisdiction (McCullough 2022). Salt fog testing for 10,000 hours of two different SIOZ formulations demonstrated that "a moderately high zinc load as well as an ethyl silicate base was … the best combination for long term performance in Florida".

Kakaei et al. (2013) evaluated the effect of wet-dry cycles on the galvanic potential of various formulations of water-based SIOZ coatings using accelerated laboratory testing. They found that following a wet-dry cycle, the coatings demonstrated an increase in galvanic protection capability.

The literature also contains mentions of several environments that are not appropriate for SIOZ. These do not generally apply to bridge applications, but include environments such as low or high pH, submerged in water, underground, or subjected to hot fresh water.

REPAIR

Overview of Approaches

One of the first considerations in repairing damaged or deteriorated SIOZ is whether repair is performed in localized problematic areas (i.e., spot or zone painting) or more generally over entire members or structures. It has been argued that spot and zone painting are more practical for SIOZ. This is logical from the perspective that, in field conditions, corrosion of SIOZ is often limited to localized areas where the initial fabrication resulted in low DFT or site conditions (e.g., leaking joints) caused localized corrosion problems.

Specifically, Szokolik and Rapattoni (1998) state that SIOZ "should never need complete removal provided that adequate maintenance is carried out to ensure that coating breakdown and rusting does not exceed 5% of the total surface area at any stage". It should be noted that while 5% is a relatively low number, in terms of percent surface rusting, this is a relatively advanced state of corrosion corresponding to a 4 on the 0 to 10 scale (with 10 being the best condition) based on the *ASTM Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces* (ASTM 2019b). The Australian and New Zealand (where SIOZ has been relatively thoroughly evaluated) *Guide to the Protection of Structural Steel Against Atmospheric Corrosion by the Use of Protective Coatings* (Standards Australia, 2002) recommends repair "when about 2% of the surface in any particular area shows signs of rusting". This condition corresponds to a rating of 5 on the ASTM scale mentioned previously. Spot or zone painting has been estimated as being less economical than full repainting when 10 to 20% of the surface needs repair (KTA-Tator 2014). However, this estimate is likely based on the assumption that this area is distributed throughout the structure. In contrast, 10% of the surface in a localized area (which is often the case with SIOZ) can be easily addressed with a spot repair (Francis and Szololik 2013). Francis et al. (2013) also argue that these repairs are largely for aesthetic purposes because the deterioration of SIOZ does not involve undercutting of the coating and therefore corresponds to little corrosion of the steel substrate.

Once the area to be repaired is determined, the next considerations are the new coating type and the procedure for applying it. There are two general procedures for performing the repair: overcoating the existing SIOZ or removing the full thickness of the existing SIOZ and then recoating. If the existing coating is removed, it has been found to be generally appropriate to recoat the structure with SIOZ. In this situation, the application best practices discussed above are generally applicable. Additional discussion of surface preparation in field conditions is discussed below.

If instead the damaged or deteriorated SIOZ is overcoated (with SIOZ), the adhesion between the original and new coating becomes a consideration. Specifics on improving this adhesion are discussed below. However, this adhesion has been shown in micrographs (Jaeger and Sherwood 1975) to be relatively easy to achieve when overcoating SIOZ with additional SIOZ due to its chemical structure. Specifically, because the zinc particles are suspended in a silicate matrix, the zinc particles from the new coating have been shown to naturally migrate into voids in the original coating as long as loose corrosion products are removed prior to overcoating, with the recommendations given below taking this need into consideration. It should also be noted that because of this governing chemical process, adhesion between original and new SIOZ coatings has been shown to improve with time, with one to two years being the time scale evaluated to reach this conclusion in prior studies (Francis et al. 2013).

Surface Preparation

The first consideration in surface preparation is whether the surface is being prepared for overcoating or full-thickness removal of the existing coating. If a full-thickness removal is to be performed, then the surface should be returned to a near white condition as done for the initial coating. When a full-thickness removal is desired, this approach can be limited to the spots or zones where repair is needed, and the surrounding areas more lightly blasted and feathered. This approach was taken for a case study reported by Francis et al. (2013) where "adhesion of repaired regions was excellent … as was adhesion of the new coating to the existing" SIOZ.

The influences of alternative surface preparation techniques for overcoating – such as abrasive blasting (with or without complementary cleaning with water), power tool cleaning after water cleaning, hand tool cleaning (e.g., brushes, with or without complementary cleaning with water), low pressure water cleaning with abrasive injection, and low pressure water cleaning – have been evaluated in prior work (Riding 1997, Zhang and Walker 2013, Francis et al. 2013). The general conclusion from this work is that performance is insensitive to the preparation technique. This is supported by the results of Riding (1997), who exposed specimens coated with water-based SIOZ for 16 and 29 months and then recoated the specimens with the same product. Adhesion between the coating layers after an additional 6 and 12 months was not affected by the surface preparation method. However, the limited time scale prior to recoating could be viewed as a possible limitation of these findings. However, Zhang and Walker (2013) report similar findings of a more long-term field evaluation of surface preparation methods on both water-based and solvent-based SIOZ, applied per various manufacturers' recommendations. In this evaluation, all combinations of SIOZ and surface preparation methods rated as excellent based on visual inspection and very good to excellent based on adhesion testing after 8 years of atmospheric exposure. Other coating types that were evaluated (namely zinc-rich epoxy) were found to be more sensitive to surface preparation method.

These results can be considered relative to the purposes of the surface preparation. Recalling the four surface preparation steps outlined above (pretreatment, cleaning, blasting, and avoiding contamination), it can be summarized that the main purposes of surface preparation are to provide a clean (e.g., debris free and chemically favorable) and appropriately rough surface. Zhang and Walker (2013) specifically evaluated the surface roughness resulting from four different surface preparation methods prior to overcoating: abrasive blast, power tool abrading, and low-pressure water clean with and without abrasive injection. Interestingly, both forms of water cleaning did not change the surface profile while the abrasive blasting increased the roughness and the power tool abrading decreased the roughness (presumably by removing the high points on the existing surface profile). However, all methods resulted in surface profiles at or above typical maximum recommendations for surface profiles for SIOZ. As discussed above, all these methods generated good results. Therefore, it can be concluded that the surface profile and cleanliness of the surface is more important than how these conditions are achieved, and that there are many possible ways of achieving these conditions.

Counterexamples to the good performance discussed above do exist (Francis et al. 2013). However, none of the surface preparation methods discussed above has repeatedly resulted in unsatisfactory performance, suggesting that in these situations the performance was diminished by factors other than the surface preparation (e.g., the ambient conditions or the time lapse between the surface prep and recoating which resulted in the formation of corrosion products on the prepared surfaces). Francis et al. (2013) has also concluded from micrographs by Jaeger and Sherwood (1975) that brush blasting (presumably high-pressure mechanical blasting) is superior to wire brushing (presumably with hand or power tools) when the surface is "heavily degraded or contaminated". There is no indication that the performance due to the wire brushing is inadequate, yet this (coupled with the relatively good condition of the surfaces evaluated in the other studies cited in this section) may be the reason that the draft Australian specifications (Francis, 2019) do not allow wire brushing to be used for surface preparation during SIOZ repairs.

Coating Selection

There are a significant number of studies indicating that when SIOZ is in need of repair, an additional coat of inorganic zinc is an appropriate or ideal repair. In the same study discussed in the previous section, Zhang and Walker (2013) assessed the long-term performance of water-based and solvent-based SIOZ repairs to SIOZ after eight years of atmospheric exposure. Both SIOZ types performed well and were recommended for future use, with the water-based formulation resulting in slightly better performance. Francis (2013b) elaborates that, from his perspective of working in Australian environments, the same formulation of SIOZ as used in the original structure is not required, rather the choice of water- versus solvent-based SIOZ should be selected based on weather conditions and applicator skill. Zhang and Walker (2013) also studied the use of zinc-rich moisture cured urethane and zinc-rich epoxy coatings to SIOZ. These coatings resulted in rust formation during the eight-year timespan of the study.

In the above study, the repair coatings were applied per the manufacturers' recommendations. Alternatively, Baxter (1993) has recommended increasing the liquid content in the repair coating by "10 to 15% so that there is sufficient liquid to prevent the surface layer becoming underbound and lack in adhesion. Spraying the zinc with water before applying a repair coat to create corrosion products that fill the porosity has also been suggested" (Francis 2013b). However, the other studies and concepts reviewed above lead to a questioning of the necessity of these recommendations.

Application

Following surface preparation, application of an overcoat or a coat of SIOZ on uncoated steel in the field generally follows the same recommendations as discussed for original SIOZ applications above. As with original coatings, it is imperative that curing conditions are considered and monitored. For the physical application of the coating, any practical method may be used, although Francis et al. (2013) stated that spraying is preferred but brushing is possible for areas with difficult access or requiring small touchups. In addition to the discussion on thickness given above for original coatings, Francis et al. (2013) notes the particular challenges of applying a coating of uniform thickness in corners and tight spaces between constructed structural members. Therefore, these authors recommend that when excessive thickness results in mud-cracking, reblasting and recoating should be required. Although, they also note that mudcracking of SIOZ is "far less of a problem … than cracking in a conventional coating" due to the minor effect of the cracks that have been discussed elsewhere herein.

Chapter 2
Existing SIOZ Coated Bridges

BACKGROUND

Corrosion protection is one of the main factors that influences long-term performance and life cycle cost of steel bridges. As previously introduced in Chapter 1, there are a number of protection systems available, from specially formulated corrosion resistant steels (e.g., weathering steel, stainless steels) to various coating systems (e.g., paint, galvanizing, metallizing), all offering varying degrees of cost-effectiveness. SIOZ coatings offer the potential for faster steel fabrication and lower initial cost. A recent NSBA survey (discussed below) showed renewed interest in SIOZ for these reasons and ultimately led to the commencement of this work.

SURVEY

NSBA conducted a survey of state transportation departments on their use of corrosion protection systems for steel bridges. Included in the survey were several specific questions about SIOZ coatings. 45 participants from 43 States responded to the survey.

Based on the survey responses, the following States have used or currently use SIOZ as a sole corrosion protection system. The number of SIOZ bridges in each State's inventory is shown in parentheses.

- California (unknown)
- Florida (unknown)
- Missouri (30-35)
- Virginia (1)
- Washington (2)

As demonstrated by this short list, the known use of SIOZ has been limited in the United States. Those states that have used SIOZ rated its performance favorably (Figure 9). Most respondents were unfamiliar with SIOZ and therefore were mainly concerned with long-term performance metrics such as durability, cost, and maintenance (Figure 10). However, many states with no experience using SIOZ indicated that they would be open to using it in the future. Based on the limited use of SIOZ gleaned from the survey results, NSBA issued an RFP to develop this synthesis on SIOZ.

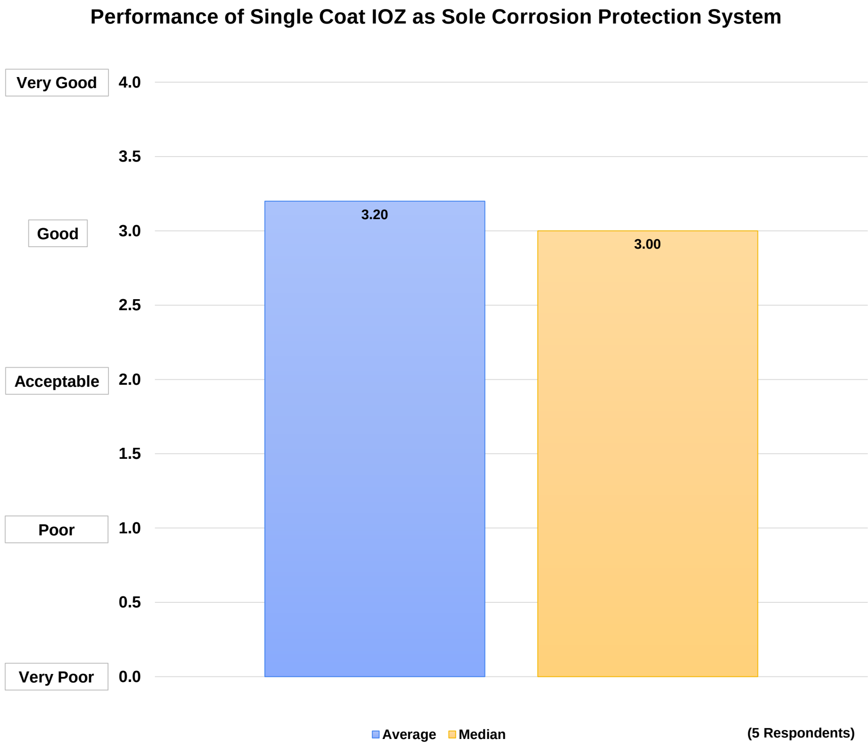


Figure 9. Survey results for State experience with SIOZ performance (Carlson, 2020).

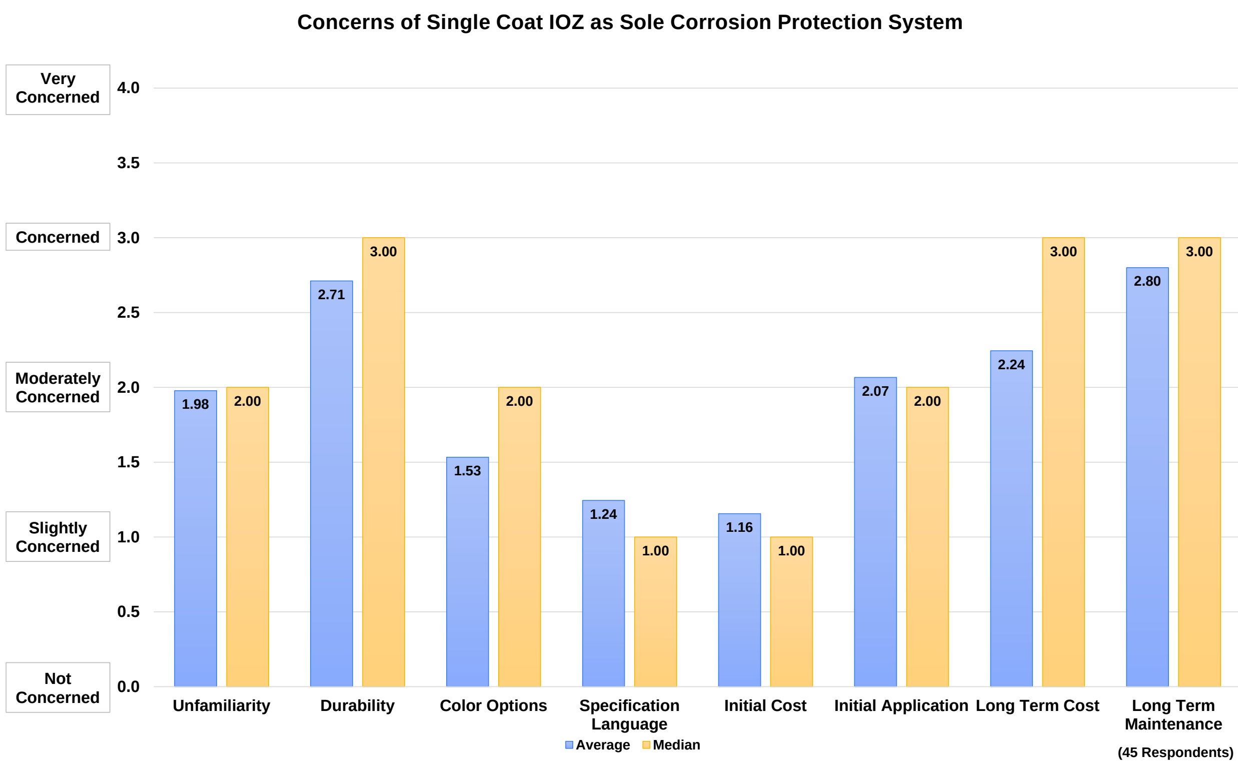


Figure 10. Survey results for State concerns with using SIOZ (Carlson, 2020).

DATABASE

Based on the limited use of SIOZ gleaned from the survey results, NSBA issued an RFP to develop this synthesis on SIOZ. One of the first tasks of the project was to compile a list of steel bridges in the United States that utilize SIOZ as the sole corrosion protection system. The responses to the survey discussed above were used as a starting point to identify which States have used SIOZ. Once the SIOZ bridges were identified, data related to the SIOZ coating and bridge characteristics was gathered for each bridge using available National Bridge Inventory (NBI), National Bridge Element (NBE), and Bridge Management Element (BME) databases. It was not possible to compile a complete SIOZ bridge list or to obtain comprehensive data on each bridge due to data availability and historical record keeping limitations. Some of the key information and data is discussed in the sections that follow. See Appendix A for the complete list of SIOZ bridges and associated information that was compiled. This includes further details on the topics summarized below as well as the available information on paint application. It is noted that the information reported regarding paint application (shop versus field and thicknesses) is the information supplied by the owner. Visual inspection results discussed in Chapter 3 reveal some discrepancies with this information.

Characteristic Data

Data related to the bridge characteristics is provided in Table 1. Most of the existing SIOZ bridges are highway girder bridges that are overpasses or water crossings. Table 2 provides coating age information deduced from the available data. As shown, most of the SIOZ coatings were applied in the early to mid-1990s (20 to 30 years old at the time of writing).

Table 1. Characteristic data for inspected SIOZ bridges.

Structure #	State	Year Built	Service Type	Use	Bridge Type
8386	Missouri	1965	highway	Urban Local	Girder
6487	Missouri	1958	highway	Urban Local	Girder
1183	Missouri	1966	highway + RR	Interstate Highway	Girder
1184	Missouri	1966	highway + RR	Interstate Highway	Girder
4115	Missouri	1993	highway	Urban Other Principal Arterial	Girder
4213	Missouri	1994	highway	Urban Principal Arterial	Girder
4105	Missouri	1995	highway	Urban Collector	Girder
4314	Missouri	1995	highway	Urban Minor Arterial	Girder
3996	Missouri	1995	highway	Urban Minor Arterial	Girder
6604	Missouri	1960	water	Interstate Highway	Girder
800	Missouri	1962	water	Interstate Highway	Girder
4816	Missouri	1953	water	Interstate Highway	Girder
441	Missouri	1964	water	Interstate Highway	Girder
442	Missouri	1964	water	Interstate Highway	Girder
6603	Missouri	1960	water	Interstate Highway	Girder
24209	Virginia	1994	water	Urban Minor Arterial	Girder, K-Frame
0016609A	Washington	2004	water	Rural Principal Arterial	Girder
0016276A	Washington	2003	water	Rural Principal Arterial	Girder

Table 2. Coating data for inspected SIOZ bridges.

Structure #	Year Coating applied	Year coating re-applied	Existing Coating Age (years)
8386	No Data	1996	26
6487	No Data	1996	26
1183	1995	N/A	27
1184	1995	N/A	27
4115	1994	N/A	28
4213	1994	N/A	28
4105	1994	N/A	28
4314	1994	N/A	28
3996	1995	N/A	27
6604	1973	1995	27
800	No Data	1996	26
4816	1996	N/A	26
441	No Data	1995	27
442	No Data	1995	27
6603	1973	1995	27
24209	1995	N/A	27
0016609A	No Data	No Data	18
0016276A	No Data	No Data	19

Environment

Data related to the environmental factors is presented in Table 3, including details known by owners regarding deicing salt application and International Energy Conservation Code (IECC) climate designations. As shown in the table, there was not detailed deicing salt data, rather mostly general application windows. All of the bridges were either in a mixed humid or mixed marine environment (IECC categories 4A and 4C, respectively).

Table 3. Environmental data for inspected SIOZ bridges.

Structure #	Deicing Rate on structure (tCL-/ lane-mile)	Deicing Rate under structure (tCL-/ lane-mile)	Climate Description
8386	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
6487	Salt applied between Nov. and March	N/A	Mixed Humid
1183	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
1184	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
4115	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
4213	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
4105	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
4314	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
3996	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
6604	Salt applied between Nov. and March	N/A	Mixed Humid
800	Salt applied between Nov. and March	N/A	Mixed Humid
4816	Salt applied between Nov. and March	N/A	Mixed Humid
441	Salt applied between Nov. and March	N/A	Mixed Humid
442	Salt applied between Nov. and March	N/A	Mixed Humid
6603	Salt applied between Nov. and March	Salt applied between Nov. and March	Mixed Humid
24209	7.52	N/A	Mixed Humid
0016609A	Most likely no application due to location	N/A	Mixed Marine
0016276A	Mostl likely some application due to location	N/A	Mixed Marine

Condition

The superstructure condition rating as a function of the SIOZ coating age is plotted in Figure 11. While not a direct measure of SIOZ performance, the superstructure condition rating data indicates that the SIOZ coatings are doing relatively well at protecting the superstructure steel from deteriorating. Only one superstructure condition was rated as fair, all others were satisfactory or better.

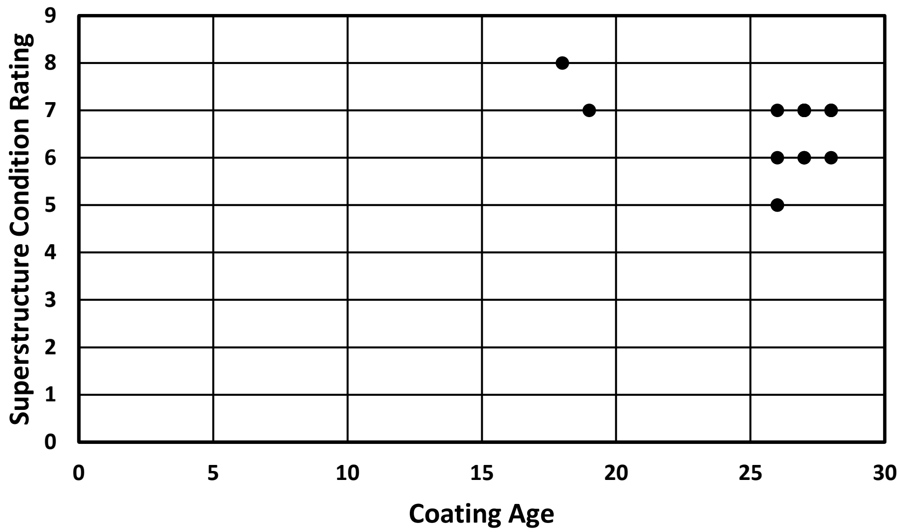


Figure 11. Superstructure condition rating versus SIOZ coating age.

A more direct indication of SIOZ performance is measured using the NBE Element Number 515 condition state, which is reserved for steel protective coatings. Condition states are assigned to regions of the coated areas based on observed defects, including chalking, peeling/bubbling/cracking, oxide film degradation and color texture adherence, effectiveness, and damage. Possible condition state values range from 1 (good) to 4 (severe). Using the available condition state data, a singular weighted condition state was calculated for the SIOZ coating on each bridge (Figure 12). As shown, all of the SIOZ coatings are between good and fair weighted condition states at their current ages.

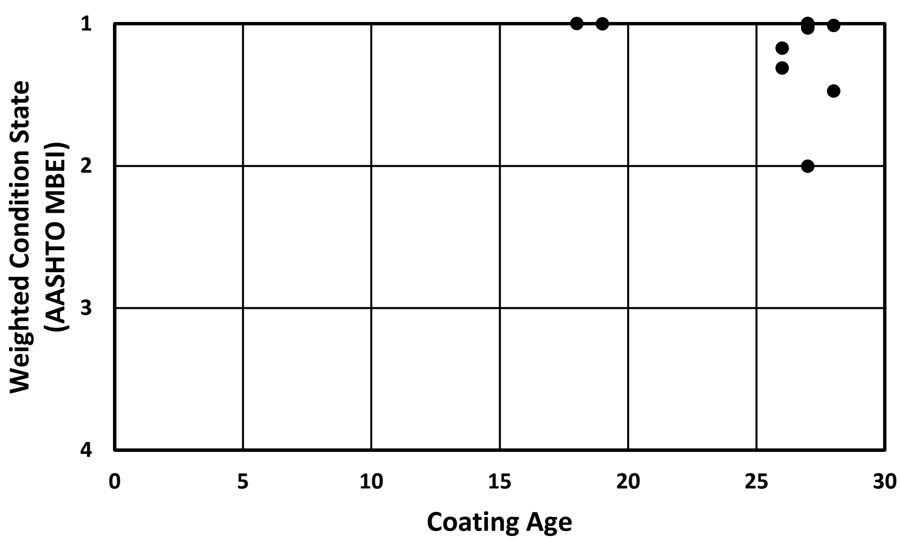


Figure 12. Weighted condition state versus SIOZ coating age.

Chapter 3
Visual Inspection Results

BRIDGES INSPECTED

A total of 18 bridges were inspected across 3 states: 15 in Missouri, 2 in Washington, and 1 in Virginia.

INSPECTION PROTOCOLS

Inspection protocols were developed to clearly identify the scope of the inspections and for consistency across bridges and inspectors. The objectives of the inspections were to:

1. Assess the current condition of the coating system and its protection of the substrate steel.
2. Identify factors that contributed to the current condition of the coating system and substrate steel, in terms of both good and bad performance.

The superstructure coatings were inspected from the ground and primarily visual in nature. The lone exception to this rule was that DFT measurements were taken when possible.

The inspection protocols created prior to performing the inspections are included in Appendix B. The actual field inspections deviated from the protocols in the following ways:

- Marking and dimensional measurement of substrate corrosion or deteriorated coating areas was not performed. Due to access limitations, it was not possible to get hands-on measurements for many of these regions. Therefore, it did not seem appropriate to only take detailed measurements of the accessible regions and draw conclusions based on the results. Photographs and notes were still taken for these regions.

- Due to the limited access, it was not possible to assign overall performance metrics to the entirety of each bridge, for example using the SSPC-VIS 2 Rust Grade scale. Instead, the Rust Grade scale was used as an approximate assessment of the accessible and visible regions of each bridge so that performance could be generally compared across bridges. However, no formal post-processing or analyses of the performance metrics were carried out.

KEY FINDINGS

The following sections present the key findings inferred from the performance patterns noticed in the inspection results. In general, the SIOZ coatings were in good condition after decades of service. Some instances of coating failure were identified and attributed to leaking drainage systems, roadway splash zones, inadequate application, or construction damage. Additional details on these observations are provided below. Notes on each bridge inspected are summarized in Appendix C.

Macro-Environments

None of the bridges inspected are located in what could be considered an extremely aggressive macro-environment.

The bridges inspected in Missouri and Virginia are subject to roadway deicing salts during the winter months, although the exact details related to application rates, duration, etc. are unknown. Limited information on the Missouri bridges indicated that deicing salts are typically applied between November and March. A quantified estimate of the application rate for the Virginia bridge is noted in Appendix A.

The two bridges inspected in Washington are located in what could be considered a marine environment, but the closest one to the coast was approximately 5 miles inland. Neither are subject to direct contact with seawater, and the atmospheric salinity content is presumably low at both bridge locations.

The macro-environment did not appear to have an effect on SIOZ performance for the bridges inspected. The observations made of SIOZ performance during the inspections were attributed to other sources discussed in later sections.

Micro-Environments

It was clear from the inspection results that SIOZ coatings are susceptible to deterioration and substrate corrosion at locations where aggressive micro-environments exists. These manly consisted of (1) regions beneath deck joints and (2) areas within the splash/spray zone of the roadway below the bridge. It should be stressed that these performance problems were driven by exposure to moisture and likely deicing agents and not necessarily a function of the coating itself. All other coating and material types experience similar deterioration in these micro-environments. Additional details on these general observations are provided below.

Deck Joints and Drainage

Failed deck joints and other sources that allowed drainage to contact the superstructure resulted in poor coating performance. Several examples are shown in Figure 13. A simple inference is that drainage sources, with deck joints being a prime culprit, lead to coating failure which leads to steel corrosion.

(a) efflorescence and corrosion of end diaphragm, connection plate, girder, and bearing plate

(b) deck overhang deterioration allowing unintended drainage onto the fascia girder resulting in coating failure and corrosion

(c) efflorescence and corrosion of girder, bearing stiffener, and bearing plates

(d) bottom flange splice coating deterioration and steel corrosion caused by the same deck joint failure from (c)

Figure 13. Examples of deck joint failure and moisture sources leading to coating deterioration and steel corrosion.

Where superstructure regions beneath deck joints were maintenance-painted more frequently, sometimes with a multi-coat system, the coating performance was much improved (Figure 14). While this practice somewhat counteracts the benefits of using a single-coat system, the strategic use of more frequent maintenance coating within aggressive micro-environments is beneficial to the corrosion performance.

(a) girder end at an abutment *(b) superstructure region over a pier*

Figure 14. Overcoating/maintenance coating beneath deck joints.

Over roadway splash/spray zones

SIOZ coating performance within the splash/spray zones of below roadways was similar to that described above for deck joints and other drainage areas, i.e., susceptible to failure and underlying steel corrosion. For the bridges inspected that were over roadways, observable splash/spray zone staining and deterioration on the bridge fascia were common. Figure 15 exemplifies how a splash/spray zone is dependent on the direction of travel of the traffic below the bridge.

It is noted that, generally speaking, corrosion problems are only sometimes observed in the slash zone of the roadway beneath the bridge. This was also true for the bridges inspected in this work. There was only an apparent effect on SIOZ performance in the splash zone for some of the highway overpasses located in the Kansas City, MO metropolitan area. In contrast, similar bridges in the St. Louis metropolitan area (the only other known SIOZ highway overpasses) had good performing SIOZ coatings in the splash zone.

Figure 15. Roadway splash/spray zone.

Figure 16. Underside view of the bridge from Figure 15 with coating deterioration in regions over the roadway.

Nonaggressive Micro-Environments

In regions away from the aggressive micro-environments discussed in the preceding sections, the SIOZ coatings generally performed well and were in good condition. Besides some of the application and construction related problems presented in subsequent sections, there were no atmospheric corrosion problems observed. Examples of good performance are shown in Figure 17.

(a) over a creek

(b) over a river

(c) large vertical clearance over a roadway

(d) typical vertical clearance over a roadway and railroad

Figure 17. Examples of good overall SIOZ performance.

Application-Related Observations

Over the course of the inspections, it became apparent that a number of the observed coating defects were not material or environment related but rather a result of improper application. These observations included low dry film thickness, missed application on specific surfaces, improper preparation of welds, and insufficient field coating of bolted connections, all of which are discussed in the following sections.

Low Dry Film Thickness (DFT)

A number of the inspected bridges had surfaces with insufficient DFT as a result of improper shop application. It was clear that this was an application issue when there were no obvious corrosion sources (e.g., moisture) or similar problems on like members. Examples are provided in Figure 18. Specifying and achieving a sufficient DFT is important for all coating systems but is even more crucial for single coat systems like SIOZ that only supply one layer of protection.

Figure 18. Examples of surfaces with low DFT.

Edges and Bottom Surfaces

A related observation to low DFT was that specific surfaces were more susceptible to having low or nonexistent DFT. These surfaces included edges and bottom surfaces (see Figure 19). As discussed in Chapter 1, edge failure is common for most coatings due to their tendency to shrink around edges during curing. The low DFT observed on bottom surfaces was likely due to access limitations in the shop or field during application (i.e., harder to reach and spray bottom surfaces).

(a) flange edges

(b) edges of cover plates and undersides of bottom flanges

(c) edges and bottom surfaces of cross frames, undersides of bottom flanges

(d) edges of cover plates, undersides of bottom flanges, edges and bottom surfaces of cross frames

Figure 19. Examples of surfaces prone to insufficient DFT.

Welds

There were several locations of minor mud cracking along welds (Figure 20). The examples shown in Figure 20 also show some corrosion resulting from the mud cracking, but more commonly the mud cracking was not associated with any apparent corrosion. As mentioned in Chapter 1, mud cracking over welds caused by excessive coating thickness is common due to the increased hardness of the weld material which results in a low post-blasting surface profile.

(a) at bottom flange

(b) at top flange

Figure 20. Mud cracking over welds.

In addition, there was one bridge with welded splices with a noticeable coating difference over the welds compared to the rest of the bridge. A majority of the locations were in good condition, but at least one location was exhibiting substrate steel corrosion (Figure 21). It was not clear why there was a difference in coating performance at these welds. Other similar locations showed a visually distinct difference in the appearance of the paint at these splice locations compared to the appearance of the paint on the majority of the members. It was speculated that either the initial condition of this paint was different or that these locations had been spot repaired in some but not all instances. It was impossible to determine which possibility was more likely. It was presumed that the coating over the welds was SIOZ.

(a) typical condition

(b) location of corrosion

Figure 21. Coating differences over welded splices.

Bolted Splices and Connections

Depending on the specifications and construction practices at the time of coating application, some of the bolted splices were field coated after steel erection. Bolts and edges of plates on splices of several bridges were not sufficiently coated (Figure 22a). In addition, the coating was not sprayed from all directions during field application, resulting in missed surfaces (Figure 22b).

Similar to bolted splices, the coating performance of field coated bolted connections (e.g., in cross frames) was dependent on proper application (Figure 23).

(a) bolted splice that was insufficiently coated over bolts and along plate edges

(b) surfaces of a bolted splice that were missed during field coating application

Figure 22. Observed performance of bolted splices.

(a) insufficient coating and missed surfaces of a field coated bolted connection

(b) properly field coated bolted connection

Figure 23. Observed performance of bolted connections.

Construction-Related Observations

The final set of SIOZ performance observations were related to construction practices. These included coating damage from tools and equipment, and the choice in fastener type used in connections.

Damage from Tools and Equipment

Several of the inspected bridges showed patterns of coating damage resulting from construction practices (Figure 24). Most of the damage was attributed to allowing construction tools and equipment to contact coated surfaces without protection, such as equipment used to construct deck slabs. Preventing damage is a concern for most coatings but is of particular concern for single coat systems like SIOZ because there is only one layer of protection.

Figure 24. Examples of coating damage attributed to construction practices.

Fasteners

Observations related to the performance of field coated bolted splices and connections were discussed in a previous section. A related observation was the choice in fastener type to use for connections. There are two main options available: (1) use SIOZ coated fasteners or (2) use galvanized fasteners. Both options are acceptable, but the results of the inspections showed performance differences (Figure 25). SIOZ coated fasteners were susceptible to missed surfaces, low DFT, and coating deterioration (Figure 25a). On the other hand, galvanized fasteners did not display any performance issues (Figure 25b). In addition, galvanized fasteners presumably speed up the construction schedule by eliminating the need to field coat fasteners post steel erection.

(a) SIOZ coated fasteners *(b) galvanized fasteners*

Figure 25. Bolt types used on SIOZ bridges.

CONCLUSIONS

The main findings from the results of the field inspections can be summarized as follows:

- No influence of macro-environment was observed on SIOZ bridges; however, none of the bridges were located in a particularly severe micro-environment.
- Aggressive micro-environments caused by leaking drainage systems should be eliminated whenever possible, or additional protection strategies should be employed in these regions. Otherwise, SIOZ coating performance may be compromised. As with other corrosion protection systems, there appears to be a unknown threshold that causes corrosion in the splash zone of highway overpasses based on the inconsistent observations in these micro-environments.
- Specifying and achieving a sufficient DFT on all surfaces is of upmost importance for SIOZ coatings.
- During the surface preparation and application processes, extra attention should be given to edges and bottom surfaces, welds, and bolted connections so that these locations are properly coated.

- During all construction stages, contact with coated surfaces should be avoided. If that is not possible, methods to protect the coating where in contact should be employed.

- Galvanized fasteners are recommended for all bolted connections on SIOZ coated steel.

References

AASHTO / NSBA (2002), "S 8.1 – Guide Specification for Coating Systems with Inorganic Zinc-Rich Primer", AASHTO / NSBA, Washington, DC / Chicago, IL.

ASTM (1999), "D4585-99: Standard Practice for Testing Water Resistance of Coatings using Controlled Condensation," ASTM, West Conshohocken, PA.

ASTM (2015), "D870-15: Standard Practice for Testing Water Resistance of Coatings Using Water Immersion," ASTM, West Conshohocken, PA.

ASTM (2019a), "G85-19: Standard Practice for Modified Salt Spray (Fog) Testing," ASTM, West Conshohocken, PA.

ASTM (2019b), "D610-08: Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces," ASTM, West Conshohocken, PA.

Baxter, I. (1993), Corrosion Australasia, 18(2), 11–12.

Baxter, I. (2013), "Inorganic Zinc Coatings," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Biddle, G.J. (2013), "Inorganic Zinc Silicate Coatings," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Brevoort, G.H. and Roebuck, A.H. (1993), "A Review and Update of the Paint and Coatings Cost and Selection Guide," *Materials Performance*, National Association of Corrosion Engineers, p 31–45.

Calle, L. (2019), "NASA's Corrosion Technology Laboratory at the Kennedy Space Center: Anticipating, Managing, and Preventing Corrosion," European Corrosion Conference, Graz, Austria.

Carlson, J. (2020), Personal communication.

Eccleston, G. (1998), "The Effect of Cure Temperature and Humidity on the Properties of Solvent-Borne Zinc Silicate Coatings," *Protective & Marine Coatings*, 1(1), 36–45.

Eccleston, G. (2013), "Effect of Atmospheric Conditions on the Long Term Properties of Solvent-borne Zinc Silicate Coatings," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Feliu, S. Jr., Morcillo, M. and Feliu, S. (2001), "Deterioration of cathodic protection action of zinc-rich paint coatings in atmospheric exposure," *Corrosion*, 57(7), 591–597.

Francis, R. (2013a), "Inorganic Zinc Silicate Coatings – The Early Days; Part I: Invention and Early Applications," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Francis, R. (2013b), "Inorganic Zinc or Galvanizing: Choosing the Ideal Corrosion Protection for Structural Steel," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Francis, R. (2013c), "Inorganic Zinc Silicate Coatings: Fallacies and Facts," *Corrosion & Prevention*, Paper 026.

Francis, R. (2016), "Surface Preparation for Inorganic Zinc Silicate Coatings," *Corrosion & Materials*, 62–63.

Francis, R. (2019), "Specification for Coating Steelwork with a Single Coat Solvent-Borne Inorganic Zinc Silicate," Draft Version 1.0, personal communication.

Francis, R. and Szokolik, A. (2013), "A Comparison of the Corrosion Behaviour of Inorganic Zinc and Conventionally-Coated Bridges," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Francis, R., Ellis, D. and Walker, A. (2013), "Repair of Single Coat Inorganic Zinc Silicate Coatings," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Helsel, J.L. (2007), "Practical Considerations for the Life Cycle Evaluation of Zinc Rich Coatings, Galvanized Steel and Thermal Sprayed Metals for Industrial Structures in Moderate Environmental Exposures," *Proceedings of the Paint and Coatings Expo (PACE)*, Dallas, TX, Society of Protective Coatings (SSPC).

Hemmings, E. and Demirdjian, N. (2013), "Water-based Inorganic Zincs – Performance vs Practicability," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

ISO (2007), "ISO 8501 – Preparation of Steel Substrates Before Application of Paints and Related Products — Visual Assessment of Surface Cleanliness," International Standards Organization, Geneva, Switzerland.

ISO (2017), "ISO 9223 – Corrosion of Metals and Alloys — Corrosivity of Atmospheres — Classification, Determination and Estimation," International Standards Organization, Geneva, Switzerland.

Jaeger, H. and Sherwood, R. (1975), "The Structure of Inorganic Zinc-Rich Coatings Examined with Optical and Electron Microscopy," *Proceedings of the 6th InterCongress on Metallic Corrosion*, Sydney, Australia, Dec 1975, 802–815.

Jaeger, H.; Donald, D.W. and Yuan, F. (2013), "Testing of Inorganic Zinc-Rich Anticorrosion Coatings in Different Atmospheres," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Kakaei, M., Danaee, I. and Zaarei, D. (2013), "Evaluation of Cathodic Protection Behavior of Waterborne Inorganic Zinc-Rich Silicates Containing Various Contents of MIO Pigments," *Anti-Corrosion Methods and Materials*, 60(1), 37–44.

KTA-Tator (2014), "Transportation Agency Practices Currently Employed for Bridge Maintenance Painting Operations: Findings from a National Survey," *Transportation Research Synthesis TRS 1404*, Minnesota Department of Transportation, St. Paul, MN.

Laliberte, L., Miller, R., Shaw, B. and Escarsega, J. (2005), "An Evaluation of Sacrificial Metallic Coatings for Service Life Extension of U.S. Army Vehicles," *Corrosion*, Paper No. 05210, NACE International, Houston, TX.

Lofhelm, K., Hemmings, E. and Szokolik, A. (2006), "Metallic Zinc based Coating Systems – Evaluation of Performance," *Corrosion & Prevention*, Paper 003, Hobart, Tasmania.

Lofhelm, K., Hemmings, E., and Szokolik, A. (2013), "Metallic Zinc Based Coating Systems – Evaluation of Performance," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Mandeno, W. (2017), "Water-Borne Inorganic Zinc Silicate: Two NZ Bridges," *Corrosion & Prevention*, Paper 32.

McCullough, T. (2022), Personal communication.

Miller, J. (2019), Personal communication.

Morcillo, M., Barajas, R., Feliu, S. and Bastidas, J.M. (1990), "A SEM study on the galvanic protection of zinc-rich paints," *Journal of Materials Science*, 25(5), 2441–2446.

NASA (2016), "Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment," NASA Technical Standard, NASA-STD-5008B w/ Change 1, NASA, Washington, DC.

Paton, W. (1973), "Performance Characteristics of Zinc-Rich Coatings Applied to Carbon Steel," NASA Technical Note D-7336, NASA, Washington, DC.

Riding, E. (1997), "Inorganic zinc silicates coatings – Chemistry and protective properties," Seminar on Inorganic Zinc, Melbourne, Australia.

Salome, F. (2013), "Climatic Conditions for Successful Application of Zinc-rich Coatings," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

SSPC (2007a), "Near White Metal Blast Cleaning," *SSPC-SP 10/NACE No. 2*, SSPC, Houston, TX.

SSPC (2007b), "Commercial Blast Cleaning," *SSPC-SP 6/NACE No. 3*, SSPC, Houston, TX.

Son, S.-M. (2013), "Crack Resistance Improvement of Inorganic Zinc Rich Paint," NACE International Corrosion Conference Series, NACE, Houston, TX.

Standards Australia (2002), "AS/NZS 2312 – Guide to the Protection of Structural Steel Against Atmospheric Corrosion by the Use of Protective Coatings," Sydney, Australia.

Szokolik, A. (2013), "Inorganic Zinc Silicates as Single-Coat Protective Systems for Steel," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Szokolik, A. and Rapattoni, F. (1998), "Coatings Guide for New Steel Bridges," BHP Integrated Steel, Wollongong, Australia.

Wattyl (1999), "Zinc Silicates; Quality Aspects Application," Wattyl Protective Coatings, Australia.

Zhang, J. and Walker, A. (2013), "Potential Re-coating Treatment for Inorganic Zinc Silicate Coatings," *Inorganic Zinc Coatings: History, Chemistry, Properties, Applications and Alternatives*, 2nd Edition, Australasian Corrosion Association, Victoria, Australia.

Appendix A
Data on Existing SIOZ Bridges

Structure #	BridgeType	City	County	State	Structure Name	Year Built	State FIPS code
8386	Girder	Kearney	Clay	Missouri	128th St E	1965	29
6487	Girder	Gladstone	Clay	Missouri	Bryant St	1958	29
1183	Girder	Overland Park	Jackson	Missouri	IS 435 S	1966	29
1184	Girder	Overland Park	Jackson	Missouri	IS 435 N	1966	29
4115	Girder	Villa Ridge	Franklin	Missouri	SP 100 E	1993	29
4213	Girder	Boschertown	St. Charles	Missouri	MO 370 W	1994	29
4105	Girder	St. Peters	St. Charles	Missouri	OR 70 E	1995	29
4314	Girder	Fenton	St. Louis	Missouri	Sappington Rd S	1995	29
3996	Girder	Fenton	St. Louis	Missouri	Matis Rd E	1995	29
6604	Girder	Eureka	St. Louis	Missouri	IS 44 W	1960	29
800	Girder	St. Peters	St. Charles	Missouri	IS 70 W	1962	29
4816	Girder	St. Peters	St. Charles	Missouri	IS 70 E	1953	29
441	Girder	Arnold	St. Louis	Missouri	IS 55S	1964	29
442	Girder	Arnold	Jefferson	Missouri	IS 55N	1964	29
6603	Girder	Eureka	St. Louis	Missouri	IS 44 E	1960	29
24209	Girder, K-Frame	Buckhall	Prince William	Virginia	RT 294	1994	51
0016609A	Girder	Oil City	Jefferson	Washington	US 101 Nolan Creek	2004	53
0016276A	Girder	Halford	Snohomish	Washington	US 2 Barclay Creek	2003	53

Structure #	latitude	longitude	Feature Carried	Feature Intersected	Service Type	Use	Underclearance
8386	39.32436	-94.39576	128th St E	IS 35	highway	Urban Local	16.1
6487	39.20379	-94.50067	Bryan St	IS 35	highway	Urban Local	16
1183	38.93988	-94.56744	IS 435 S	CST 104th St, UP RR	highway + RR	Interstate Highway	18.1
1184	38.93971	-94.56739	IS 435 N	CST 104th St, UP RR	highway + RR	Interstate Highway	18.1
4115	38.47441	-90.85029	SP 100 E	IS 44	highway	Urban Other Principal Arterial	16.5
4213	38.82435	-90.5181	MO 370 W	CST Elm St	highway	Urban Principal Arterial	17.3
4105	38.8012	-90.59024	OR 70 E	RP MO370W TO IS70E, RP I	highway	Urban Collector	17.3
4314	38.51552	-90.38025	Sappington Rd S	IS 270	highway	Urban Minor Arterial	16.9
3996	38.49541	-90.34674	Mattis Rd E	IS 55	highway	Urban Minor Arterial	16.9
6604	38.50269	-90.69958	IS 44 W	Fox Creek	water	Interstate Highway	N/A
800	38.70873	-90.60567	IS 70 W	Spencer Creek	water	Interstate Highway	N/A
4816	38.79853	-90.60568	IS 70 E	Spencer Creek	water	Interstate Highway	N/A
441	38.4529	-90.37675	IS 55 S	Meramec River	water	Interstate Highway	N/A
442	38.45293	-90.37652	IS 55 N	Meramec River	water	Interstate Highway	N/A
6603	38.50254	-90.69958	IS 44 E	Fox Creek	water	Interstate Highway	N/A
24209	38.71074	-77.4108	Prince William Pky	Occoquan Reservoir	water	Urban Minor Arterial	N/A
0016609A	47.75153	-124.3229	US 101	Nolan Creek	water	Rural Principal Arterial	N/A
0016276A	47.78565	-121.5012	US 2	Barclay Creek	water	Rural Principal Arterial	N/A

Structure #	ADT Sum	ADT under (A)	ADT Under (B)	ADT (C)	ADT (D)	%ADTT under A	%ADTT under B	%ADTT under C	%ADTT under D
8386	0	14970	14745	N/A	N/A	21	23	N/A	N/A
6487	0	27665	30434	N/A	N/A	18	18	N/A	N/A
1183	0	5546	N/A	N/A	N/A	5	N/A	N/A	N/A
1184	0	5546	N/A	N/A	N/A	5	N/A	N/A	N/A
4115	46304	25810	20494	N/A	N/A	29	22	N/A	N/A
4213	9804	9804	N/A	N/A	N/A	5	N/A	N/A	N/A
4105	33608	613	362	15985	16648	10	16	5	5
4314	165609	76777	88832	N/A	N/A	12	12	N/A	N/A
3996	267332	133666	133666	N/A	N/A	18	18	N/A	N/A
6604	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
800	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4816	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
441	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
442	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6603	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24209	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0016609A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0016276A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Structure #	ADT over	%ADTT over	Year reconstructed	Year Coating applied	Initial Thickness (mm)	Current Thickness	Surface Prep.	Cost of SIOZ
8386	212	5	2019	No Data	3 to 6	No Data	No Dara	No Data
6487	3380	5	N/A	No Data	3 to 6	No Data	No Data	No Data
1183	70599	18	2019	1995	3 to 6	No Data	No Data	No Data
1184	70585	18	2019	1995	3 to 6	No Data	No Data	No Data
4115	15297	5	N/A	1994	3 to 6	No Data	No Data	No Data
4213	27748	5	N/A	1994	3 to 6	No Data	No Data	No Data
4105	5228	8	N/A	1994	3 to 6	No Data	No Data	No Data
4314	11175	5	N/A	1994	3 to 6	No Data	No Data	No Data
3996	1510	5	N/A	1995	3 to 6	No Data	No Data	No Data
6604	27176	26	1994	1973	3 to 6	No Data	No Data	No Data
800	68945	12	1995	No Data	3 to 6	No Data	No Dara	No Data
4816	70916	12	1995	1996	3 to 6	No Data	No Data	No Data
441	59205	18	1993	No Data	3 to 6	No Data	No Dara	No Data
442	60260	18	1993	No Data	3 to 6	No Data	No Dara	No Data
6603	25347	22	1994	1973	3 to 6	No Data	No Data	No Data
24209	30815	2	N/A	1995	6 to 10	No Data	No Data	No Data
0016609A	1150	18	N/A	No Data	2.5 min	No Data	SSPC-SP10	No Data
0016276A	5704	9	N/A	No Data	2.5 min	No Data	SSPC-SP10	No Data

Structure #	Deicing Rate on structure tCL-/ lane-mile	Deicing Rate under structure	Coating Maintenance
8386	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
6487	Salt applied between Nov. and March	N/A	State Practice blast and recoated as needed
1183	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
1184	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
4115	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
4213	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
4105	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
4314	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
3996	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
6604	Salt applied between Nov. and March	N/A	State Practice blast and recoated as needed
800	Salt applied between Nov. and March	N/A	State Practice blast and recoated as needed
4816	Salt applied between Nov. and March	N/A	State Practice blast and recoated as needed
441	Salt applied between Nov. and March	N/A	State Practice blast and recoated as needed
442	Salt applied between Nov. and March	N/A	State Practice blast and recoated as needed
6603	Salt applied between Nov. and March	Salt applied between Nov. and March	State Practice blast and recoated as needed
24209	7.52	N/A	0
0016609A	Most likely no application due to location	N/A	None
0016276A	Mostl likely some application due to location	N/A	None

Structure #	Reported Issues	Location of coating	Year coating re-applied	Superstructure Condition rating
8386	None	Shop prepared	1996	7
6487	None	Shop prepared	1996	6
1183	None	Shop prepared	N/A	7
1184	None	Shop prepared	N/A	7
4115	None	Shop prepared	N/A	6
4213	None	Shop prepared	N/A	7
4105	None	Shop prepared	N/A	7
4314	None	Shop prepared	N/A	7
3996	None	Shop prepared	N/A	7
6604	None	Shop prepared	1995	7
800	None	Shop prepared	1996	5
4816	None	Shop prepared	N/A	5
441	None	Shop prepared	1995	6
442	None	Shop prepared	1995	6
6603	None	Shop prepared	1995	7
24209	coating in excellent condition	No Data	N/A	7
0016609A	None	No Data	No Data	8
0016276A	~10 SF of surface rust	No Data	No Data	7

Structure #	NBE 515 TQ (SF)	NBE 515 CS 1 (%)	NBE 515 CS 2 (%)	NBE 515 CS 3 (%)	NBE 515 CS 4 (%)	Climate Code	Climate Description	Inspected
8386	No Data	No Data	No Data	No Data	No Data	4A	Mixed Humid	Yes
6487	No Data	No Data	No Data	No Data	No Data	4A	Mixed Humid	Yes
1183	28455	99	1	0	0	4A	Mixed Humid	Yes
1184	28378	99	1	0	0	4A	Mixed Humid	Yes
4115	11684	54	44	0	1	4A	Mixed Humid	Yes
4213	25497	99	0.04	0.3	0.2	4A	Mixed Humid	Yes
4105	No Data	No Data	No Data	No Data	No Data	4A	Mixed Humid	Yes
4314	No Data	No Data	No Data	No Data	No Data	4A	Mixed Humid	Yes
3996	No Data	No Data	No Data	No Data	No Data	4A	Mixed Humid	Yes
6604	11513	66	0.03	0.35	33	4A	Mixed Humid	Yes
800	8082	82	6	8	3	4A	Mixed Humid	Yes
4816	7101	90	3	4	2	4A	Mixed Humid	Yes
441	207444	100	0	0	0	4A	Mixed Humid	Yes
442	207444	100	0	0	0	4A	Mixed Humid	Yes
6603	23027	99	0	0	1	4A	Mixed Humid	Yes
24209	132768	97	2	0.05	0	4A	Mixed Humid	Yes
0016609A	13770	100	0	0	0	4c	Mixed Marine	Yes
0016276A	10000	99.9	0	0.05	0.05	4c	Mixed Marine	Yes

Appendix B
Inspection Protocols

DEVIATIONS

The inspection protocols used for the field inspections start on the proceeding page. The actual field inspections deviated from the planned protocols in the following ways:

- Marking and dimensional measurement of substrate corrosion or deteriorated coating areas was not performed. Due to access limitations, it was not possible to get hands-on measurements for many of these regions. Therefore, it did not seem appropriate to only take detailed measurements of the accessible regions and draw conclusions based on the results. Photographs and notes were still taken for these regions.

- Due to the limited access, it was not possible to assign overall performance metrics to the entirety of each bridge, for example using the SSPC-VIS 2 Rust Grade scale. Instead, the Rust Grade scale was used as an approximate assessment of the accessible and visible regions of each bridge so that performance could be generally compared across bridges. However, no formal post-processing or analyses of the performance metrics were carried out.

GENERAL

Background

This protocol provides guidance on identifying corroded areas on coated steel superstructure elements and the deterioration of the coating on these elements. Guidance on documenting the extent and location of corrosion and coating condition is also provided.

The most common types of defects in bridge coatings include chalking, cracking, loss of adhesion, and peeling. Data collection involves identifying areas where coating defects are evident and documenting the location and size of the affected areas.

The main cause of steel corrosion in coated bridges is the lack and/or breakdown of the protective coating. Once this occurs, the exposure to corrosive agents (water, salts, and chemicals) begins a disintegration process on the surface metal. Corrosion grows from a few, small starting points, and then expands as steel molecules that are directly in contact with the corroded area also corrode; eventually, small, medium, and large contiguous areas of corrosion are evident. Data collection involves identifying areas where corrosion is evident and documenting the approximate location and size of the affected areas.

Pictures of corroded and non-corroded areas should be taken in order to document coating condition. The intent of this documentation is to show the extent of the coating breakdown in such a manner to assess the current performance and to potentially track breakdown over time if future coating inspections are performed. The primary concern with coating breakdown regards the subsequent corrosion (deterioration) of underlying structural steel. It is the metal section loss that eventually occurs at defects in coatings that presents the concern to the structural integrity of the bridge.

Objectives

1. Inspect and assess the current condition of the coating system and substrate steel for each bridge.

2. Identify factors (e.g., site conditions, detailing practices, fabrication issues, coating application procedures, age, maintenance practices) that may contribute to the current condition of the coating system and substrate steel for each bridge, in terms of both good and bad performance.

Scope

The inspections will be visual and ground based. Any inspection techniques beyond visual are not required and should only be performed with Owner approval and time permitting. Inspection from areas beyond ground locations will not be performed (e.g., snooper trucks) and traffic control will not be provided. The protocols and procedures provided in this document need only be followed for ground accessible areas of each bridge. Deviation from the protocols and procedures may be warranted depending on site-specific conditions.

The inspections will identify and document the type, extent, and location of coating deterioration and substrate steel corrosion visible from the ground. The data gathered from the inspections will be used to evaluate the performance of the coating and substrate steel using the standards referenced in this document.

REFERENCE STANDARDS

ASTM

D610 Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces

D661 Standard Test Method for Evaluating Degree of Cracking of Exterior Paints

D714 Standard Test Method for Evaluating Degree of Blistering of Paints

D772 Standard Test Method for Evaluating Degree of Flaking (Scaling) of Exterior Paints

D4214 Standard Test Method for Evaluating Degree of Chalking of Exterior Paint Films

SSPC

PA 2 Procedure for Determining Conformance to Dry Coating Thickness Requirements

VIS 2 Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces

EQUIPMENT

- PPE
- Tape measure
- 6 ft. folding ruler
- Metal scraper
- Wire brush
- Hand broom
- DFT gage
- 1-½" diameter stencil
- Temporary marker
- Permanent marker
- White chalk
- Pencil, sketch pad, and clipboard
- Digital camera
- Binoculars
- Laser measuring device

EVALUATION PARAMETERS

Evaluation parameters for corrosion of coated steel surfaces and coating condition are listed in Tables 1 and 2, respectively. Any other defects encountered during inspection should be noted as well.

Table 1. Corrosion of Coated Surfaces

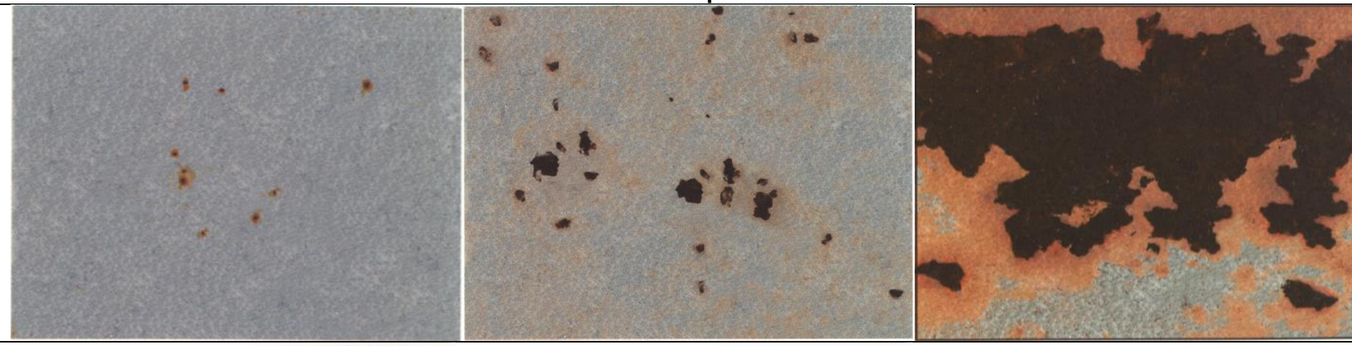
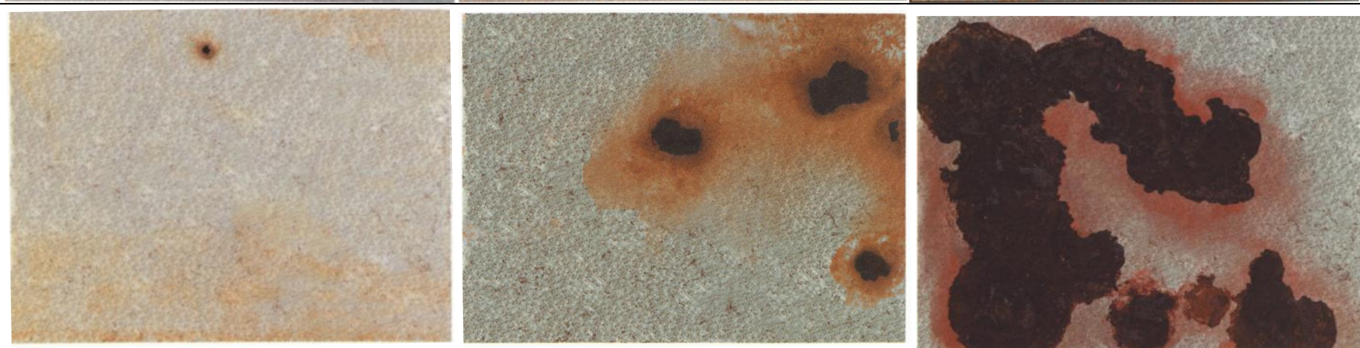
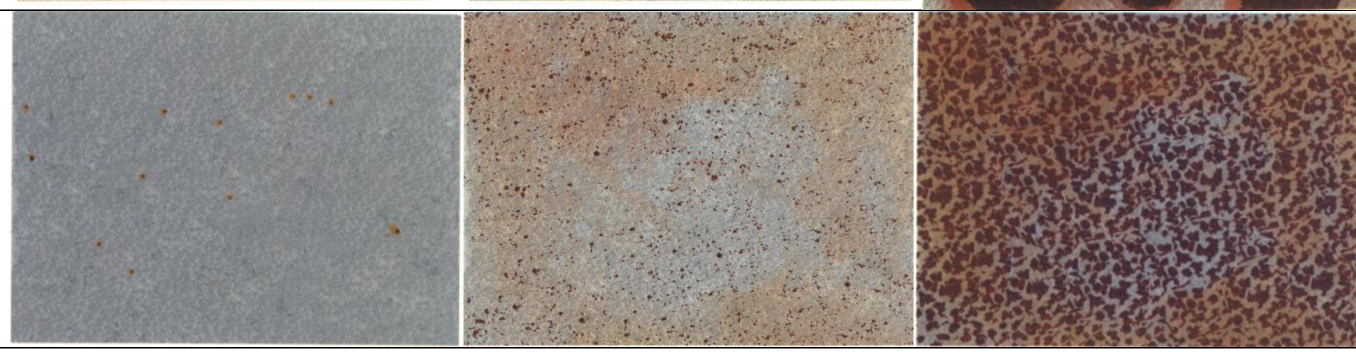
Corrosion Type	Test Method	Example Photos
General: Occurs when various size rust spots are randomly distributed across the surface.	ASTM D610 (SSPC-VIS 2)	
Spot: Occurs when the bulk of the rusting is concentrated in a few localized areas of the painted surface.	ASTM D610 (SSPC-VIS 2)	
Pinpoint: Occurs when the rust is distributed across the surface as very small individual specks of rust.	ASTM D610 (SSPC-VIS 2)	

Table 2. Coating Condition

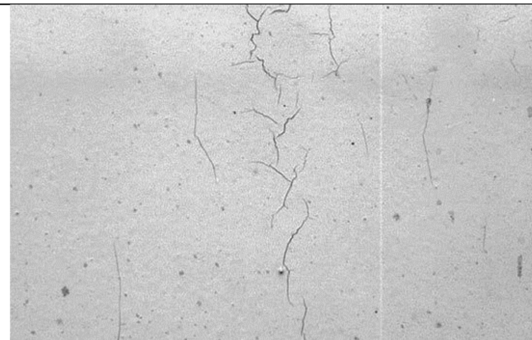
Condition	Test Method	Example Photos
Checking: That phenomenon manifested in paint films by slight breaks in the film that do not penetrate to the underlying surface.	ASTM D660	
Cracking: That phenomenon manifested in paint films by a break extending through to the surface painted.	ASTM D661	 
Blistering: Dome-shaped projections or blisters in the dry paint film through local loss of adhesion and lifting of the film from the underlying surface.	ASTM D714	  

Table 2. Coating Condition

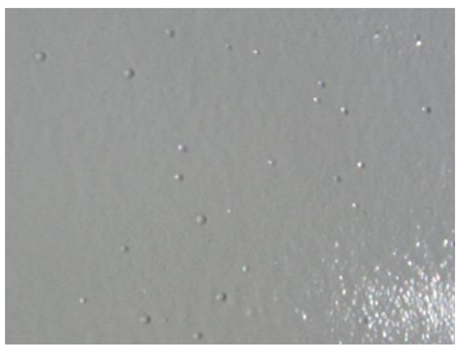
Condition	Test Method	Example Photos
Flaking: A form of adhesion failure where paint flakes from the substrate.	ASTM D772	 
Chalking: The formation on a pigmented coating of a friable powder evolved from the film itself at or just beneath the surface.	ASTM D4214	 
Bubbling: Trapped air or solvent due to improper drying, entrainment during mixing, or high ambient temperature during application. May be intact or broken (leaving a crater). Should not be confused with blistering.	-	 

Table 2. Coating Condition

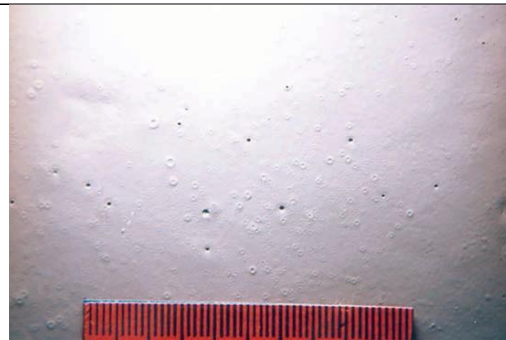
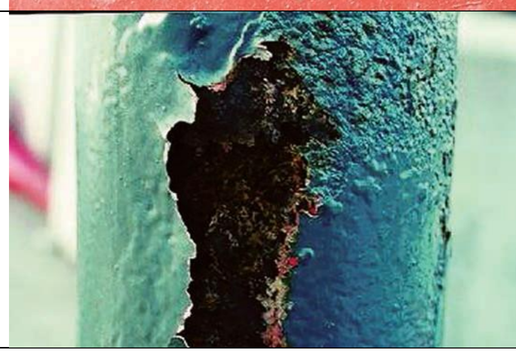
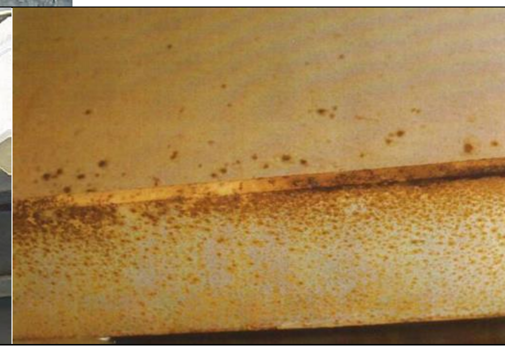
Condition	Test Method	Example Photos
Pinholes: Small holes that form in the wet coating during application and drying due to bubbles that burst, resulting in small craters or holes that fail to coalesce prior to setting.	-	
Runs: Downward movement of a coat due to accumulation of excessive coating quantities.	-	
Undercutting: Visual corrosion beneath a paint film, often called creep. Corrosion travels beneath the paint film and lifts the paint from the substrate.	-	

Table 2. Coating Condition		
Condition	**Test Method**	**Example Photos**
Wrinkling: Development of wrinkles in the coating during drying.	-	
Edge Rusting: Corrosion beneath coated edges due to inadequate coating thickness caused by surface tension during drying. Locations include sharp edges, holes, welds, corners, and crevices.	-	 

FORMS

See Appendix A for example inspection forms.

INSPECTION PROCEDURE

Upfront

Identify the structure, its location (by route, feature intersected, latitude and longitude), and date of inspection.

Assemble an inspection team, including an owner's representative if possible.

Arrange for the necessary access, clearance permits, safety equipment, and inspection equipment.

Prepare and distribute forms for field evaluation.

Record Basic Information

Record date and start time.

Record environmental conditions and other damaging factors that might affect the performance of the coatings (e.g., salt dripping, abrasion, wind, and vandalism).

Visual Documentation

Take photographs of the overall bridge and specific areas of coating and/or substrate steel deterioration using the guidance below. The type and number of photos taken may be modified depending on the ground-based access available at each bridge site.

Create a photo log to document each photo taken. At minimum, the photo log should include each photo name, the element and region being photographed (e.g., girder *n* bottom flange), directional identifiers (e.g., looking up, looking west) and a short description explaining the reasoning for taking the photo (e.g., blistering of coating).

Overall photographs are to be taken with every site visit depicting broad views of the bridge. The mandatory photos, contingent on adequate ground-based access, include (all referenced photos courtesy of FHWA):

- Wide view of bridge viewing fascia girders/beams, capturing Girder segments 1A through *N*A and Girder segments 1*n* thru *Nn* (i.e., both entering and exiting fascias). This photograph shall be taken from a distance of approximately 100 feet back from the bridge, but within the safe access limits, or on the shoulder of the road if necessary. An example is shown in Figure B1.

- Girders at typical bearing locations (abutment bearing lines AA and AB minimum, and any and all pier bearing lines Px). An example is shown in Figure B2.

- A wide view of interior girders for accessible spans (Girder B through *n*-1). An example is shown in Figure B3.

- One close-up photo of a typical splice plate on fascia girders (if applicable). An example is shown in Figure B4.

- One close-up photo of a lateral bracing to girder connection (if applicable). An example is shown in Figure B5. This photograph should focus on bolted connections, such as between cross-frame members and transverse stiffeners serving as lateral bracing connection plates, in areas where any pack rust is developing if applicable.

- At least one photo depicting the general environmental exposure of the structure (e.g., over water) should be included if not captured in the wide view of the fascia girder. An example is shown in Figure B6.

- Any identifiers on the bridge superstructure, such as the bridge number. These are often stenciled on a girder. An example is shown in Figure B7.

Figure B26. Photo. Example of wide view of bridge.

Figure B27. Photo. Example of view of bearing location.

Figure B28. Photo. Example of wide view of bridge interior.

Figure B29. Photo. Example of view of girder splice plate.

Figure B30. Photo. Example of view of lateral bracing to girder connection.

Figure B31. Photo. Overall view of general environment of bridge.

Figure B32. Photo. Example of bridge identifier.

Photographs of specific areas of coating and/or substrate steel deterioration shall be taken whenever the corrosion types from Table 1 or the coating conditions from Table 2 are encountered. Examples are shown in Figures B8 and B9.

Figure B33. Photo. Example overall view of coating and substrate steel deterioration.

Figure B34. Photo. Example closeup view of coating and substrate steel deterioration.

Clean

Where access from the ground is available, cleaning may be used to expose coated surfaces for inspection. Use the hand broom to clean any dirt or debris from coated surfaces. Take a photo of the area before and after cleaning.

Use the scraper and wire brush to clean loose, deteriorated protective coating and surface corrosion, if any are present (optional).

Visually Inspect Coating and Substrate

Close-up visual inspection is contingent upon access from the ground, which may or may not be available for all bridges or all coated surfaces. Modify procedure as necessary based on site specifics.

Inspect and note each area with substrate corrosion (Table 1) or deteriorated coating conditions (Table 2).

Take two photographs of each area at minimum, one overall view and one closeup view (see Figures 8 and 9). Additional photos may be warranted depending on the extent of corrosion or coating deterioration. The overview photo should be taken normal to the surface wherever possible

Use sketches as needed to document inspected areas, substrate corrosion, coating conditions, etc.

Measure Coating Dry Film Thickness (Optional)

Where desired and when coated surfaces are accessible, measure the Dry Film Thickness (DFT) of the coating according to SSPC-PA 2.

Determine and record the type of DFT measurement to be taken, a spot or area measurement. A spot measurement is the average of three or more gage readings made within a 1-½" diameter circle. An area measurement is the average of five spot measurements over each 100 square feet of coated surface.

Mark the limits of each 1-½" diameter circle sample area using a stencil and temporary marker. Take the DFT readings. Measure and record the location of the sampled area(s). Note the type of measurement (i.e., spot or area).

Take two photographs of each sampled area at minimum, one overview and one macroscopic view.

Close Out

Record end time.

Sign/initial inspection forms and sketches. Obtain signatures of participants and observers (optional).

POST PROCESSING

Scan and upload all documentation to a cloud-based folder shared with the project team and NSBA.

Data Validation

Compare measurements with measurements from previous inspections of the same structure, if available, to ensure values make sense.

Compare measurements with photo documentation to make sure results shown in photos are consistent with items measured.

If an element's condition is improved when compared to the condition documented in a previous inspection, check with the Owner to determine if any maintenance, repair, and/or bridge preservation actions have occurred. If so, document these maintenance, repair, and/or bridge preservation actions using the appropriate protocols.

Assess and Analyze Data

Tabulate and evaluate the data from each inspection. Data should be organized to show:

- Ratings of each coating system's performance at each inspection.
- Other performance evaluation metrics at each inspection.

Identify the types of deterioration or failures that occurred for the coatings tested.

REFERENCES

ASTM. 1999. F1130 *Standard Practice for Inspecting the Coating System of a Ship*, ASTM International, Conshohocken, PA.

SSPC. 2004. Technology Guide No. 9, *Guide for Atmospheric Testing of Coatings in the Field*, The Society for Protective Coatings (SSPC), Pittsburgh, PA.

INSPECTION FORMS

See the following pages for inspection form templates.

COATING INSPECTION FORM

STRUCTURE: ____________________ DATE: __________ PAGE __________ OF __________

INSPECTOR: ____________________ TIME: __________ (START) __________ (END)

REQUIRED PHOTOGRAPHS

1. OVERALL (5-7 MIN.) [ ] (check)
2. SPECIFIC AREAS [ ] (check)

(SEE INSPECTION PROTOCOL FOR REQUIRED PHOTO DOCUMENTATION)

ENVIRONMENTAL CONDITIONS:

____

____

CORROSION

Circle/note preliminary Rust Grade(s) judgement.

RUST GRADE	PERCENT OF SURFACE RUSTED	PHOTOGRAPHIC STANDARD		
		SPOT	GENERAL	PINPOINT
10	Less than or equal to 0.01%	NONE		
9	Greater than 0.01% to 0.03%	9-S	9-G	9-P
8	Greater than 0.03% to 0.1%	8-S	8-G	8-P
7	Greater than 0.1% to 0.3%	7-S	7-G	7-P
6	Greater than 0.3% to 1%	6-S	6-G	6-P
5	Greater than 1% to 3%	5-S	5-G	5-P
4	Greater than 3% to 10%	4-S	4-G	4-P
3	Greater than 10% to 16%	3-S	3-G	3-P
2	Greater than 16% to 33%	2-S	2-G	2-P
1	Greater than 33% to 50%	1-S	1-G	1-P
0	Greater than 50%	NONE		

OTHER CORROSION TYPES:

1. ____________________
2. ____________________
3. ____________________

COATING CONDITION

	PRESENT? (CHECK)	EXTENT (%)
CHECKING		
CRACKING		
BLISTERING		
FLAKING		
CHALKING		
BUBBLING		
PINHOLES		

	PRESENT? (CHECK)	EXTENT (%)	
RUNS			
UNDERCUTTING			
WRINKLING			
EDGE RUSTING			
			(OTHER)
			(OTHER)
			(OTHER)

ADDITIONAL NOTES

DFT MEASUREMENT FORM

STRUCTURE: ____________________ DATE: __________ PAGE ______ OF ______

INSPECTOR: ____________________

ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

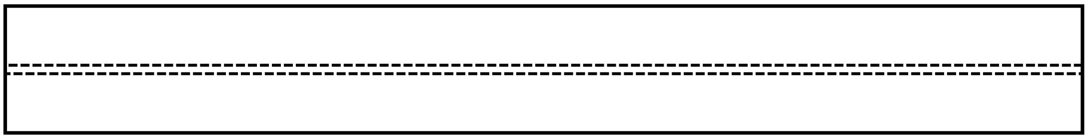
ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

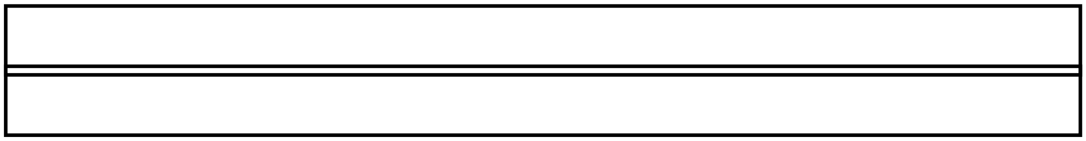
ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

ITEM/AREA DESCRIPTION	SPOT	READING			AVG
		1	2	3	
	A				
	B				
	C				
	D				
	E				
APPROX. SQ. FT.				TOTAL	
				AVG	

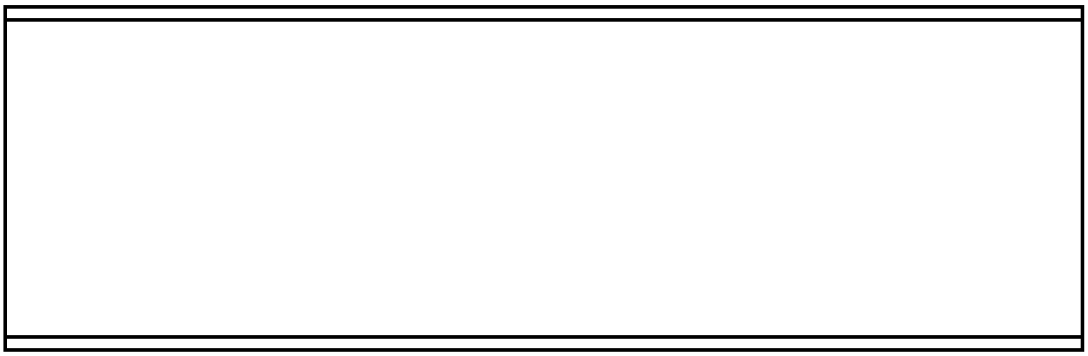
SKETCH TEMPLATES



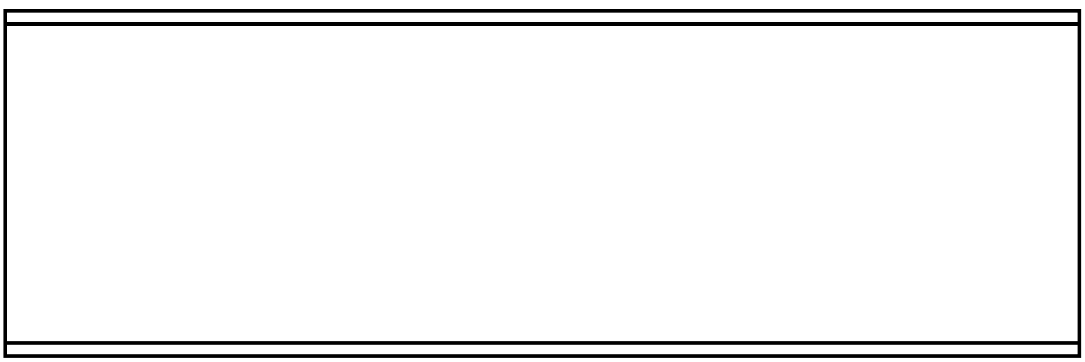
TOP FLANGE (OUTSIDE)



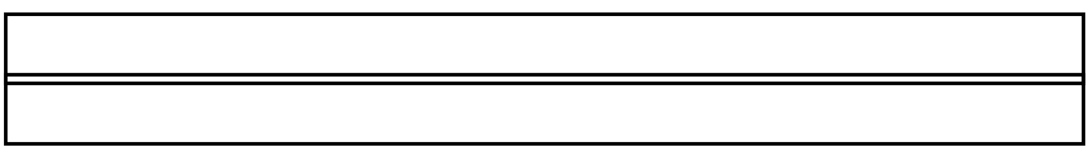
TOP FLANGE (INSIDE)



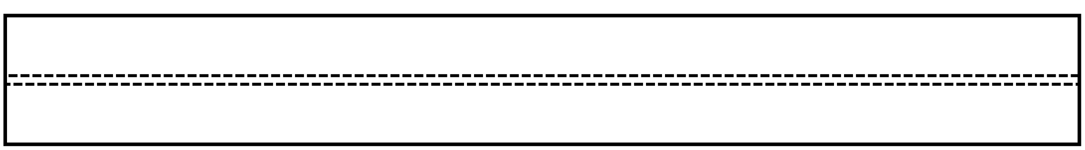
WEB (FACE 1)



WEB (FACE 2)



BOTTOM FLANGE (INSIDE)



BOTTOM FLANGE (OUTSIDE)

Appendix C
Inspection Notes

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/25/22	441/442	• Possible moisture from river below (Meramec River); although vertical clearance was very high at time of inspection • Joints at the abutments with visible moisture; joints at several piers. • Some graffiti present.	• Various severities and extents of spot, general, pinpoint, and edge rusting (with rust grades judged to be between 5 and 10 for various girders). The rusting was visible on the bottom of the bottom flanges, the bottom of the top flanges, the webs, and the cross frames. These defects were concentrated in the 5 most-interior girders (Girders 3-7), which were the oldest. • The first two exterior girders on each side and each bridge (Girders 1-2, 8-9) were in the best condition. These girders are newer because the bridges were widened at some point and the coating was shop applied, while the coating of the remaining girders was field applied (per MoDOT personnel verbal communication). • A large portion of the underlying steel corrosion appeared to be caused by a combination of high surface profile and small coating thickness. The small thickness could also explain the large amounts of edge rusting observed. • There was not an apparent pattern to the coating failure and corrosion (i.e., not concentrated at the joints); therefore, the defects appear to be caused by a combination of general breakdown due to age, insufficient coating thickness, and poor application. • The superstructure was spot painted at the piers where deck joints were present; also the location of pin and hanger systems. It was apparent that this spot coat was field applied, but the type and date of application were unknown (CONFIRM). It's unclear what the condition of the SIOZ coat or steel were prior to spot coating, but presumably it was poor. • The graffiti did not appear to be negatively affecting the coating. • DFT of 4 – 9 mils was measured.	1. Despite the presence of joints at the abutments, the coating is in fairly good condition in these areas despite its age. 2. Small localized DFT caused by insufficient coating application or poor workmanship led to coating failure and substrate steel corrosion; although the steel is in good condition for its age. Were the interior and exterior girders all last coated in 1995?

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/25/22	3996	• Salt spray from Interstate below (I-55) • No deck joints (integral abutments and continuous otherwise)	• Good condition (stencil said 1995 but looks newer), with rust grades judged to be between 8 and 10. • Thought to be shop applied • The deck was obviously newer; precast panels. • Minor corrosion of the bottom flanges and bottom of webs at abutment interface. Could be caused by water flowing down the bottom flange to this low point, or by condensation at the steel-concrete interface • Checking and cracking of the coating at the top flange-web fillet on one side at one girder location. • Minor spot rusting on the top flange at one girder location, both sides of web. • The graffiti and spot painting over it did not appear to be negatively affecting the coating. • No signs of differing performance over traffic lanes from available vantage points. • DFT of 5 to 14 mils was measured.	1. Fillet areas seem prone to checking and cracking.
4/25/22	6603 / 6604	• Moisture from creek below (Fox Creek); evidence of past flood events (e.g., debris in cross frames) • No deck joints (integral abutments and continuous otherwise)	• Corrosion on the bottom sides of members (cross frames, girders); mainly spot, general, and edge rusting. Most of the corrosion on the girders was near the piers. Not clear if this was due to application or an environmental factor (e.g., moisture collecting at these areas). Rust grades judged to be between 1 in localized areas, to 5 on average for the worst span of the worst girder, to 9 or 10 (depending on inspectors' judgment) for most locations. • Coating on the bearing components was also failing and substrate steel was corroding. • Location of flood debris indicates flood waters have reached superstructure. • Some girders contain field applied paint and some contain shop applied paint. This appears to cause dramatically different performance in this structure (see Photo P4252912). • DFT of 4 to 12 mils was measured.	1. The corrosion on the bottom surfaces could be the result of small coating thickness caused by poor application. These surfaces could have been difficult to reach, especially if field applied. Alternatively, moisture could have been collecting at piers, which could be low points, and causing coating failure and steel corrosion. 2. Flood events could also have contributed to coating failure.

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/25/22	4115	• Splash/spray zone due to roadway below (I-44) • Joints at the abutments that have failed at various points in the past	• Overall good condition, but general and spot rusting of the girder webs and flanges at the abutments. Rust grades judged to be 10 overall, but 9-S and 4-G in some locations. • On the end cross frame, edge failure and rusting on the members, gussets, connection plates; failure and rusting on the fasteners; crevice corrosion at faying surfaces. • At the bearings, near complete coating failure on the girder bottom flanges and the sole plates with underlying steel corrosion. Some coating flaking at the boundaries of this failure. • The deck was replaced at some point after the coating was applied. It appeared that equipment used for re-decking (e.g., overhang falsework) damaged the coating in certain locations, and spot coating was applied to repair the areas. • DFT between 4 and 8 mils was measured at web locations. DFT between 9 and 10 mils was measured on exterior flange. DFT between 16 and 18 was measured on interior flange.	1. Joints lead to coating failure and underlying steel corrosion.
4/25/22	4816 / 800	• Moisture from creek below (Spencer Creek); evidence of past flood events (e.g., girders were dirty); almost like a culvert • Joints at the abutments and piers (based on Google maps)	• Limited access due to creek so close-up visual inspection was not possible • No significant defects were noticed from a distant view	[N/A due to access limitations]

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/25/22	4105	• Overpass ramp structure with large vertical clearance (i.e., probably little to no salt spray from roadway below) • Joint at the abutment and at the end pier (3 spans SIOZ steel, others concrete) • Insect and bird nests	• Minor pinpoint and spot rusting on the top flange and web of several girders. Overall rust grade judged to be 9 or 10 (depending on inspectors' judgment). • Coating failure/spot rusting on the exterior girder bottom flange and bearing sole plate at the West pier. Spot rusting on the bottom flange of the same exterior girder at a splice location. • Local small spot rust locations on several cross-frame connection plate-to-girder welds. • Spot painted beneath the joint at the pier. Unknown type and application date. • Galvanized bolts used for cross frame connections. • DFT measurements ranged between 6 to 7 mils for webs and 9 to 11 mils for the top surface of bottom flanges.	1. Joints led to coating failure and underlying steel corrosion. The presence of spot coating is evidence of this. 2. Good condition otherwise away from joints.
4/25/22	4213 / 4202	• Overpass (RTE 370 over Elm St), some salt spray likely • No deck joints (integral abutments and continuous otherwise) • Bird nests	• Pattern of pinpoint and spot rusting intermittently on bottom of bottom flanges; spot rusting most pronounced at cross frame lines. Rust grades judged to be: 10 most locations, 9-G overall, 7-G on average for the worst girder in the worst span, and some localized locations with 2-G to 5-G. • Some edge rusting on along edges of girder top and bottom flanges. • Edge rusting and crevice corrosion on several cross frames • The deck appeared to have been replaced. Precast panels look fairly new. • Galvanized bolts used for cross frame connections • SIOZ coating thought to be Sherwin Williams because it is darker; Carboline is usually lighter. • No visible difference in performance over traffic from available vantage points. • DFT was measured to be between 4 (exterior web) and 11 (interior flange), but no consistent trend in DFT measurements.	1. The intermittent locations of coating failure and corrosion on the girders do not seem to be environment related; rather, the pattern indicates poor application or damage during re-decking.

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/26/22	8386	• Salt spray from Interstate below (I-35) • Joints at the abutments	• Rust grade judged to be 8 or 9 (depending on inspectors' judgment) for the end span that was most directly accessible; worse condition exists over traffic. • Field painted • Deck replaced within the past 4 years • End of superstructure coated with MoDOT's standard epoxy intermediate coat during the deck replacement • Possible spot painting in the interior spans (over roadways) • Intermittent spot rusting with minor flaking and minor checking. Spots were approximately 2" diameter in the web/top flange region. This appears to be attributed to rigging/equipment used during the deck replacement. • Bottom of the bottom flanges showed spot/general/pinpoint rusting over the roadways. The girders were cover plated in these regions as well, possibly due to corrosion problems. • Bottom of the bottom flange had spot/general corrosion at the pier bearings. • Some edge rusting of the diaphragm flanges • DFT measurements ranged between 3 (interior flange) and 7 (exterior web) mils for the portions with the original SIOZ. Repainted areas have DFT from 12 to 14 mils.	1. Joints lead to corrosion. Repairing and end coating is beneficial. 2. Regions over the roadways are in an aggressive micro environment that is causing coating breakdown and steel corrosion. 3. The coating is in good condition away from the aggressive micro environments. 4. Proper application along edges and corners is important.

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/26/22	6487	• Salt spray from Interstate below (I-35) • Joints at the abutments	• Coating failure and corrosion are concentrated at the abutments and over the roadway. Rust grades of 8-G, 8-P, 7-G, and 7-P were generally noted, although the portion over traffic lanes was assigned a grade of 4-G. • At the abutments, the deck joints have failed and allowed moisture to reach the superstructure steel. There was spot rusting, general rusting, pinpoint rusting, and edge rusting of the girders and end diaphragms in this region. • Over the bearings the coating was blistering and undercutting, and the substrate steel was corroding. The bearing stiffeners were fabricated from rolled angles and did not have clips/snipes, so moisture and debris was likely collecting because there was no drainage path. • At the piers and over the roadways, there was general and pinpoint rusting of the girders and cross frames, particularly on the bottom surfaces. • There was very fine checking in some areas of the webs and along the fillets with minor flaking in select areas. This corresponded to areas with higher DFT, of 12 to 15 mils. Other areas had DFT measurements of 7 to 9 mils. • There were a couple of locations with running of the coating.	1. Joints lead to coating failure and underlying steel corrosion. 2. Regions over the roadways are in an aggressive micro environment that is causing coating breakdown and steel corrosion. 3. The coating is in good condition away from the aggressive micro environments. Despite its age, there were only minor signs of coating failure in these regions.

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/26/22	1183 / 1184	• Minor salt spray from roadway below (the bridge is on I-435 over a local road so not much salt anticipated from below). • Over a railroad (small amounts of diesel exhaust?) • Large vertical clearance probably helps mitigate both of the above • No deck joints (integral abutments and continuous otherwise)	• Integral abutment bridge • The deck appeared to have been replaced at some point due to the concrete stains on the girders. • There are two separate bridges (longitudinal joint separates the two). The bridges appeared to have been widened at some point because there were several exterior lines of UWS girders on the south side of the south bridge, and 4 separate pier structures (2 per bridge). • Intermittent spot rusting with minor flaking. Spots were approximately 1-2" diameter in the web/top flange region. Possibly attributed to rigging/equipment used during the deck replacement. • Pinpoint rusting of the top of the bottom flange and web near the east abutment. The rating varied from 9 (generally) to 6-P and was observed for the visible length of girder. • DFT values were relatively consistent and measured to be between 6 and 8 mils, with one reading of 9 mils.	1. The lack of deck joints combined with the high vertical clearance over a railroad and local road with lower salt application reduce the severity of the micro environment. These had led to the coating performing as intended. 2. Despite its age, there were only minor signs of coating failure.

6/6/22	24209 (VA)	• Possible moisture from creek/river below (Occoquan Reservoir feeder); although vertical clearance was very high at time of inspection. Depending on the flood stage levels, the columns could be partially submerged during these events. There was some debris on a few column bases. • Joints at the abutments that have failed at several locations; intermediate deck relief joints or construction joints. • Some graffiti present, particularly near the north abutment where there is access from a pedestrian walkway. • Insect and bird nests	• The worst conditions were observed at girders where deck joints have failed, allowing moisture to run down the bottom flange and cause coating failure and corrosion. This occurred at the west exterior girder on the north side of the bridge (worst), and several girders on the south side of the bridge (one-third to one-half of the girders). There was visible efflorescence on parts of the bottom flange and bottom of the web on these girders. This has led to isolated locations of coating deterioration and failure at several bearings, splices, and bottom flanges. (Rust grade = 10, generally due to limited nature of this relative to size of structure) • There was efflorescence on the west exterior girder in the main (middle) span similar to that noted above. However, the source of moisture was not clear. Could have been coming through the deck somehow, or through joints in the parapet. • Spot rusting at several of the column to girder welded splices. These locations were either field coated or overcoated. (Rust grade = 6-G if only considering the columns) • Spot/general rusting at several stiffeners of girder-to-column transition radius. There were clips in the plates for weld access and drainage, but larger size clips would have been preferable. • Minor spot rusting was present at a common bolt detail through the top flange near the abutments. Presumably, the connection was for SIP forms. • At one girder line, spot/general rusting and undercutting of the bottom flange of the inclined column leg near the bearing. • Touch-up/overcoating of the girder ends at the north abutment due to graffiti • Minor edge rusting occurred mainly on cross frame members, and a few isolated locations on bottom flanges. • A couple of visible locations of coating running, but no problems. • Undercutting only occurred where moisture could get to (locations described above) and cause the coating to fail. • Galvanized fasteners	1. Joint failure leads to coating failure and underlying steel corrosion. 2. Welded locations seem more prone to coating failure and corrosion. The cause was not clear, but could have been due to improper surface preparation, or weld effects.

Date	Structure ID	Environmental Conditions	Notes	Takeaways

			• DFT measurements (4 to 12 mils):
			  • Highest on top surfaces of bottom flange (relative to bottom surface of bottom flange and web, 2 locations): range of 9 to 12 with average of 10
			  • Bottom of bottom flanges (2 locations): range of 4 to 9 with average of 6
			  • Web (1 location): range of 7 to 8 with average of 8
			  • Note: 3 measurements taken per location	

4/27/22	0016276A (WA)	• Over Barclay Creek with relatively low clearance (approximately 10' or less from photos)	• Possibly a coated weathering steel bridge. • Coating was shop applied to all steel except splices, which were field coated. • Few isolated locations of spot corrosion (Rust grade = 9S). • Coating deterioration and corrosion common at bolts. OZ was field applied to bolted connections (girder splices, cross frame connections). • Minor corrosion adjacent to splice and cross frame connection locations. Attributed to overblasting. • Coating damage and deterioration with minor corrosion at isolated locations attributed to construction practices. • Deck joints were in great condition with no issues noted. • Some edge rusting. • There were noticeable color differences in the coating at the joints. • Some striping on the webs. • DFT measurements: 4 to 8 mils (see form)	1. Overblasting at connections can lead to insufficient coating and corrosion. 2. Field coating bolts can be difficult. May be easier to specify galvanized bolts for field connections.

Date	Structure ID	Environmental Conditions	Notes	Takeaways
4/27/22	0016609A (WA)	• Over Nolan Creek with relatively low clearance (approximately 10’ or less from photos, 8’-9” min from design plans) • 5 miles from the coast	• Coating was shop applied to all steel except splices, which were field coated. • Few isolated locations of spot corrosion (Rust grade = 9S). • Coating deterioration and corrosion common at bolts. OZ was field applied to bolted connections (girder splices, cross frame connections). • Minor corrosion adjacent to splice locations. Attributed to overblasting. • Coating damage and deterioration with minor corrosion at isolated locations attributed to construction practices (e.g., blocking locations). • No leaking at deck joints. • Minor edge rusting. • Discoloration noted in the web at some locations. Attributed to a feature of the specific product. No difference in DFT measured at these locations. • DFT measurements between 4 and 7 mils (see form)	1. Overblasting at connections can lead to insufficient coating and corrosion. 2. Field coating splices can be difficult and is susceptible to missing surfaces. This is evident by the lack of coating and steel corrosion on similar facing surfaces (e.g., faces of fasteners facing the same direction showing similar corrosion). 3. Field coating bolts can be difficult. May be easier to specify galvanized bolts for field connections.

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